Thermal Manikins and Modelling

Edited by Jintu Fan

The Hong Kong Polytechnic University
Hong Kong
SIXTH INTERNATIONAL THERMAL MANIKIN AND MODELLING MEETING (6I3M)

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Edited by Jintu Fan
The Hong Kong Polytechnic University
Hong Kong

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Preface

Thermal manikins are essential tools for the objective and accurate assessment of thermal comfort or stress. They are particularly useful for investigations under harsh conditions that simulate extreme environments such as wind blown mountaintops, scorching deserts or even hostile space, but also indispensable for the development of functional clothing (e.g. sportswear, protective clothing, army uniforms) and HVAC (i.e. heating, ventilation and air-conditioning) systems for the creation of safer and more comfortable living.

Along with the development of thermal manikins, modelling of the human body, clothing and environment system is also very important as it enables us to predict human performance in different conditions.

This volume contains papers presented at the sixth international thermal manikin and modelling meeting (6I3M) held in Hong Kong from 16th to 18th October 2006. These papers cover different aspects of thermal manikin and modelling including early development history, current original researches, improvements in standardization and innovative applications.

This book is an essential reference for research scientists, technologists, safety engineers, product developers and health care professionals as well as students in the areas of environmental ergonomics, functional clothing, thermal engineering and occupational safety.

I would like to take this opportunity to thank members of the Board of Scientific Program Committee of 6I3M for their academic leadership and invaluable advice. I also wish to express my sincere gratitude to the Institute of Textiles and Clothing (PolyU), Hong Kong Research Institute of Textiles and Apparel, and Modern Testing Service Ltd for their generous sponsorship to the Meeting. I am also indebted to Prof. L. Hunter of CSIR, South Africa for proofreading and editing the writing of all the manuscripts. Last but not least, I would like to thank members of the organizing committee, especially Lydia Fung, Cathy Tsang and the Apparelkey team for the dedication in organizing the event.

Jintu Fan

Hong Kong
October, 2006
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Section I
Keynote Lectures
Thermal Manikins, Their Origins and Role

Ralph F. Goldman

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**COMFORT**

Perhaps the first use of a manikin in any thermal role was in about 1650 at Magdeburg University in Germany, where Otto von Guericke developed a manikin, rotating on some kind of spring. The manikin had an outstretched hand whose finger pointed to a set of numbers ranging from 1 to 7, labeled from “Maximum Frigor” to “Maximum Caldor”. Unfortunately, use of a 7-point scale for human thermal comfort by the American Society of Heating & Ventilation Engineers (ASHVE, the predecessor of ASHRAE), dating to the 1920’s, has been problematic; humans cannot reliably discriminate between hot, warm, slightly warm, comfortable, slightly cool, cool and cold. Also, comfort is not a “state variable”, but rather a state of mind. As shown by McIntyre, in the following Figure, the Standard Deviation of a Predicted Mean Vote (PMV) is one full scale unit; i.e., a “Comfort Vote” of 4, ± 2 Standard Deviations, has a 95% confidence interval ranging from 6, “warm”, to 2’ “cool”, or using Fanger’s rotation, where Comfort = a PMV of 0, the 95% confidence range is +2 to –2. Thus, those with access to tools to measure human heat transfer should avoid such psychological, mind based, “PMV” estimates of comfort, and instead rely on the much more reliable physics/biophysics of heat exchange to evaluate human comfort.
CLOTHING COMFORT

Similarly, clothing comfort is not a state variable. Instead I have suggested it depends on the four factors I term “The Four Fs of Clothing: Fashion; Feel; Fit and Function”. Fashion is primarily created by advertising; if you question that, just look at your children’s clothing. Feel, i.e. the “hand” of fabrics, has been well delineated by Professor Kawabata. He characterized “fabric hand” using such parameters as roughness, smoothness, softness, crispness, bulk, et al., provided a series of booklets for sampling the range of many of these parameters by including swatches scaled from 1 to 10 of many of these parameters, and developed a series of instruments for some of them. Fit, including such factors as fabric drape and garment cut, is largely a function of pressure. An instrumented torso manikin was developed with pressure sensing switches indicating $<1, 2$ to $4$ or $>5$ psi pressures for use in developing military body armor; its application led to the adoption of the “Personal Armor System, Ground Troops” (PASGT) used by the U.S. Army in record time. In assisting clients, I built an instrumented female torso with pressure sensors for use in designing brassieres, and also developed a portable, infra-clothing, pressure sensor system that some graduate students have used for clothing design studies on jackets, shirt collars and the like. The Figure below summarizes some of the findings on Fit.

Fibers, Fabrics & the like

Evaluation of clothing fibers, fabrics, membranes and the like should not be done with manikins. Their five key parameters are too often masked by such factors as drape, fit, specific contact area and weight to glean appropriate information from manikin studies. These material properties are: 1) fabric insulation; 2) fabric moisture permeability; 3) wicking characteristics; 4) water uptake/holding characteristics; and 5) drying time. Instead, the classic “Cleveland guarded, heated flat plate”, in a climate controlled box chamber with high air motion over the plate
(and not the newer version with air flow from one side, where one cannot be sure of the effective ambient temperature over the test section) should be used to measure the Clo value of materials. Also, material thickness should not be measured in accord with the ASTM Standard, which calls for measurement under a 7 gram per square centimeter pressure, but with a swinging pendulum technique, i.e., a common pin suspended on a fine thread attached to a °C Vernier caliper is set into motion and the Vernier gauge lowered slowly until the tip of the pin motion is just interfered with by the fine surface fibrils of the material. If the measured value is not 1.57 Clo/cm of material thickness, repeat the thickness and Clo measurement, since either one or the other measurement is wrong, or the material is unusually dense for clothing or has too little fiber bulk (e.g., micro-fiber batting) to block the normal heat transfer by radiation. As will be illustrated in the presentation, air is by far the dominant insulator in clothing, either contained in the fibers or between clothing layers.

MY FIVE LEVELS of ANALYSIS

I highly recommend this approach, which evolved during my 50 years of R&D in this area and will be cited during the rest of my presentation; running from Level 1 to 5, these are:

1. **Physical analysis** of problem elements is carried out; e.g., fabrics, environment, load carried. No subjects are required, costs are minimal and the result is usually extremely helpful.

2. **Biophysical analysis** of the items (e.g., garments fabricated from new fabrics) is carried out. Prediction **modelling** to identify probable differences under various conditions, is a key element at this level. Again, no human subjects are involved although models, mock-ups, manikins, etc. may be, but these cost far less than human subject studies.

3. **Human physiological** (small scale with 6 to 8 Ss), "validating" studies under tightly controlled conditions (e.g., in climatic chambers, on treadmills, stopwatch paced, etc.) are carried out to confirm that the projected differences do indeed occur.
These are unlikely to be successful unless Level 2 modelling was used to select an appropriate forcing function (work rate, rest/work/recovery cycles, exposure duration, environmental conditions).

4. **Controlled field trials**, modest in scale (~20 to 50 Ss), are conducted; the items are used by the intended users in the actual conditions of proposed use, but under conditions that Level 3 suggested would be neither excessive nor inadequate. Relatively expensive, but introduce “real world” variability; any surprises mean back to Level 3 for study.

5. **User trials** ("test marketing" in the civilian community, "user wear or operational trials" in the military; “field construction projects” in the working world) are the final step; these are usually large scale, time consuming and expensive, and may well prove fruitless, difficult or provide questionable information, unless levels 3 and 4 have preceded them.

This progression of test levels decreases in scientific information yield and reproducibility, and increases in cost and possible confounding from level one to level five. Many new approaches and/or ideas can be eliminated even at level one, with enormous savings of subsequent research effort. Still more may be eliminated at level two, but the real savings here comes in the selection of "adequate forcing functions" (i.e., optimal test conditions) for demonstrating supposed differences in user response to the test item. If the essential "background" studies of levels one and two are conscientiously carried out, there should be few surprises during level three testing. Real world factors, which might otherwise confound laboratory results, can usually be dissected out in level four studies. Finally, user acceptance or resistance can be rationally assessed, although the real merit of the item versus the claims made for it may not be detectible at level five. Of course, that is if one is looking for practical, meaningful differences rather than statistically significant ones, at least from level three on up.

**THERMAL MANIKINS**

It all began with Sleeping Bags. In the late 1920s, a wealthy industrialist endowed a research program at Harvard Medical School to study the effects of “Fatigue” on workers. Most of the early studies were on work physiology, which fit well with the Medical School agenda. However, after baseline studies on work physiology were completed and the research focus shifted to problems in applied physiology, the “Harvard Fatigue Lab” was promptly shunted to the basement of Harvard Business School. By 1940 the Lab, directed by L.J. Henderson a respiratory physiologist, was well known for its studies of work at altitude and for studies by David Bruce Dill on work in the heat during the construction of the Boulder Dam in the Nevada desert. Along with collaborators from the Harvard Medical School and Massachusetts General Hospital, the Fatigue Lab staff provided the cadre for the laboratories that the United States set up to support its troops during 1942 after its entry into WW II on Dec. 7th, 1941. These, among others, included the U.S. Army
Medical Armored Research Lab. (AMRL) at Fort Knox, Kentucky, which dealt with problems of armored vehicles during desert operations, and the U.S. Army Quartermaster Climatic Research Lab (CRL) at Lawrence, Massachusetts, with Harwood E. Belding (who became its Director in 1946, and others from the Fatigue Lab.) to study the problems of cold weather operations in Northern Europe and Alaska, where more soldiers were injured by cold than battle. CRL became the Environmental Research Division (EPRD) and moved to Natick, MA shortly before I went to work there in 1955. Parts of EPRD and AMRL were merged in the 1960s to form the U.S. Army Research Institute of Environmental Medicine (“USARIEM”). The field I developed during my 27 years in Natick, “Military Ergonomics”, started with the pioneering work by Alan Burton of Canada, who had published (J. Nutrition 9:261, 1935) his two compartment (skin and core) body model, with a mean body temperature based on 1/3 skin and 2/3 core temperature, using an average specific heat for the body tissues of 0.83 kcal/kg.°C, and by Gagge, Burton and Bazett who introduced (Science 94:24, 1938) a clothing insulation unit, the Clo, equivalent to the 14% larger, “R value” used for thermal insulation in the construction and HVAC industries.

A major focus for the Climatic Research Lab/Harvard Fatigue Lab team mobilized in Lawrence (where a large wool supply company had built a chamber capable of reaching – 40 ° to de-fat raw wool), was development of a sleeping bag to provide more cold protection than the Standard Government Issue, thin, single layer wool “blanket” bag and air mattress. The goal was to provide a bag which would “allow six hours of restful sleep at – 40 °C”; this goal has yet to be reached (physics rules - it requires ~ 12 Clo, which cannot be achieved because of the associated increase in surface area that accompanies increasing thickness of insulation around any cylindrical object, whether a human finger or body), so the “goal posts were moved” in stages to today’s requirement of “2 hours of restful sleep”; i.e., body heat debt should be ~ 80 kcal in about two hours, a value that Belding suggested would wake a sleeping soldier, and my studies suggest would drive a working man to a re-warming shelter. The earliest studies in 1942 tested a variety of sleeping bags with at least 2 or 3 subjects trying to sleep at -18, -25, -32 and -40 °C, wearing 2 pair of heavy wool sox, 1 pair of arctic sox, 2 pairs of wool long underwear, a worsted wool shirt, 1 pair of heavy woolen mittens, plus a head toque muffler for the face. If a given subject found a bag acceptable, the test was repeated at the lower temperatures until it was not. One of the first 1942 reports (a Harvard Fatigue Lab study reported as CRL Rpt # 25) concluded that: 1) if a subject slept on his side, while the upper side might be ~ 35 °C initially, the lower side would start at least 3 °C colder, dropping to ~22 °C in 3 hours (from an initial reading of ~29 °C); 2) average human weight compression force at the hip was about 1 psi; 3) only the hardiest subjects could endure a hip temperature of 20.5 °C; and 4) a toe temperature of ~16 °C would be the end of any subject’s tolerance. Even these first studies were useful; an air mattress, fitted inside with an insulating pad attached to its upper surface was tested in November 1942 and increased stay time. But analysis of subject variability for a repeat test on the same subject at the same air temperature gave a difference of ~ 9%; for the same man at 2 different temperatures it was ~ 17%; for 2 different men at the same temperature, ~ 15% and for 2 different subjects at 2 different temperatures it was ~ 14%.
J.R. Breckenridge, then an Army Technician 3rd class attached to CRL, who I selected to head my Biophysics Branch in the 1970’s, told me of one of the earliest attempts to develop a heated manikin to use to reduce the variability of such human subject testing (and possibly eliminate the considerable subjective discomfort). "LUMPY" consisted of a set of water tight tin cans; four, roughly the size of a can of soup, served as hands and feet, larger ones simulated lower arms and legs, still larger ones upper arms and thighs, etc. The cans were linked by water tight tubing connections, and controlled temperature hot water was circulated between the cans. The temperature drop between inlet and outlet with time was used as a measure of bag insulation. However, as others have found in attempting to construct a circulating suit thermal calorimeter, it was very difficult to measure both the flow and inlet outlet $\Delta T$ with sufficient precision, to say nothing about the problems of mixing, so “Lumpy” was discarded.

By November of 1942 (CRL Report # 43/Harvard Fatigue Lab. Rpt # 8), the science had advanced considerably. Human subject measurements now included 9 point mean skin temperature, measured every 15 minutes, rectal temperature measured hourly and body heat production (respiratory $O_2$ consumption) measured continuously; and body heat debt was calculated as $0.3xT_s+0.7xT_r$. Pete Scholander was at the Harvard Fatigue Lab, along with Bruce Dill [and his future son-in law, Steve Horvath, who had just completed his Ph.D. studies at Harvard], Lucien Brouha [who I co-taught a class with at SUNY, Buffalo in 1961] and many other distinguished physiologists were active with the group. A “Cenco Fitch calorimeter” had been constructed, consisting of an upper metal vessel holding boiling water and a lower, well insulated, metal receiver with thermocouple temperature sensor, designed to exert a pressure of 1 psi (the pressure of a man’s hip against the lower surface of his sleeping bag) allowed direct physical measurement of the sleeping bag material. The first model of an “Electrically Heated Dummy” with an internal fan blowing air across internal heating coils throughout the torso and down the extremities, using on-off thermostatic control to simulate human skin temperature, was introduced. The report concluded that: this dummy did not compress the sleeping bag adequately; at least two bag sizes had to be manufactured to fit the range of soldiers; and an auxiliary, highly insulated, foot bag was needed. An “ADEQUATE SLEEPING BAG” could now be defined in physical, biophysical and physiological terms; it “must keep lower hip skin temperature above 80 to 85 °F (~22.5 to 29.5 °C) for 3 hours and limit heat loss to ~ 40 to 45 kcal/ m².hr. A field trial with human subjects was run in December at Ladd Field, Alaska. By April, 1943 an improved “electrical dummy”, with the electrical fan blowing air through tubes to the extremities was built. Run without head or arms, this dummy weighed 18 kg, surface area for heat loss was 1.5 m² and, with an internal temperature of ~ 40 °C, average skin temperature approximated human value. Using a watt-hour meter to measure internal heat supplied and “Clo value” to characterize heat loss, a 2% accuracy was achieved on repeated tests. The value measured for the dummy wearing wool knit underwear, with heavy wool sox + arctic sox was reported as 1.3 Clo.

By September 1943 (Fatigue Lab Report # 122) the physiologic measurements had been upgraded to an 11-point mean weighted skin temperature, using weightings proportional to the surface area involved, rectal temperature measurement was
standardized at a depth of 15 cm. and plotted every 15 minutes, and the calculation of mean body temperature was corrected to \( \frac{1}{3} T_s + \frac{2}{3} T_e \). A wide variety of clothing materials were being measured on a new, “Cleveland” heated flat plate, guarded on all 4 sides, and across the bottom by heated sections set at the identical temperature as the central test section; this is still the recommended technique for measuring material insulation, but cannot simulate the effects of material weight or garment drape, size, cut, closures, etc. A new heated hand, and foot, for hand- and foot-wear Clo determinations had been constructed, and a new electrically heated dummy, made of 1.6 cm thick sheet copper, heated internally by resistance wire and electric light bulbs, with internal fan and on/off thermostatic control of temperature had been fabricated. A difference in measured insulation values of 5% was now considered significant. Based on the success of using the manikins to supplement physiological determinations, e.g., the loss of clothing insulation worn by marching soldiers in the cold calculated from heat balance equations, as shown in the following Figure, Dr. Belding was ready to contract for a series of standard manikins.

A renowned artist Gutson Borglum, sculptor of the enormous, stone, Presidential faces on Mount Rushmore, was commissioned to sculpt the manikins in electrically conductive wax, using the mean anthropometric dimensions from a survey of almost 3000 aviation cadets at Wright Field. These wax figures were then electroplated to a ~3 mm thickness of copper, and then the wax melted out; this “cere perdu” process had been used since pre-historic time to make jewelry. The head, thumbs and forward part of the feet were made removable, and the shoulders were articulated to rotate 180 degrees, both for internal access and to facilitate donning clothing, hand and footwear. A small company, involved in making the earliest electrically heated blankets, provided panels of wires for six separate heating elements (head, torso, upper and lower arms, and upper and lower legs, with heating capacity proportional to the surface area to be heated) to be glued to cover the inner surfaces of the manikins; that company is now General Electric Corporation. Resistors were used to heat the hands and feet, whose temperatures could be adjusted apart from the thermostat used to control the overall skin temperature. Thermocouple temperature sensors, placed in 22 caliber bullet cartridge cases inserted into the skin at appropriate sites, were used to measure the average skin temperature of each section of the manikin, whose skin was blackened to more closely approximate the thermal emissivity of human skin. The first of these, named “Chauncy” by Dr. Belding,
arrived early in 1946, and had connectors for power, thermostat control and skin temperature sensors in the area of what would have been the human navel. In a climatic chamber at an ambient air temperature of 10 °C, mean skin temperature averaged ~ 37.5 °C in a vertical position, with a measured surface air layer insulation of 0.64 Clo, and ~ 38.6 °C in a horizontal position, with a measured Ia of 0.73 as reported in CRL Report # 107, A Study of the Copper Man”, 28 August 1946.

I believe ten manikins were eventually fabricated this way; one, whose fate is unknown, went to the U.S. Navy in Philadelphia (Dr, Ed Hendler); one went to the ASHVE Laboratory in Cincinnati, Ohio, was transferred (along with their climatic chambers) to Kansas State University when ASHRAE their successor Society closed that facility, and is still in use by Professor Elizabeth McCullough; one went to Prof. A. P. Gagge at the J.B. Pierce Foundation Institute in New Haven, Connecticut and was eventually thrown out with the trash after most of the information on the Clo values of clothing was known; Dr. Belding took Chauncy with him when he left the government to take a University position (“so his children could afford to go to college”); and three, one of which was a sectional manikin and another a seated version for aircraft cockpit studies, went to the U.S. Army Air Force at Wright Patterson Air Force Base. I acquired these three for USARIEM in the 1970s, when they needed major rewiring, and later arranged to purchase Chauncy for use at USARIEM. These four were united with the original three that had been at EPRD, two of which did not have articulated shoulders, had their wiring connected through the eye sockets, and thus could be used for sleeping bag studies or immersion in water to nose depth studies.

The following picture includes (Left to Right): James Bogart, who ran the USARIEM immersion pool; the water immersion manikin; Professor Harwood E. Belding; Chauncy; a, much younger, Professor Dr. Goldman; the original sweating man, wearing the original form fitting cotton skin I had tailored for him for sweating studies; and Mr. J. Robert Breckenridge who, was rated as an Army Technician 3rd Class with the original CRL team in the early 1940s, became a first rate Biophysicist, my mentor and my right hand as head of the Biophysics Branch of my Military Ergonomics Division at USARIEM, and is still a close friend.
When I first arrived at Natick, I found that most of the Copper manikins elsewhere, aside from the one in the Home Economics Department at KSU, had been put in storage, discarded, or were little used. Studies on the heated guarded flat plate apparatus, in heavy use to measure the insulation properties of new materials, had shown that clothing insulation was a linear function of the increasing circumference of the layers of clothing, and the air layers trapped between them, with practically negligible influence from any specific aspect of the materials or their fibers except their thickness, as shown in the following figures.

![Diagram of Thermal Insulation Around the Torso of an Individual Wearing a T-shirt, Shirt, and Winter Jacket](image-url)

<table>
<thead>
<tr>
<th>Layer (#)</th>
<th>Nature</th>
<th>Insulation* (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surface still air layer</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Jacket cover fabric</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>Trapped still air layer</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>Insulating batting</td>
<td>0.2 - 0.5 - 0.9 - 1.2</td>
</tr>
<tr>
<td>5</td>
<td>Trapped still air layer</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>Jacket lining</td>
<td>0.1</td>
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<tr>
<td>7</td>
<td>Trapped still air layer</td>
<td>0.15</td>
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<tr>
<td>8</td>
<td>Shirt</td>
<td>0.1</td>
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<tr>
<td>9</td>
<td>Trapped still air layer</td>
<td>0.2</td>
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<tr>
<td>10</td>
<td>Underwear</td>
<td>0.15 - 0.6</td>
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<tr>
<td>11</td>
<td>Trapped still air layer</td>
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<tr>
<td></td>
<td>Torso surface total clo</td>
<td>1.6 + 0.7 - 1.0 = 2.3 - 2.6</td>
</tr>
</tbody>
</table>

*Insulation values are approximate and can vary based on specific materials and conditions.
Even at Natick, the R&D center for the U.S. Quartermaster Clothing & Equipment Development center, most of the manikin studies were at the Level 2 measurement and modelling of cold weather operations. The power of being able to select an adequate forcing function for subsequent human Level 3, validating studies is shown in the next Figure.

The close agreement ($r = .89$) between measured heat debt and sleeping bag insulation across a range of ~ 4 to 9 Clo sleeping bags with a three hour exposure, could not have been found without using the Level 2 analysis to choose the conditions for the human subject test.

**The MOISTURE PERMEABILITY INDEX (Im)**

During the “Cold War” of the early 1960’s, reports that large warehouses had been built near many of the airports led to discovery that large amounts of Chemical Warfare (CW) munitions were being stored in them. The question of the ability of U.S. troops to operate in the CW protective ensemble developed during WW II, but worn on very few occasions then, and not since then, was raised. This ensemble, worn with a gas mask, consisted of a set of CCl$_3$ impregnated long underwear worn under a buttoned up, CCl$_3$ impregnated, combat uniform, with impregnated, long cotton gauntlets and long, impregnated cotton sox, with a rubberized over-boot worn over the standard combat boots. A joint team from the Surgeon General’s Armored Medical Lab at Ft. Knox, KY and the Quartermaster Lab at Natick was tasked to run a small-scale field study (Level 4, in my system). The subjects, a 44 –man Platoon, set out on a morning march, with full combat loads, on a comfortably warm April morning in Virginia; in about one hour > 50% had suffered heat exhaustion, and I had a new career direction.

Fortunately, Dr. Alan Woodcock had been studying the evaporative transfer from a forearm sized, wetted cylinder, and had developed a permeability index ranging from 0 when the sweating cylinder was covered by a totally moisture vapor
impermeable cover, to 1 if the evaporative cooling from the wet surface of the cylinder was equal to the maximum evaporative cooling \((E_{\text{max}})\) available in the ambient environment. For the case of an uncovered wet cylinder, \(E_{\text{max}}\) equaled the difference between the vapor pressure of water \((\approx \text{sweat})\) at the cylinder surface temperature, and the vapor pressure of the ambient air, provided that there was a high air motion to prevent any meaningful still air layer build up around the cylinder surface. He used the slope of the wet-bulb temperature lines on a standard “Molier psychrometric chart”, which is \(2 \, ^\circ\text{C per mmHg}\) vapor pressure difference, to convert the vapor pressure difference to an equivalent temperature difference, and then calculated the available evaporative cooling power as the appropriate measured \(\text{Im}\) fraction of that. When I stated that I could get a copper man to “sweat” Dr. Woodcock was sure I couldn’t do that, and when I explained that I would then use his, “only theoretical”, approach to calculate the actual evaporative cooling a man could get wearing any clothing system for which I had generated an \(\text{Im}\) on such a manikin he thought I had lost my mind.

The ORIGIN of the SWEATING MANIKIN

I had an expert tailor from the Quartermaster group make a form fitting cotton skin top, bottom, full head cover and mittens, of good quality cotton with a high water holding capacity. After wrapping the manikin carefully in Saran© wrap, I dressed the manikin in this skin, put on the test clothing ensemble, ran a new “dry Clo value for the manikin + dry skin + test clothing to use as a baseline for calculating the additional heat loss when the manikin skin was wet. This was necessary because, no matter how carefully I wrapped, inevitably there were air pockets trapped under the arms and in the groin area. After this “Dry skin Clo” determination for the ensemble being tested, the clothing was opened as far as possible (i.e., pants dropped, shirt open, cuffs unbuttoned, etc.) and a hand pressurized garden sprayer, filled with water at near skin temperature (i.e., \(\sim 35 \, ^\circ\text{C}\)) was used to repeatedly mist as much of the cotton skin and sock area until saturation was achieved, when the manikin was promptly redressed, with all apertures closed as normally worn. When all manikin skin temperature sites returned to the \(35 \, ^\circ\text{C}\) level used for sweating runs, steady state \(\text{Im}\) values were recorded until a fall in the power demand by any section of the manikin (usually the head or hand) was observed, and the clothing opened and skin sprayed again until fully rewetted. If these two measured \(\text{Im}\) values agreed to the second decimal, that \(\text{Im}\) was accepted and the test ended; if not the rewet, retest procedure was repeated until they did. The amount of water supplied initially was always well in excess of 1 Liter, the sustainable maximum human hourly sweat rate, and generally \(>\) 2 Liters, in keeping with the maximum sweat rate of \(\sim 2.5\) L/hr observed in some of my most severe heat stress studies. I question the validity of \(\text{Im}\) values determined on any manikin with maximal sweat rates on the order of 1 L/hr or less.

1While running a manikin study this month (September 2006) with Mr. Joseph Giblo at the U.S. Navy Clothing Test Facility in Natick, he showed data that he had collected on a water proof manikin that did not need such wraps to avoid internal water damage when its cotton skin was thoroughly wet; the difference between values of clothing ensemble measurements calculated based on the Clo values,
whether the dry cotton skin was used as the baseline or not, was negligible. Thus, with such manikins there is no need for the extra measurement.

The discriminating power of the manikins now was extended from cold weather effects of clothing, to the effects in hot weather, or during physical work when sweat production was required to get the necessary evaporative cooling. An example comes from a study evaluating proposed differences between wearing no underwear, conventional T-Shirt and boxer shorts, conventional Brynje underwear (diamond shaped openings) or “Turmsk Brynje (ladder shaped columns), under a U.S. Army fatigue Uniform in desert conditions.

<table>
<thead>
<tr>
<th>Clothing Systems</th>
<th>Clo</th>
<th>im</th>
<th>im/Clo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert Uniform with No Underwear</td>
<td>1.46</td>
<td>0.40</td>
<td>0.27</td>
</tr>
<tr>
<td>Desert Uniform with Shorts and T-Shirt Underwear</td>
<td>1.64</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>Desert Uniform with Fish Net ‘Brynje’ Underwear</td>
<td>1.65</td>
<td>0.39</td>
<td>0.24</td>
</tr>
<tr>
<td>Desert Uniform with Ladder Net ‘Brynje’ Underwear</td>
<td>1.65</td>
<td>0.37</td>
<td>0.23</td>
</tr>
</tbody>
</table>

A Level 3, small-scale carefully controlled chamber study was designed using this data. Eight heat acclimatized subjects (the preferred number for Level 3 tests, since one subject’s responses could actually be opposite to that of the other seven without eliminating the possibility of reaching a 5% level of statistically significant difference among the test variables) volunteered as subjects for the five-day study. Day one was a re-acclimatization and familiarization day, and also helped avoid the usual Day 1 anxiety and confusion. The next four days involved a Latin Square designed wear of the four test ensembles (each by 2 men each day) in a 49 Climatic chamber at 20 % RH (Wet Bulb = 29 °C), starting with a 40’ treadmill walk at 4.8 km/hr, followed by a 20’ rest, and concluding with a final 40’ walk. These test conditions were chosen based on predicted heat storage under these test conditions, and my experience which strongly recommended the use of alternating periods of rest and work. The results are shown in the following figure.
The only difference observed was in the Ts and Tre with no underwear (0.27 Im/Clo).

**The ORIGIN of the WALKING MANIKIN**

The findings from a study of raincoats indicated the need for a “pumping coefficient” to account for the effects of unusual differences in garment designs as shown in the next figure.

![Graph showing heat storage during rest and walk](image)

It was expected that the heat storage wearing the poncho (Im/Clo = .10), would be the highest, that the storage wearing either coated raincoat would be next, and identical with or without the small vent slit across the back, at shoulder level, (0.15 Im/Clo for both), while the Standard raincoat, made of a fairly air permeable fabric would be least, and identical with or without the slit (Im/Clo = .23). At 29.4 °C with a wet bulb temperature of 22.2 °C, even after 2 hours at rest, there was little meaningful heat storage; that proved to be an inadequate forcing function to discriminate between these systems, but the temperature and humidity conditions had been chosen to ensure that heat storage during the 60 minute treadmill walk stayed well below the 80 kcal level at which our volunteer subjects typically opted to terminate that days exposure.

Note that the coated raincoat, without vent, resulted in the greatest heat storage, while the heat storage wearing the coated raincoat with a vent was just a little higher than the poncho. The standard, permeable raincoat incurred the least heat storage, with identical values with or without the vent. Clearly, the poncho was “pumping” ambient air up under the garment as it flapped with each step; the slit across the shoulders of the, impermeable, coated fabric rain coat had a similar effect, but produced no meaningful additional air exchange in the permeable rain gear. A “pumping coefficient” was devised to account for this factor for both Im and Clo, and a walking version of the Copper man was produced to evaluate it. Subsequent
studies suggested that a walking manikin was unnecessary since these pumping coefficients could be generated simply by using three different wind speeds, as shown below. Studies of wind penetration into clothing systems run by George Fonseca of my Biophysics Branch had shown that once air flow (wind) had penetrated the outer layer, and apertures, of clothing, there was not enough velocity left to penetrate subsequent layers; instead the air flowed around the body between the outer and next layer, exiting the outer layer at the back without penetrating further.

CALCULATING PUMPING COEFFICIENTS

You need to measure clo and Im at a least two different wind speeds. Initially, we used three wind speeds. Later, we supplemented these by using the walking manikin set at one or two walking speeds chosen to generate “effective wind speeds” between the actual wind speeds used.

e.g.: US Standard CW protective over-garment, w/mask, hood, gloves.

\[
\text{CLO} = A(\text{Ve}^{B})
\]

Then: \(\ln \text{clo} = \ln A + B \ln \text{Ve};\) when \(\text{Ve} = 1\text{ m/s}, \ln \text{Ve} = 0\)

\[A\text{ was calculated as } 1.60\text{ at } 1\text{ m/s wind speed.}\]

Then \(B = \frac{\ln 0.98 - \ln 2.2}{\ln 6 - \ln 0.3}\) i.e. values measured at 6 m/s and at 0.3 m/s

\[S_{B} = -0.0202 - 0.7884 = -0.270 \text{ Thus Clo} = 1.60 \left(\text{Ve}^{-0.27}\right)\]

\[1.7918 + 1.2033\]

AND

\[
\text{Im/Clo} = C(\text{Ve}^{D})
\]

Then: \(\ln \text{Im/clo} = \ln C + B \ln \text{Ve};\) when \(\text{Ve} = 1\text{ m/s}, \ln \text{Ve} = 0\)

\[C\text{ was calculated as } 0.21\text{ at } 1\text{ m/s wind speed.}\]

Then \(D = \frac{\ln 0.54 - \ln 1.11}{\ln 6 - \ln 0.3}\) i.e. values measured at 6 m/s and at 0.3 m/s

\[S_{D} = -0.6162 + 2.2072 = +0.531 \text{ Thus Im/Clo} = 0.21 \left(\text{Ve}^{+0.53}\right)\]

\[1.792 + 1.2033\]

RECENT MEASUREMENTS for some US Military Uniform are:

<table>
<thead>
<tr>
<th>UNIFORM</th>
<th>CLO</th>
<th>(P_{\text{clo}})</th>
<th>(\text{Im/Clo})</th>
<th>(P_{\text{Im/Clo}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard w/ body armor+ load bearing</td>
<td>1.45</td>
<td>-0.23</td>
<td>0.29</td>
<td>+0.32</td>
</tr>
<tr>
<td>Standard + CW over-garment w/ body armor+ load bearing</td>
<td>2.20</td>
<td>-0.18</td>
<td>0.10</td>
<td>+0.33</td>
</tr>
</tbody>
</table>
IN CONCLUSION

There are two models for studying clothing as shown in the following Figure.

While my wife has difficulty believing me (and, at times, I wonder myself), if I want to determine the warmth of these $7,000 fur coats, the model on the right will rave about the beauty and warmth of the coat, but cannot characterize its actual warmth, while the Copper manikin on the left cannot even see the coat but can provide a precise value (second decimal, repeatable from test to test, even two years apart), for the thermal insulation it provides in the form of its measured Clo value. As a Scientist, which model would you rather work with?

And finally, there are two levels of manikin measurement values. If you are simply comparing the insulation and moisture permeability values of two clothing items (or even of two clothing ensembles), almost any manikin run in a consistent manner at any constant temperature, humidity, and wind speed can be used. If you are generating clothing coefficients to use in predictive modelling, the demand to calibrate everything precisely, and ensure that everything is working correctly is at a different level, and very few manikin and climatic chamber facilities are run that well.
**TWO FINAL COMMENTS**

**ROUND ROBIN TESTING**

The practice of sending a garment, or series of them, to various laboratories to compare standard testing techniques and their results is frequently hindered by failure to include a measurement of the chamber conditions with a 15 cm. Black Globe Thermometer, sited right at the position where the manikin will be located to measure the radiant characteristics as well as the air motion in the test chamber. Of course there are often slight differences in manikin size and shape, but these should provide a consistent inter-laboratory difference from test to test.

**USING Re & Re INSTEAD of Clo & Im**

Currently, there has been an increasing tendency to express insulation using Re, rather than Clo, values. While this blurs the fact that the Clo value is a combined value incorporating both convective and radiant heat transfer (and accordingly, operative temperature, rather than air temperature should be used as the gradient against skin temperature), as long as one is aware of the difference this works. However, the wonderful ease of calculating the heat loss from a standard (1.8 m²) man as 10/clo kcal/hr/°C difference between skin and air temperature is lost. However, using Re -- which is calculated based on Re – practically guarantees that it will be difficult to determine whether the source of a heat stress problem is too high an insulation value of the clothing worn, or too low an evaporative cooling potential, whereas the simple “Clothing Permeability Index” (Im/Clo), not only identifies the source of any heat stress problem from the clothing but also specifies the precise percentage of the evaporative cooling power available in a given ambient environment as a function of the vapor pressure difference between sweat at skin temperature (42 mmHg for skin without much cover at 35 °C; 44 mmHg for skin at 36 °C, when heavier clothing is worn; or even ~ 48 mmHg or higher for men approaching heat exhaustion collapse), and the ambient vapor pressure; i.e., an Im/Clo of 0.3 indicates that only 33% of the maximum evaporative cooling power of the ambient environment \( [E_{\text{max}} = 5.55 \text{kcal/m}^2\text{.hr/Clo} \times 2.2^2 \times (P_{\text{sweat}} - P_a)] \) can be obtained by the wearer. Try calculating that using Rc & Re? Are we trying to help or confuse with such “scientific” sophistry?

---

2 After several years of calculating heat loss using the 2 °C per mmHg conversion, which Woodcock had derived from the slope of the wet bulb temperature lines on a psychrometric chart (Molier Diagram), my friend Pharo Gagge pointed out that we should be using the Lewis Number value of 2.2 °C/mmHg vapor pressure difference; the slope of the psychrometric wet bulb line reflected a 10% radiant regain by the wet bulb surface from ambient air temperature.
Use of Thermal Manikins in International Standards

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Abstract

The first standards based on thermal manikin measurements were developed in the 1980s. In the Nordic countries tests for thermal insulation measurements of sleeping bags and cold protective clothing were developed. Similar standards were published in Germany by DIN and in the US by ASTM. At a European level, EN 342 describes test methods and requirements for cold protective clothing based on manikin measurements. EN 511 describes a method for determining glove insulation using a thermal hand model. In 2005 ASTM published a standard for determining water vapour resistance with a sweating manikin. ISO 9920 already described in 1992 how clothing insulation could be measured with a thermal manikin. This procedure, however, is more precisely specified in ISO 15831 published in 2003. Another field of application for thermal manikins is the evaluation of thermal environments. In particular, the automobile industry has shown great interest in using manikins for vehicle climate evaluation. An international standard, ISO/DIS 14505, dealing with this particular application is on the way.

1. Introduction

Thermal manikins are sophisticated instruments for the evaluation of heat exchange between the human body and the environment. In recent years, the interest in the use and application of manikins has increased (Holmér 2004). Thermal manikins are commercially available in various shapes, forms and functions. Most manikins are used for research purposes but industry has found several applications for manikin measurements in product development and control. Both research and industrial applications call for standardized methods for using manikins in measurement and evaluation of thermal conditions.
The first manikins were developed for the measurement of the thermal insulation of clothing (Holmér 2004). Mathematical models for the prediction of human heat balance called for the definition and quantification of properties of clothing that had an influence on heat exchange. The first and easiest to define was thermal insulation and the clo-value (Gagge et al. 1941). The second property is water vapour resistance. Only in recent years have we seen the development of sweating manikins that can measure this property in a relevant and accurate way.

This paper reviews the use of thermal manikins in international standards.

2. Nordic Standards

The first standards based on thermal manikin measurements were developed in the 1980s. In the Nordic countries four standards for thermal insulation measurements of cold protective clothing were proposed around 1986 (INSTA 352-355). The first proposal listed definitions, units and symbols (INSTA 352). The second proposal described in detail the form, construction and measures of a thermal manikin (INSTA 353). The third and fourth proposals specified conditions and procedures for the measurement of a single piece of a garment (INSTA 354) and a complete clothing ensemble (INSTA 355), respectively. Denmark was the first country to incorporate the INSTA standards into national standards. Other Nordic countries also planned to do so, but the publication of new EU Directives on personal protective equipment (PPE) in 1989 stopped the introduction of national standards for members of the EU. The two new directives deal with minimal safety and health requirements for the use of PPE (EU-Directive-89/656 1989) and with testing, manufacturing and marketing of PPE (EU-Directive-89/686 1989). As a consequence, a large number of standards were developed by the European standardization organization (CEN) in order to enable manufacturers to test their products and guarantee compliance with the Directive. The need for ensuring higher requirements than minimal in many situations, called for standards in which PPE were classified according to the result of testing.

3. European Standards

In 1989 CEN TC162/WG4 developed a proposal for a standard for protective clothing against cold. Clothing ensembles are put on a thermal manikin “walking” at a defined speed, controlled by step length and step rate. The basic insulation value (total value minus surface air layer insulation) is measured and the value is written on the label in the garment. In the present version of the standard (ENV-342 2003) the details of the manikin testing are excluded. Instead a reference is made to (ISO-15831 2003).

CEN/TC162/WG8 developed a standard for protective gloves against cold in 1993 and revised it in 2004 (EN-511 2005). Similarly to EN342, a complete glove is tested on a thermal model of a hand. The total insulation value is measured at a wind
speed of 4 m/s. The result is assigned to one of four classes of insulation values and put in the label of the glove.

As a follow-up of a German standard CEN published in 2002 a standard for measuring sleeping bags. The standard (EN-13537 2002) specifies requirements on sleeping bags and methods for measurement. This includes measurement with a thermal manikin.

At its recent meeting in Stockholm in July 2006 CEN TC161/WG1 decided to investigate the option of revising EN 344 in terms of testing the cold protection properties of footwear. A new proposal for testing cold protective properties using a thermal foot model will be discussed at forthcoming meetings.

4. US Standards

In parallel and with some communication and exchange of information between members of the US groups and CEN groups, two ASTM standards have been published (ASTM-F1291 2005 and ASTM-F1720 1996). F1291 describes a heated thermal manikin and how it is used to measure thermal insulation of clothing. This standard was first published in 1990. F1720 describes how a thermal manikin can be used to measure the thermal insulation of a sleeping bag.

5. International Standards

At the ISO level there is presently one clothing standard available based on manikin measurements (ISO-15831 2003). This standard describes measures and functions of a thermal manikin and procedures for measurement and calculation of thermal insulation. ISO 9920 (ISO-9920 2006) also briefly describes a thermal manikin, but is basically a database of insulation values collected from various sources.

As already mentioned the need for more accurate prediction of human thermal stress, requires the introduction of values for clothing heat transfer properties. Presently, there are three ISO standards for evaluation of human thermal environments, that require thermal insulation values for clothing.

ISO 7730 (ISO-7730 2006) is a standard for assessment of moderate thermal environments – mostly indoor environments. On the basis of the four primary climatic parameters (air temperature, mean radiant temperature, air velocity and humidity), activity level and thermal insulation of clothing the PMV-index is calculated. PMV is a “measure” of the thermal sensation of people occupying the environment.

ISO 7933 (ISO-7933 2002) is a heat stress standard and provides an improved calculation of clothing heat transfer by using values for insulation and water vapour resistance – measured or calculated. The latest version of the standard includes algorithms for correction of insulation and vapour resistance values for the effect of
walking and wind. The four basic climate parameters, activity level and the clothing parameters are input values for the calculation. The program calculates the increase in rectal temperature and sweating rate for the specified exposure time. The time to reach certain, for the variables defined, critical values are calculated as well.

ISO/FDIS 11079 is a cold stress standard with two options. It calculates the required clothing insulation (IREQ) on the basis of activity and climatic conditions. If thermal insulation of the worn clothing system is known, the standard calculates the recommended exposure time. This time may be eight hours or more if clothing insulation matches the IREQ value or shorter (hours or minutes) if insulation is lesser than IREQ.

6. Other Manikin Standards

Another field of application is the use of a thermal manikin as an instrument for measuring and evaluating thermal environments, in particular, in confined spaces such as in automobiles, trains, aircrafts etc. A European research project (Bohm et al. 1999) studied different methods for the evaluation of thermal environments in vehicles. One result was the proposal of a thermal manikin as a relevant, valid and reliable method. In particular, a multi-segmented thermal manikin is able to detect thermal effects on small parts of the human body in asymmetric thermal environments. On the basis of this research a standard was proposed for evaluation of thermal environments in vehicles (ISO/CD-14505/2 2003).

7. Discussion

The introduction of international standards for thermal insulation measurements of clothing has improved conditions for the production and marketing of high quality clothing products that meet certain defined performance levels. It becomes easier for the end-user to select products according to his or her requirements or needs. It also becomes easier for manufacturers to produce clothing for certain, specified demands. A prerequisite for this is the availability of standards that can predict the performance and protection offered by a tested clothing ensemble in different user scenarios, as described in section 5.

A basic requirement for the assessment of protection is the validity of the measurements of clothing thermal insulation. In ISO-15831 and in EN-342 two alternative methods for the calculation of clothing thermal insulation are presented – a “serial” and a “parallel” method. Both methods are, in fact, parallel as they describe a heat flow from a uniform, warm surface (34 °C) that passes through layers of clothing covering different segments of the surface, lying side by side.

A thermal manikin is constructed with a number of independently heated and controlled segments that totally covers the body surface. Number of zones may vary from one to 30 or more, but is normally between 15 and 20. The total heat flow from the body surface is the sum of the segment heat flows corrected for their percentage
of the total surface area. The resistance to the heat flow is made up of all the parallel resistances of the segments that is provided by the local clothing components. The resulting resistance is calculated according to Ohm’s law.

\[ \frac{1}{R} = a_1 \frac{1}{R_1} + a_2 \frac{1}{R_2} + a_3 \frac{1}{R_3} \ldots a_n \frac{1}{R_n} \]

where \( R \) is the resulting resistance to the flow of heat over the whole body surface, \( R_1 \) is the resistance of segment 1 and \( a_i \) is the fraction of total body surface area of segment 1 etc.

This formula is in contrast to the formula for the serial calculation that requires a direct summation of the area weighted resistances. Parallel resistances cannot be summated in this way. In fact the formula above describes that the total dry heat transfer coefficient \( (1/R) \) is equal to the sum of the area weighted segment coefficients, which makes sense.

Unfortunately, the standard makers could not agree on the most valid of the two methods. However, the bulk of scientific evidence to date has provided support for the use of the “parallel” method (Havenith 2005, Havenith et al. 2006, Meinander et al. 2003, Nilsson 1997). For winter clothing with different thickness of insulation over the body surface, the serial method might give an insulation value that is 30-40\% higher than the parallel method. This over estimation of insulation may endanger the heat balance of the user in a real situation and involve a risk of unexpected body cooling. Therefore it is strongly recommended to use insulation values based on parallel calculations only, for prediction of protection. The two ASTM standards use the parallel method.

Although thermal manikin measurements represent a significant step forward towards relevant and realistic description of clothing effects on heat exchange, improvements can be made. This is particularly true for such effects as wind permeation, solar radiation, wetting of clothing and body motion. Some of these factors have been addressed in a recent EU research project (Havenith et al. 2006) and are supposed to be incorporated in existing standards under revision.
8. References
ISO-7730. 2006. Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.
Section II
Thermal Comfort
Effect of Clothing Insulation on Attenuation of Radiative Heat Gain

EA Den Hartog\textsuperscript{1}, P. Broede\textsuperscript{2}, V. Candas\textsuperscript{3}, G. Havenith\textsuperscript{4} and ThermProtect network

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Abstract

The Thermprotect project, as financed by the European Union, aimed at addressing the effects of radiative heat and moisture on clothing insulation, especially focussing at the effect these sources of heat transfer may have on current standards of protective clothing. In one work package the effect of heat radiation on heat exchange was studied in manikins as well as humans. As a wide variety of clothing and radiative environments was studied, there was a need on modelling the data to be able to fully comprehend the results. Also, the modelling effort should serve as a basis to transfer the results to standards on protective clothing. In this paper a modelling approach is presented, that is aimed to describe the effect of different levels of insulation on the attenuation of radiative heat gain from external sources. The properties of the model are briefly discussed and then the prediction of the model is compared to the results of the manikin experiments within the ThermProtect project. Initially only the data in which basic Nomex\textsuperscript{®} fabrics were measured were used. These data contain measurements of the manikin heat loss in
infrared and visible radiation, with clothing ensembles consisting of two and three layers and at different wind speeds from 0.5 m/s up to 2 m/s. Comparison of the model predictions with this experimental data shows that the clothing model explains a large part of the variation of the experimental data. However, when more complex types of (reflective) clothing are incorporated, the model clearly does not explain all experimental variation. This is due to the direct effect of the clothing on the radiative properties (reflection) and requires an extension of the model to describe the attenuation of the radiative field by clothing with low emissivity values. A model to describe that has been studied within the Thermprotect project and may be published later. The current model does show that increasing the clothing insulation decreases the effect of the radiation up to a point where the radiative environment is such that increased clothing insulation is beneficial to the wearer. These results are confirmed by the practice in which protective clothing insulation is increased at high levels of radiation, such as for fire fighters.
Effect of Long Wave Radiation on Heat Loss Through Protective Clothing Ensembles – Material, Manikin and Human Subject Evaluation

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²Institut für Arbeitsphysiologie an der Universität Dortmund (IfADo), Germany
³V. Candas, E. Den Hartog, B. Griefahn, G. Havenith, I. Holmér, W. Nocker, M. Richards

Abstract

Three experimental steps were performed to assess the thermal properties of protective clothing in the European THERMPROTECT project:
- material tests for clothing material selection,
- thermal manikin tests for physical measurements of clothing ensembles,
- human experiments in climatic chambers for physiological and subjective reactions.

One workpackage of the project was concerned with the influence of radiation (short and long wave).

The influence of long wave (infrared) radiation was measured at TUT using an epiradiateur radiation source. Material measurements were done with a sweating cylinder, simulating the human torso, and manikin tests with the sweating thermal manikin Coppelius. Corresponding human tests were done at IfADo using radiation towers equipped with heated ceramic panels.

In the screening of material candidates a number of underwear + outerwear material combinations were tested, including conventional and highly reflective aluminized outer fabrics. Two outerwear (one conventional and one reflective) and three underwear (cotton, polyester and polypropylene) materials were chosen for the
manikin tests, and simple design outerwear coveralls were produced for the tests. The human tests also used a conventional and a reflective coverall, but only one type of underwear (polypropylene).

Both material and manikin experiments showed large differences in the behaviour of conventional versus reflective outerwear under influence of long wave radiation. Comparing the physically measured values (cylinder and manikin), the aluminized garment gave a better protection against radiation, which was seen in only slight increases in temperatures in the clothing and almost no decreases in heat losses. Heat losses increased in the sweating tests, but the very low water vapour permeability of the aluminized garment caused a substantial condensation of moisture in the clothing, so that the total heat losses with both outer materials become closer.

This view was confirmed by the human experiments, that showed the beneficial effects of the reflective garment only for the initial phase of the working period with low sweating activity. Later on the observed physiological heat strain did not differ significantly between the two suits.

1. Introduction

Protective clothing in high radiant environments is used to reduce the radiant heat gain and thereby reduce the heat strain. The protection level is dependent on the type of outer material in combination with the spectral properties of the radiant heat source and the position of the wearer in relation to the source. A reflective material typically reduces the water vapour permeability of the clothing, which reduces the evaporative heat loss from the wearer’s skin and leads to increased heat strain. One objective of the THERMPROTECT project was to quantify the influence of different types of clothing ensembles on the heat exchange in different radiant environments. This paper deals with material, manikin and human subject measurements on the effect of long wave (infrared) radiation.

2. Methodology

2.1 Material measurements (sweating cylinder)

The sweating cylinder is used for the measurement of heat and moisture transmission through clothing materials or material combinations, in the climatic chamber (Meinander 1988). Figure 2.1 a shows the cylinder standing on a balance, in this case with the Epiradiateur radiation source in a stand at a distance of 35 cm from the cylinder surface. The principle of a sweat gland is shown in Figure 2.1 b. 24 of these sweat glands are placed symmetrically on the measurement area of the cylinder. A predetermined amount of liquid water is supplied to the sweat gland (1) and is spread over an area of approximately 100 cm² by the wicking layer (7). The microporous skin material (8) transmits water in vapour form only, and the top mesh knit (9) protects the surface physically. The cylinder is electrically heated to a
predetermined surface temperature by heating wires (3). The dimensions of the sweating measurement area are; height 300 mm and diameter 300mm. Heated guard rings on top and bottom prevent heat leakage upwards and downwards from the measurement area.

![Figure 2.1](image)

**Figure 2.1**

a) The sweating cylinder with the Epiradiateur radiation source

b) Cross section of a sweat gland

Cylinder surface temperature (°C), sweating level (g/m²·h), test time (min) and ambient temperature (°C) and humidity (%) are set for the test. Measured values are heat supply (W/m²), cylinder surface temperature (°C), temperatures at different points (°C), total weight increase during the test (g) and weight increase of the individual material layers (g). Measurements are done without sweating (dry test, 90 min) and with sweating (200 g/m²·h, 120 min). Based on the measured values, the dry thermal resistance (m²·K/W), the evaporative heat loss (W/m²) and the corrected thermal resistance are calculated.

The measurements were done using the Epiradiateur radiation source (long wave radiation), Quarz & Silice, RC2S/506 M, 500 W. Exact technical details of the Epiradiateur were unfortunately not available, but it was estimated that the heat flux at the distance of 35 cm was approximately 400 W/m². The environmental conditions were: temperature +10 °C and relative humidity 65 %.

Four outerwear fabrics were compared in the cylinder tests: orange and black Nomex®, Siloflec Nomex® (with small glass bulbs) and reflective aluminised Nomex®. A polypropylene knitted underwear fabric was used in all tests.

### 2.2 Manikin measurements (sweating thermal manikin)

The sweating thermal manikin Coppelius is used for measurements of heat and moisture transmission through garments or clothing ensembles, in the climatic chamber (Meinander 1997). The sweating principle is similar to that of the sweating cylinder. The surface of the manikin is divided into 18 separate heating segments, and 187 sweat glands are distributed over the surface (except head, hands and feet, which are non-sweating). Figure 2 a shows Coppelius hanging from a balance in the climatic chamber, dressed with the tested aluminium coverall, and Figure 2 b shows
schematically the test set-up with the manikin in the climatic chamber and computer control and water supply from the control room.

The Epiradiateur radiation source was placed at the distance of 35 cm to radiate the chest segment of the manikin. The environmental conditions were the same as in the cylinder tests (10 °C / 65 % RH). The set, measured and calculated values were also the same for the manikin and the cylinder tests, except the test times (60 min dry and 180 min sweating).

Simple design coveralls were produced for the manikin and the human experiments. The tests at TUT were done with two coverall materials: the black Nomex® (PERM) and the aluminised Nomex® (REFL). Three knitted underwear sets were used: cotton (CO), polyester (PES) and polypropylene (PP).

### 2.3 Human experiments

Human wear trials were carried out by IfADo in order to compare the effects of reflective and non-reflective outer garments under conditions without and with additional far infrared radiation (FIR).

The facilities at IfADo allow for the application of high intensities of FIR while keeping the other climatic parameters (in particular air and wall temperature) constant. For the simulation of FIR the chamber uses four so-called radiation towers (R1-R4, Fig. 2.3), each equipped with 30 ceramic panels installed about 3 m above the ceiling. They emit FIR of wave lengths between 2-10 µm, that is routed into the chamber via reflecting shields. The FIR emitted by 2 active towers (R3+R4, Fig. 2.3) had an asymmetric shape, like a bulged half-cylinder with some radiation from the
Section II: Thermal Comfort

back (Fig. 2.3), as some radiant heat was reflected by the walls made of sheet metal (Fig. 2.4 c).

Eight healthy male students (22.75 ± 1.28 yrs, 1.81 ± 0.06 m, 75.05 ± 6.63 kg) gave written consent to participate in the study, that had been approved by IfADo’s ethics committee. Stopping criteria were formulated as follows: heart rate greater than 200-age (yrs), rectal temperature above 38.5 °C, and the person’s request to stop.

![Figure 2.3: Schematic drawing of a person placed on the treadmill (light grey rectangle) and exposed to infrared radiation from two operating radiation towers (R3, R4). The red line indicates the distribution of radiant heat flux measured in the horizontal plane compared to a nominal all-side value with the same radiant heat flux (100% contour) for the applied asymmetrical frontal radiation setting, data from (Wenzel et al. 1991).]

The experiments were carried out with an air temperature (ta) of 20 °C, relative humidity (rh) of 43% and air velocity of 0.5 m/s. Two different conditions with respect to radiant heat load were studied, one reference condition without additional radiant load (NoRad), where mean radiant temperature (tr) was equal to air temperature, and one radiant condition (Rad) of frontally applied FIR with tr = 60.2 °C.

Two different clothing conditions were realized by using the two outer garments from the manikin tests, a black Nomex® (PERM, Fig. 2.4 b) and a reflective Nomex® with an aluminized coating (REFL, Fig. 2.4 c). The subjects wore their own briefs, socks and sport shoes and, beneath the outer layer, polypropylene underwear (Helly Hansen Super Bodywear™ 140 g/m², HHS, Fig. 2.4 a). Each participant visited the laboratory for 4 sessions (2 climatic conditions, each with 2 different outer layers) at identical daytimes. The sequence of conditions was permuted systematically between subjects applying a doubled 4x4-latin-square matrix. The sessions consisted of a single phase with 90 minutes of treadmill walking (4.5 km/h, 0° slope) following a 30 minute pre-exercise resting period.

By weighing the nude persons and the clothing before and after the experiment, the produced sweat and the amount of absorbed and evaporated moisture were determined. Metabolic rate was calculated according to ISO 8996 (2004) from the
content of CO₂ and O₂ in the expired air that was collected with a Douglas bag during the final 15 minutes of exercise. Heart rate (HR) was calculated from the electrocardiogram, and rectal (Trec) and skin (Tsk) temperatures at 8 body sites according to a slightly modified scheme from ISO 9886 (1992) were continuously recorded with thermistors.

From the final and baseline values of HR and Trec, the physiological strain index (PSI) was calculated according to (Moran, Shitzer, & Pandolf, 1998) as:

\[
PSI = 5 \times \frac{(T_{rec\_end} - T_{rec\_base})}{(39.5 - T_{rec\_base})} + 5 \times \frac{(HR_{end} - HR_{base})}{(180 - HR_{base})}
\]  

The results are presented as means ± SD for the experimental conditions and are tested for statistical significance applying a doubly repeated measurement ANOVA for the factors radiation and outerwear, calculated as a linear mixed model with unstructured covariance matrix.

Figure 2.4: Different clothing layers worn by the subjects: (a) HHS underwear with thermistors taped at the scapula and dorsal thigh, (b) black Nomex® coverall, and (c) reflective Nomex® coverall.

3. Results

3.1 Material measurements

The total heat loss values from the cylinder in the different test conditions are shown in Figure 3.1 a). In the basic condition (dry without radiation), the aluminized fabric has a lower heat loss (105 W/m²) than the other three fabrics (177 – 184 W/m²), due to its greater thickness and thermal insulation. Sweating always increases the heat loss, as the supplied water partly evaporates and partly condenses in the material layers and thereby increases the conductive heat loss. The relative increase is higher
for the permeable fabrics (66–72 % without radiation and 116–140 % with radiation) than for the impermeable aluminized fabric (44 % without and 43 % with radiation).

Radiation decreases the heat loss from the cylinder but the effect is much smaller in the case of the highly reflective aluminized outerwear fabric (11 % in the dry and 12 % in the sweating tests) than for the more conventional fabrics (36-42 % in the dry and 18-20 % in the sweating tests). No significant differences between the values for the orange, black and siloflec fabrics were noted.

The evaporative heat loss values from the sweating tests are shown in Figure 3.1 b). The orange, black and siloflec fabrics have all a low water vapour resistance and the heat loss values are high (106-114 W/m² without and 118-123 W/m² with radiation). The aluminized fabric, with a very high water vapour resistance, shows very low values for evaporative heat loss, both without and with radiation (approx. 4 W/m²).

The underwear surface temperature values measured at the radiated side are shown in Figure 3.2. The aluminized fabric shows higher temperatures in the tests without radiation than the conventional fabrics, which all are on a similar level. Radiation increases the temperatures for all fabrics, but the increase is small for the aluminized fabric (34,4 to 36,7 °C in the dry and 36,3 to 39,1 °C in the sweating tests), whereas it is large for the conventional fabrics (between 28 and 30,5 °C without and between 54,8 and 60,3 °C with radiation, both in the dry and in the sweating tests).
3.2 Manikin measurements

The radiation was directed towards the manikin’s chest segment, and the total heat loss from the manikin and specifically from the chest segment are therefore shown in Figure 3.3.

Figure 3.3 a) shows that the heat loss from the manikin in the dry test is a little lower for the permeable than for the reflective outerwear (88-91 and 98-101 W/m², respectively). Sweating however increases the total heat loss much more for the permeable than for the reflective coverall (96-101 and 46-57 W/m², respectively). The difference between the two outerwear coveralls is more clearly shown in the heat loss from the chest segment, Figure 3.3 b): The dry heat loss from the non-reflective ensemble is 0, due to the intense radiation on the chest. In the reflective coverall most of the radiation is reflected, and the heat loss from the chest is only
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about 25 % lower than from the average of the manikin. The efficiency of sweating is high for the permeable ensembles (93-99 W/m²).

Figure 3.4 shows the measured amounts of water at the end of the test. The evaporation is quite efficient in the permeable ensembles, as more than 60 % of the supplied moisture evaporated. For the reflective ensembles, the evaporation is much lower (14-20 %). Absorption in the clothing is consequently low in the permeable and high in the reflective ensembles. The cotton underwear increased the absorption compared to polyester and polypropylene. Dripping was only minimal in these tests (0-0,4 g), whereas the manikin skin contained between 20 and 26 % of the supplied water.

![Moisture transfer](image)

**Figure 3.4** Moisture evaporation, absorption in clothing layers, drip and residue in manikin skin

![Underwear surface temperatures, manikin chest](image)

**Figure 3.5** The underwear surface temperatures at the manikin chest segment in dry and sweating tests with radiation.

The underwear surface temperature values in the radiation tests are shown in Figure 3.5. The values are higher for the permeable than for the aluminized ensembles, both in the dry and in the sweating tests. The difference is not as large as in the cylinder tests, Figure 3.2, which can be explained by the thicker air gap between the outerwear and the underwear in the manikin tests. The underwear temperature decreases due to sweating in the permeable ensembles whereas it increases in the aluminized ensembles.
3.3 Human experiments

<table>
<thead>
<tr>
<th>Variable</th>
<th>PERM, NoRad</th>
<th>PERM, Rad</th>
<th>REFL, NoRad</th>
<th>REFL, Rad</th>
<th>P (^\text{§})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic</td>
<td>167.1 ± 6.3</td>
<td>167.9 ± 6.2</td>
<td>175.8 ± 9.3</td>
<td>176.6 ± 9.2</td>
<td>a,^\text{--}</td>
</tr>
<tr>
<td>Sweat / moisture produced</td>
<td>329.9 ± 45.5</td>
<td>602.9 ± 67.6</td>
<td>413.5 ± 74.6</td>
<td>613.6 ± 167.3</td>
<td>b,^\text{--}</td>
</tr>
<tr>
<td>absorbed</td>
<td>12.9 ± 3.9</td>
<td>17.8 ± 11.4</td>
<td>107.5 ± 44.6</td>
<td>223.1 ± 135.8</td>
<td>abc,^\text{abc}</td>
</tr>
<tr>
<td>evaporated</td>
<td>317.0 ± 43.4</td>
<td>585.1 ± 59.8</td>
<td>306.0 ± 48.1</td>
<td>390.5 ± 52.3</td>
<td>abc,^\text{abc}</td>
</tr>
<tr>
<td>PSI</td>
<td>2.5 ± 0.8</td>
<td>2.8 ± 0.9</td>
<td>2.7 ± 0.7</td>
<td>3.3 ± 0.8</td>
<td>b,^\text{--}</td>
</tr>
</tbody>
</table>

\(^\text{§}\) P: indicating significant effects \((P<0.05)\) from mixed model ANOVA for repeated measurements
\(^a\): outer layer effect, \(^b\): radiation effect, \(^c\): interaction effect

Table 3.1: Means ± SD and ANOVA results for metabolic rate, produced, absorbed and evaporated sweat, and the physiological strain index (PSI) measured in the experiments with (Rad) and without (NoRad) radiation and the black (PERM) and reflective (REFL) Nomex® outer garments.

The metabolic rate was somewhat below 170 W/m² for the black and slightly above 170 W/m² for the reflective suit, independently of radiant load (Table 3.1). The difference was about 5% and turned out to be statistically significant.

Table 3.1 also presents the amount of produced sweat, moisture absorbed by the clothing layers and moisture evaporated to the environment. Weight loss significantly increased with radiation, but there was no significant difference between the two outer garments, though sweat production was more than 25% higher with the reflective garment without radiant load, whereas with FIR there was only a negligible difference between the two materials.

As with the manikin, only very small amounts of moisture were absorbed when wearing the PERM suit, whereas considerably more sweat was trapped inside the clothing with the REFL garment, most of it in the outer layer. The fraction of absorbed sweat with the reflective suit increased from 26% without FIR to 36% with radiation, and consequently, the increase of evaporated sweat under heat radiation was only moderate compared to the significantly more pronounced increase observable for the black Nomex® (Table 3.1).

The comparison of the local skin temperatures at the radiated and non-radiated body parts in Fig. 3.6 shows that the main increase for the PERM occurred at the radiated frontal body part, with an initially sharp increase and later convergence to the same final values as for the reflective suit. This was accompanied with an only moderate, transient increase at the non-radiated backside for the low-reflective PERM, whereas the reaction to radiation for the reflective suit appears to be evenly distributed between the radiated and non-radiated sides.

The values of the physiological strain index (PSI) indicated low to moderate strain (Moran, Shitzer, & Pandolf, 1998) and were significantly higher under radiant heat load (Table 3.1). There was also a tendency for PSI and its increase with radiation appearing to be higher for the reflective suit (Fig. 3.6), but the main outer layer and
the outer layer-radiation interaction effect did not reach statistical significance (P=0.07 and 0.08, respectively).

![Graph showing skin temperatures and physiological strain index](image)

**Figure 3.6** Evolution of skin temperatures (Tsk, means ± SE) at the non-radiated (left panel) and radiated (mid panel) body parts, and final values (means ± SD) of the physiological strain index (PSI, right panel) for the experiments with (Rad) and without (NoRad) radiation and the black (PERM) and reflective (REFL) Nomex® outer garments.

4. Discussion and conclusions

Comparing the physically measured values (cylinder and manikin), the aluminized garment gave a better protection against radiation, which was seen in only slight increases in temperatures in the clothing and almost no decreases in heat losses. Heat losses increased in the sweating tests, but the very low water vapour permeability of the aluminized garment caused a substantial condensation of moisture in the clothing, so that the total heat losses with both outer materials became closer. Similar results were obtained by a non-sweating manikin with dry and wetted underwear (Bröde et al. 2006).

The consequences of this were demonstrated by the wear trials, showing that the beneficial effects of the reflective outer garment, namely allowing less heat from far infrared radiation to penetrate to the skin and thus generating lower skin temperatures on the radiated body sites, only appeared for the very initial phase of the working period, when sweating activity was low, and the situation resembled that of the measurements with the non-sweating manikin.

During the working period with increasing sweating activity, lower proportions of the produced sweat could evaporate with the reflective suit due to its higher evaporative resistance. As a consequence, the observed physiological heat strain did not differ significantly between both suits. Similar observations have been also reported for short wave radiation (van Es et al. 2006). This may also partly be attributable to the slightly increased metabolic heat production observed for the heavier, but also bulkier and stiffer reflective suit.
Summarized, the results show how the beneficial effect of reflective clothing on the heat exchange under low to moderate thermal radiant load may be counteracted by its low vapour permeability. An accurate assessment requires the consideration of the interaction of thermal radiation with the modifying effects of moisture inside the clothing on the heat transfer processes, involving increased conduction (Chen, Fan, & Zhang 2003) and evaporation (Bröde et al. 2006), as well as evaporation-condensation-cycles inside clothing with low permeability (Richards et al. 2006).

5. Acknowledgements

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6. References


Examination of the Thermal Adaptive Effect of the Adjustment of a Seated Human Body’s Orientation Relative to Spot Airflow

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Abstract

For persons exposed to spot airflow, their thermal sensations are considered to be greatly influenced by their posture relative to the spot airflow because of changes in the velocity distributions around their body caused by postural adjustments. On the other hand, as one of the usual thermal adaptive activities, office workers unconsciously alter their sitting posture for more comfort. Therefore, we examined the influence of sitting posture on the thermal characteristics of a person facing the spot airflow. In this paper we adopted the coupled simulation method of convection, radiation, moisture transport and Fanger’s human thermal physiological model to examine the influence of the adjustment of the body’s orientation relative to the opening of a personal spot air-conditioner. The results indicate that the orientation of the body, relative to the spot airflow, will greatly affect its local thermal characteristics.
1. Introduction

Aiming at energy conservation, research on the development of task-ambient air-conditioning systems, using a personal air-conditioner (PAC), has increased in recent years [1,2]. In the task environment formed by these systems, the worker’s thermal adaptive behaviour, such as the adjustment of the posture etc, which is frequently done in daily life, is thought to contribute greatly to the worker’s thermal comfort, because of the non-uniform velocity and temperature distributions, especially when a spot PAC is used. Therefore, to ensure energy conservation and thermal comfort simultaneously, it is necessary to develop an adaptive model that can evaluate the influence of the person’s thermal adaptive behaviour on their thermal comfort. Therefore, in this paper a seated human body was exposed to high-speed airflow supplied by a spot PAC and the thermal adaptive effect of the adjustment of the body’s orientation relative to the supplied airflow of a spot PAC was examined by making clear the influence of this thermal adaptive behaviour on the thermal characteristics over the whole body. In addition, heat exchanges generated between a seated human body model and its surrounding environment were simulated by means of a coupled simulation of the convection, radiation, moisture transport and Fanger’s human thermal physiological model.

2. Outline of Coupled Simulation Method

2.1. Cases Analyzed

Three cases were examined as shown in Table 1. As the ambient air-conditioning system used in the room, fresh air at 26 °C was supplied from the whole floor surface at a speed of 0.05 m/s and the air in the room was exhausted through the entire ceiling surface in each case. As shown in Fig. 1, the frontal surface of the human body faced the opening of a spot PAC supplying the cooled spot airflow, the horizontal distance between the abdomen and the PAC being 61 cm. In Cases 2 and 3, the human body was placed at the same position, but turned 45° and 90°, respectively. In the simulation, a seated human body model was used. The PAC shown in Fig. 1 was modelled based on a real one which was provided by Daikin Ltd. The boundary conditions for each opening of the PAC were obtained by the experiment performed in the conditions of Case 1, using an experimental thermal manikin, as detailed in Table 3.

2.2. Simulation Conditions

A low-Reynolds-number type k-ε turbulence model [3] was used for calculating the flow field together with the SIMPLE algorithm and the UD difference scheme (Table 2). There were about 310,000, 340,000 and 320,000 spatial grids for Cases 1, 2 and 3, respectively. As shown in Fig. 2, the first 5 cell layers placed over the human body
surfaces are prism-shaped fluid cells, while the remainder of the flow field is filled with tetrahedral meshes [4]. The non-dimensionalized normal distance (i.e., the wall coordinate) measured from the body surface to the center of the first fluid cell is represented by $y^+$, which is smaller than 4 over almost the entire body surface in each case. For the human body surface meshes, they are identical for each case (n=7,338) with a total area of about 1.46 m². Moreover, the detailed boundary conditions for the calculation of the flow field are shown in Table 3.

The thermal radiation was calculated using Gebhart’s absorption factor method [5] while the configuration factors over the complex geometry were accurately calculated using a Monte-Carlo method [6] incorporating a symmetrization procedure [4]. The emissivity was set uniformly at 0.95 for all the wall surfaces in the calculation. Finally, the floor temperature was fixed at 26 °C, the temperature for the outlet boundary is equal to that of the outflow air, and the remaining wall surface temperatures were calculated by CFD simulation.

Fanger’s thermal neutral model was used for the calculation of the heat conduction inside the human body with a metabolic heat production of 1.1 Met. Here Fanger’s model was applied to simulate the temperature and sweating of each body surface mesh. Furthermore, considering the influence of the hair and the clothes, the proper

### Table 1: Cases Analyzed

<table>
<thead>
<tr>
<th>Case</th>
<th>Angle between the human body and the spot airflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>45°</td>
</tr>
<tr>
<td>3</td>
<td>90°</td>
</tr>
</tbody>
</table>

### Table 2: Outline of CFD simulation

<table>
<thead>
<tr>
<th>Turbulence Model</th>
<th>Low-Reynolds-number type k-ε turbulence model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Difference Scheme</td>
<td>First Order Up Wind</td>
</tr>
<tr>
<td>Grid System</td>
<td>Surface meshes of human body model: 7338</td>
</tr>
<tr>
<td></td>
<td>Spatial cells: about 310,000</td>
</tr>
</tbody>
</table>

### Table 3: Boundary conditions

<table>
<thead>
<tr>
<th>Body part</th>
<th>Thermal resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.091 m²·°C/W</td>
</tr>
<tr>
<td>Chest</td>
<td>0.183 m²·°C/W</td>
</tr>
<tr>
<td>Back</td>
<td>0.196 m²·°C/W</td>
</tr>
<tr>
<td>Waist</td>
<td>0.214 m²·°C/W</td>
</tr>
<tr>
<td>Upper arms</td>
<td>0.120 m²·°C/W</td>
</tr>
<tr>
<td>Thighs</td>
<td>0.113 m²·°C/W</td>
</tr>
<tr>
<td>Legs</td>
<td>0.067 m²·°C/W</td>
</tr>
<tr>
<td>Hands</td>
<td>0.105 m²·°C/W</td>
</tr>
</tbody>
</table>

### Table 4: Local thermal resistance of the clothing
thermal resistance was applied for each body part as shown in Table 4.

2.3. Process of Coupled Simulation

The coupled simulation was made up of 4 steps as follows: 1) air flow, temperature and moisture fields were calculated by CFD to determine the temperature, convective heat transfer rate and the moisture condition for each body surface mesh; 2) the radiant heat transfer rate for the surface meshes was calculated by the radiation calculation using the temperatures determined by CFD; 3) the convective and radiant heat transfer rates, surface temperature, and the moisture condition of the body surface meshes were collected for the calculation using the Fanger’s model; 4) the surface temperature and sweating were calculated using Fanger’s model as the boundary conditions for each body surface mesh at the next step of CFD. These 4 steps were repeated until the CFD simulation was completed convergently.

3. Simulation Results

Because the latent heat transfer from the human body is very small and is relatively unaffected by changing the environment conditions in each case, these results were omitted.

3.1 Flow Field around the Human Body

As shown in Fig. 3, for each case, except for the high-speed spot airflow present between the human body and the PAC, a rising airflow of about 0.05 m/s was uniformly formed over the indoor flow field. However, a weak descending airflow can be observed over the head. Moreover, the cooled spot airflow fell by gravity after being blown from the PAC, and was divided into the upward and downward flows along the body surface after colliding with the body. In Case 1, the cooled spot airflow impacted the body at the abdomen. In Case 2, the frontal body surface below the neck was covered by a flow field exceeding 0.3 m/s. In Case 3, a descending airflow with a maximum velocity of 0.5 m/s at the chest was formed in front of the torso, after the spot airflow colliding with the side of the body.

3.2 Temperature Field around Human Body

As shown in Fig. 4, except for the field cooled by the spot airflow, almost the whole room was about 26°C in each case. A distribution exceeding 26.5°C can be clearly observed around the face in Case 1. In Cases 2 and 3, the high temperature range became narrower with the change in the body’s orientation relative to the
spot airflow. Moreover, the body surface covered by the airflow with a temperature of less than 24.5 °C involved the majority of the frontal torso below the neck, but was limited to the chest and the abdomen in Case 3.

### 3.3 Temperature Distribution of Human Body

As shown in Fig. 5, the average skin temperature was approximately 34 °C in each case irrespective of the body’s orientation. At the face, the neck, the forearms and the hands, which were exposed to the air, the skin temperatures were lower than those of body parts inside the clothes. Compared with Case 1, the skin temperature in Case 2 was lower at the left upper arm close to the PAC, and higher at the right upper arm far from the PAC. Moreover, a left–right temperature gradient appeared at the face and the neck, while the temperature decreased on the side facing the PAC. In Case 3, the temperature gradient also appeared at the torso, where the temperature was much lower on the side facing the PAC and higher on the opposite side. Unsurprisingly, the temperature also increased at the crotch.

### 3.4 Convective Heat Transfer Rate Distribution of Human Body

As Fig. 6 shows, the overall mean value of the convective heat transfer rate was similar – approximately 28 W/m² for each case. At the body parts exposed to the air, the heat transfer due to convection was greater, exceeding 80 W/m² at the neck and the forearms. In
Case 1, the distribution was also almost uniform over the entire human body. At the frontal torso, front upper arms and the upper side of the thighs, although the body surfaces are inside the clothes, the convective heat transfer rate exceeded 40 W/m² due to the influence of the cooled spot airflow. With the exception of the surfaces of the top body parts and exposed body parts, the convective heat transfer rate was lower than 25 W/m². In Cases 2 and 3, owing to the orientation of the body to the spot airflow, the convective heat transfer rate increased at body parts such as the face, neck, frontal torso, arms, hands and the upper thighs, which were close to the spot airflow, and decreased at the body parts which were far from the spot airflow. Therefore, the convective heat transfer rate distributed left–right asymmetrically on the body surfaces and was larger than 80 W/m² at the left upper arm and left side of the neck, and lower than 20 W/m² at the right side of the torso. However, although the convective heat transfer had decreased, the legs maintain uniform distribution in Cases 2 and 3.

3.5 Radiant Heat Transfer Rate Distribution of Human Body

As shown in Fig. 7, the overall mean value of the radiant heat transfer rate was approximately 17 W/m². The radiant heat transfer was relatively small at the frontal torso, frontal upper arms and the upper thighs, which were affected by the spot airflow and its branches due to collision with the body surface, with the rate of lower than 10 W/m². At other body parts, it exceeded 20 W/m² and was over 35 W/m² at the face, neck and the forearms. On the other side, it showed a uniform distribution in the majority of body surfaces in Case 1. However, in Cases 2 and 3, it was smaller on the side close to the spot airflow and larger on the opposite side at the neck, frontal torso, upper arms and the upper thighs, owing to the orientation of the body relative to the spot airflow. It resulted in a left–right asymmetrical distribution. In Case 3, the radiant heat transfer rate was lower than –10 W/m² at the left upper arm affected by the spot airflow. Moreover, it maintained the uniform distribution at the legs and the feet which were not influenced by the spot airflow.

4. Examination of Thermal Adaptive Effect by Adjusting the Body’s Orientation Relative to Spot Airflow

In the above simulation, the differences on the local thermal characteristics were disregarded, since Fanger’s human thermal physiological model, which considers the whole human body as a simple node and determined whole-body heat balance rather than local balance, was used. Moreover, as the body parts which are most influenced by the spot airflow were assumed to be covered in clothes, the change of the thermal characteristics owing to the change of the flow field around the human body caused by postural adjustment, was not fully characterized. Therefore, the results from this simulation will be assessed recognizing these two points.

The mean values calculated for the whole body and local body parts were compared in terms of skin temperature and sensible heat transfer rates as shown in Figs. 8 and 9, respectively. Except for the hands, left arm and the left thigh, the change of the sensible heat transfer rate was limited to ±5 W/m² at the other body parts in the three cases. Moreover, the overall change of the skin temperature was smaller and did not exceed
±0.5°C, except for the left arm. On the other hand, the temperature at the left arm in Case 3 was 0.8°C lower than that for Case 1. This indicates that the local thermal conditions can be improved by adjusting the body’s orientation when utilizing a spot PAC. However, according to the simulation results described above, owing to the distributions of the flow and temperature fields around the human body, the skin temperature and the sensible heat transfer rate will become non-uniform when the angle between the body and the spot airflow is enlarged and it is therefore possible for people to feel uncomfortable.

5. Conclusions

In this study, the coupled simulation of convection, radiation, moisture transport and Fanger’s human thermal physiological model was used to simulate the heat transfer characteristics of a seated human body placed in the spot airflow. Based on the simulation results, the thermal adaptive effect of the adjustment of the body’s orientation to the spot airflow was examined. These results indicate that people can improve their local thermal comfort by adjusting their orientation to the spot airflow when using a spot PAC with a prominent effect of cooling the human body. However, it may make people uncomfortable because of the non-uniform distributions of skin temperature and the sensible heat transfer induced.
Acknowledgements

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References

Transient Sweat Rate Calculation from Humidity Measurements under Clothing

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Abstract

This study demonstrates a method for monitoring evaporative sweat rates (EvapSR) during steady and intermittent activities. The method was validated on a sweating thermal manikin wearing a long sleeved shirt and trousers (standard military battle dress uniform) instrumented with temperature-humidity sensors under the clothing. The manikin tests were at steady state conditions in an environmental chamber at 35°C/50%RH and wind speed ranging between 0.36 and 1.94 m•s⁻¹. The manikin was adjusted to produce sweat rates between 0 and 150 g•m⁻²•h⁻¹. EvapSR was estimated from weighted measured skin wettedness and the maximum evaporative rate, and compared to the manikin’s sweat rate. This technique was further validated with humans engaged in intermittent work. Overall, this is a simple promising approach for estimating EvapSR. The method is non-invasive and enables monitoring and assessment for safety, health and hydration status of industrial and military personnel engaged in a wide range of situations.

1. Introduction

When thermoregulatory mechanisms cannot wholly compensate for prolonged exposure to heat stress, the physiological consequences may be severe water loss from blood plasma, an increase in heart rate for skin blood flow to maintain blood pressure, and an increase in core temperature. Non-compensable heat stress decreases productivity and endurance of performance, and may eventually cause heat related illness (e.g., dehydration, fatigue, heat stroke).¹ The evaporation of sweat from the body surface is the most important thermoregulatory mechanism for dispersing excess heat from the body. Evaporation of sweat from the skin lowers core and skin temperatures, thus better enabling proper body temperatures in the
heat. However, workers (e.g., firefighters, military personnel, mining industries) exposed to uncompensated hot environmental and/or strenuous operational conditions can sweat up to 2 L•h⁻¹ for several hours¹. To sustain the sweating rate (SR), adequate hydration levels must be maintained by replacing water lost during activities in warm and hot conditions. The majority of current training and fluid replacement guidelines for heat strain prevention were primarily developed from a single element, such as air temperature, or the combinations of clothing, activity levels, and/or air temperatures⁷,¹⁰. Despite these guidelines, heat related injuries and illness in both civilian and military workplaces are still serious challenges⁴,¹⁴. In part, the guidance was established only for working and environment conditions which are covered by standard water tables. Other factors, such as levels of heat acclimation, work duration and cycles, gender, or ethnicity may create additional differences in SR. Thus, to ensure individual workers’ safety, health, and performance in warm and hot environments, the capability to monitor and estimate the accurate water loss (WL), and the consequent requirement for water replacement, is important.

A traditional approach to quantify WL for predicting water requirement is to calculate the difference in body weight and associated weights (e.g., clothing, respiration, urine) before and after work¹¹,¹². However, particularly for workers required to perform their duties for long hours under various operational and environmental stresses, this approach to assess WL can be inconvenient. As an alternative to repetitive weighing, evaporative sweat rate (EvapSR) can be continuously monitored and estimated from humidity measurements made with compact sensors placed under clothing. In this way, the individual’s SR that may be altered or controlled by different elements (e.g., clothing, work levels and cycles, durations, acclimation status) can be easily assessed. In addition, EvapSR calculations and monitoring provide guidance for operational, environmental and other factors which are not covered by standard water tables. These SR sensors enable investigators to identify critical times when individual workers require water to compensate for heat stress. This study made use of a sweating manikin and data from human studies to investigate the accuracy and dynamic response of SR calculated by the transient clothing method (TCM). The method depends on the humidity gradient across clothing fabrics and their evaporation properties to estimate EvapSR over an extended period of time.

2. Methodology

A sweating manikin was instrumented with five relative humidity (RH) and temperature sensors (RHU-600A-ARM, ShinYei Kaisha, Kobe, Japan) distributed uniformly around the front torso region. The manikin, wearing a standard battle dress uniform (intrinsic clo = 0.75), was placed for < 7 h in an environmental chamber at 35°C/50% RH with wind speeds ranging between 0.36 to 1.94 m•s⁻¹. The SR of the manikin was controlled at levels of 0, 50, 100 and 150 g•m⁻²•h⁻¹. EvapSR is estimated from weighted measured skin wettedness (w) and maximum evaporative heat loss rate (E_max):

\[ \text{EvapSR} = \frac{w \cdot E_{\text{max}}}{\lambda} \quad [\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}] \]  

[1]
where $\lambda$ is latent heat of evaporation, and $w$, the fraction of skin covered with water, is defined as a ratio of observed evaporation heat loss rate ($E$) to $E_{\text{max}}$ or:

$$w = E/E_{\text{max}}$$  \[2\]

$E_{\text{max}}$ was calculated, assuming completely wet skin ($w=1$), as:

$$E_{\text{max}} = (P_{sk} - P_a)/R_{pclt} \quad [W \cdot m^{-2}]$$ \[3\]

where $P_a$ is ambient vapour pressure (Torr) and $P_{sk}$ is saturated vapour pressure (Torr) of water at skin temperature. $R_{pclt}$ (Torr) is the total vapour resistance of the clothing from skin to ambient. $R_{pclt}$ was previously measured at various air speeds on the sweating manikin according to ASTM F2370. $E$ is similarly calculated but with actual local average vapour pressure measured under the clothing ($P_{uc}$) that may be less than $P_{sk}$ because the skin is less covered with water. Substituting $E$ and $E_{\text{max}}$ into equation 2 results in:

$$w = (P_{uc} - P_a)/(P_{sk} - P_a)$$ \[4\]

which can be readily evaluated from the skin temperature and humidity measured under clothing and in the surrounding ambient air. The EvapSR values were compared with the SR of the manikin using a Wilcoxon test due to characteristics of the data distribution and sample size.

Values estimated using TCM were also compared to laboratory measurements from two human studies. Unlike the sweating manikin, there are regional differences in SR for human skin. EvapSR was calculated using equation 1 where $w$ is weighted mean skin wettedness of the measured regional $w_i$ values:

$$w = \Sigma (w_i \cdot p_i)/\Sigma p$$ \[5\]

where $p_i = BSR_i \cdot SRR_i / (\Sigma (BSR \cdot SRR))$, $BSR_i$ = body surface ratio by region, $SRR_i$ = sweat rate distribution ratio corresponding to the region. The weighting factor ($p$) was determined by the combinations of Kuno’s SR distribution ratio (50% from the trunk, 25% from the legs, and the remaining 25%) and Lund-Browder body surface ratio (head and neck for 9% of total BSA, anterior and posterior trunks, 36%; each arm, 9%; each leg, 18%; and 1 % represent genitalia and perineum).

For the first human study (HS1), nine human subjects (age: 23 ± 4 [SD] yr, height: 174.2 ± 5.2 cm; weight: 73.4 ± 6.5 kg), exercised 170-min intermittent treadmill walking at 27°C/75% RH with a wind speed of 1.1 m•s$^{-1}$. The subjects wore hot weather battle dress uniforms (intrinsic clo = 0.70), and RH (IH-3602, Honeywell, International, Freeport, IL) and temperature (FR-025-TH44033-F6, Concept Engineering, Old Saybrook, CT) sensors were placed on back, arm, and thigh under the uniform.

Total WL for HS1 was determined by the difference in body mass, corrected for clothing weight and the SR before and after exercise. A USARIEM human
thermal regulatory model, Initial Capability Decision Aid (ICDA) model\textsuperscript{15}, was utilized to compare the temporal characteristics of WL estimated by TCM with the model’s predicted WL. ICDA is a heat stress prediction model, utilizing anthropological characteristics (age, height, weight, clothing) and of a known metabolic level or real time inputs of estimated metabolic activity derived from heart rate and local weather (ambient temperature, RH, wind speed) to make predictions and estimates of physiological responses\textsuperscript{15}. In addition, the mean difference in total body WL based on different methods (measured, ICDA, and TCM) was compared using a repeated measures analysis of variance.

For the second human study (HS2), only mean data of six adult male subjects (age: 30 yr; height: 188 cm; weight: 85.2 kg), including weighted skin temperature and w, were available. Humidity sensors were placed on various locations of the skin (upper arm, lower arm, chest, back, thigh calf). Thermocouples measured sensor temperatures at each location (IH-3602C, Honeywell International, Freeport, IL). Subjects, wearing tight fitting 100% cotton single layer long sleeved sportswear (top and bottom, intrinsic clo = 0.46) in 12°C/50%RH with still air (0.05 m\textsuperscript{s}\textsuperscript{-1}), rested for the first 30 min, bicycled ~ 4 MET for 45 min, then rested for 30 min\textsuperscript{6}. The horizontal cycle ergometer was placed on top of a sensitive balance to measure the subject’s rate of weight loss (±1g). ICDA was also utilized for comparing model predicted values with measured WL and calculated WL by TCM. For both human studies, the water retained in the clothing was added to SR to calculate the total WL. The respiration loss (W\textsubscript{res}) was also added to EvapSR to compare measured WL using the follow equation:

\[
W_{\text{res}} = \frac{0.0023 \cdot M \cdot (44-P_a)}{0.068} \quad \text{[g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}] \quad [6]
\]

where \(M\) = work rate (W\cdot\text{m}^{-2}) and \(P_a\) = ambient vapour pressure (Torr).

3. Results

3.1 Manikin validation

Table 1 is the summary of the predicted SR based on the methodology described in the previous section, together with the measured SR and mean skin w of the manikin for various wind speeds (0.36 – 1.94 m\text{\cdot s}^{-1}). When SR is constant, as wind speed increases w decreases (Experiment A). SR proportionally corresponds to w when wind speed is constant (Experiment B). In both experiments (A and B), the mean estimated EvapSR was not statistically different from the mean SR of the manikin (\(p > 0.05\)).

3.2 Human data validation

Figure 1 compares the measured mean (\(n = 9\)) for HS1 to WL values estimated using TCM and ICDA models. Overall, WL calculated by TCM showed temporal changes which accurately reflected the pattern of work-rest cycles during the experiment, as did the ICDA predictions, but TCM values were sometimes almost 10% lower than WL predicted by the model. The grand mean WL predicted by ICDA was 3.2 g\cdot\text{min}^{-1} which is very close to grand mean measured WL, 3.1 g\cdot\text{min}^{-1}. The grand mean WL using TCM was 2.8 g\cdot\text{min}^{-1}. Table 2 shows the individual and
grand mean data summary of the measured, TCM calculated, and ICDA model predicted WL. The mean difference in WL among different methods was not statistically different ($p > 0.05$).

<table>
<thead>
<tr>
<th></th>
<th>SR ($g \cdot m^{-2} \cdot h^{-1}$)</th>
<th>Wind speed (m $\cdot$ s$^{-1}$)</th>
<th>Mean w</th>
<th>Estimated SR ($g \cdot m^{-2} \cdot h^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment A.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>constant SR</td>
<td>100.0</td>
<td>0.36</td>
<td>0.57</td>
<td>98.3</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>1.15</td>
<td>0.44</td>
<td>116.9</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>1.94</td>
<td>0.18</td>
<td>81.2</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>1.15</td>
<td>0.30</td>
<td>79.4</td>
</tr>
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<td></td>
<td>100.0</td>
<td>0.36</td>
<td>0.61</td>
<td>106.7</td>
</tr>
<tr>
<td><strong>Mean (SD)</strong></td>
<td>100 (0)</td>
<td></td>
<td></td>
<td>96.5 (16.2)</td>
</tr>
<tr>
<td><strong>Experiment B.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>constant wind speed</td>
<td>100.0</td>
<td>1.15</td>
<td>0.32</td>
<td>86.8</td>
</tr>
<tr>
<td></td>
<td>150.0</td>
<td>1.15</td>
<td>0.55</td>
<td>148.2</td>
</tr>
<tr>
<td></td>
<td>50.0</td>
<td>1.15</td>
<td>0.18</td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>1.15</td>
<td>0.04</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Mean (SD)</strong></td>
<td>75 (41.7)</td>
<td></td>
<td></td>
<td>73.2 (39.9)</td>
</tr>
</tbody>
</table>

Table 1: A summary of sweat rate (SR) and mean skin wettedness (w) of manikin with various wind speeds (Experiment A), and various manikin SR (Experiment B)

![Figure 1](image-url)  

Figure 1 A summary of mean transient water loss (WL) and Initial Capability Decision Aid (ICDA) predicted WL, and measured means for Human Study 1.
### Table 2: Summary of comparisons between measured water loss (WL), and WL calculated using Initial Capability Decision Aid (ICDA) model and transient method (TCM) (unit: g•min\(^{-1}\)) for Human Study 1.

<table>
<thead>
<tr>
<th>Subject</th>
<th>measured WL</th>
<th>ICDA WL</th>
<th>Transient WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.7</td>
<td>2.3</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>3.4</td>
<td>4.0</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>3.2</td>
<td>4.3</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>4.0</td>
<td>3.1</td>
<td>2.9</td>
</tr>
<tr>
<td>7</td>
<td>2.6</td>
<td>2.8</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>2.8</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>9</td>
<td>3.7</td>
<td>3.9</td>
<td>3.0</td>
</tr>
</tbody>
</table>

| Mean (SD) | 3.13 (0.7) | 3.20 (0.7) | 2.8 (0.7) |

A comparison of the HS2 mean measured WL and the values estimated using the TCM and ICDA model is presented in Figure 2. Grand means of measured, transient, and ICDA WL were 2.0, 2.4 and 2.8 g•min\(^{-1}\). Overall, the patterns of WL estimated by both TCM and ICDA reflected a rest-exercise-recovery cycle. However, ~5 min time delay in the increases of transient SR after exercise was observed, resulting from the time lag between weight loss measured from the scale and the increase of \(w^6\).

![Figure 2](image-url)  

**Figure 2** Summary of mean measured, transient, and Initial Capability Decision Aid (ICDA) water loss (WL) in Human Study 2

## 4. Discussion and Conclusion

The transient method for estimating SR and WL was investigated. The results of the manikin and human experiment showed that this approach is promising. The measured EvapSR of the manikin based on TCM was not statistically different from the mean manikin SR output at constant and variable wind speeds and SRs. Comparisons of measured WL and the estimated WL by TCM using two human...
studies also demonstrated small mean \((0.3 – 0.4 \text{ g}\cdot\text{min}^{-1})\) differences. Transient technique calculations in this study captured the different levels of WL during intermittent exercises (HS1, HS2). The values calculated using TCM demonstrated a slight time lag in the onset of increasing sweating relative to values measured by the scale (HS2). This delay appears to be related to sensors and fabric moisture absorption. The most common way to monitor total body WL is by a single (pre-post) measurement of changes in body mass during the activity. In contrast, the continuous subject weighing procedure used in HS2 is only applicable to laboratory applications.

This TCM approach offers the advantage of monitoring temporal WL of workers continuously for long periods of intermittent activity that may also involve changing temperature and humidity conditions. Because variation in WL and SR exists between different populations (e.g., ethnic groups, gender, acclimation status)\(^{13}\) and within individuals\(^{8}\), TCM is a pragmatic approach to measure the individual characteristics of SR, subsequent to WL. The use of humidity measurements under clothing is a simple monitoring technique for characterizing the sweating responses to activity and environmental challenges, and the measuring system can be wireless. Furthermore, the methodology offers a simple, practical means to develop and expand a database to evaluate the characteristics of temporal SR estimates for existing or future thermal regulatory models.

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References

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Thermal Comfort in terms of Both Local Skin Temperatures and Local Sensible Heat Losses in Non-uniform Thermal Environments

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This paper proposes expressions for overall thermal comfort, thermal discomfort for hot head and/or hot whole body, and thermal discomfort for cold foot (foot and leg) and/or cold whole body for the sitting posture under steady state in a non-uniform thermal environment. These expressions are based on local skin temperatures, local sensible heat losses, overall comfort sensation and local discomfort sensation under anterior/posterior, right/left, and up/down asymmetric radiation fields (Sakoi et al 2006). As an indicator of the local thermal state, a local function, employing the local skin temperature and the local sensible heat loss, was defined. The overall thermal comfort and thermal discomfort factors were expressed in terms of power functions using the local functions and their mean value. The overall thermal comfort characteristically decreased with whole body heating and cooling as well as with the deviation from a fixed ratio among the local functions. The thermal discomfort for hot head and/or hot whole body characteristically increased with the heat level in the head area and the whole body. The thermal discomfort for cold foot and/or cold whole body characteristically increased with the extent of coldness in the foot area and the whole body.

Keywords: Thermal comfort, Indoor environment, Non-uniform thermal environments, Local skin temperature, Local sensible heat loss
1. Introduction

This study proposes empirical expressions for overall thermal comfort, thermal discomfort for hot head and/or hot whole body, and thermal discomfort for cold foot (foot and leg; hereafter, we refer to them collectively as foot) and/or cold whole body. These expressions pertain to a sitting posture under a steady state in a non-uniform thermal environment and employ local skin temperatures \( T_{ski} \) and local sensible heat losses \( Q_{ski} \). In a thermally comfortable state in a sitting posture, changes in the body core temperature and sweat rate are insignificant. Accordingly, we neglected the influence of these factors and focused on \( T_{ski} \) and \( Q_{ski} \) in order to deal with the combined effect of air temperature, thermal radiation, air velocity, clothing, and the non-uniformities of the factors under consideration.

2. Basic Data for Expressions

Basic data for the expressions were obtained under the influence of anterior/posterior, right/left, and up/down asymmetric radiation fields (Sakoi et al 2006). A total of 70 experimental conditions were used with ranges of 25.5°C to 30.5°C for air temperature, 11.5°C to 44.5°C for the surface temperature of the confronting radiation panels, 40% RH to 50% RH for humidity, 0.07 clo to 0.29 clo for effective clothing insulation; the inlet-air velocity to the climatic chamber was less than 0.05 m/s. For human subject experiments, six male or female participants were subjected to each condition (except one condition where only five females participated). Each human subject was exposed to the condition for a period of 60 min. The overall comfort sensation (measured on a threefold scale of “comfortable,” “neither comfortable nor uncomfortable,” and “uncomfortable”) was recorded along with the cause of local discomfort (determined on a threefold scale of “discomfort due to coldness,” “no discomfort,” and “discomfort due to heat”) and \( T_{ski} \) at 25 locations. We assumed the data obtained in the final 10 min of the exposure as corresponding to steady-state conditions. In the thermal manikin experiments, a female thermal manikin with 20 segments was used to record \( Q_{ski} \). We considered the data for distinct local areas between the right and left sides in the following manner: in the right-left asymmetric experiments, the data for each area on both sides of the human subject or the manikin were considered unique; on the other hand, in the right-left symmetric experiments, the data for both sides were averaged to a single value.

In this study, we focused on the weighted overall thermal comfort (\( OTC \), Sakoi et al 2006) as calculated in Eq. (1) as an indicator of the overall thermal comfort for each condition.

\[
OTC = 1.0 \times \text{(percentage of “comfortable”)} + 0.5 \times \text{(percentage of “neither comfortable nor uncomfortable”)} + 0.0 \times \text{(percentage of “uncomfortable”)}
\]

For analyzing the thermal discomfort for hot head and/or hot whole body and cold foot and/or
cold whole body, we defined two conditions, “hot discomfort considering a local segment i and the whole body, \( HDS_i \)” and “cold discomfort considering a local segment i and the whole body, \( CDS_i \),” respectively. Here, \( HDS_i \) is the percentage of any hot discomfort in the head area and the whole body for each condition. \( CDS_i \) is the percentage of any cold discomfort at the foot area and the whole body for each condition. We intended to obtain expressions for the \( OTC, HDS_i \), and \( CDS_i \) by using the experimentally obtained values of local skin temperatures and local sensible heat losses.

### 3. Forms of Expressions

#### 3.1 OTC

With regard to the \( OTC \), we selected a form of expression that accounted for the following two tendencies: 1) The \( OTC \) decreases due to the heating or cooling of the whole body. 2) The \( OTC \) attains its maximum value at a fixed distribution of the local thermal states and decreases due to deviation from the distribution.

For a local area i, we defined a local function \( F_i \) as an indicator of the local thermal state. As shown in Eq. (2), \( F_i \) is expressed in terms of the local skin temperature \( T_{ski} \) and the local sensible heat loss \( Q_{ski} \). \( F_i \) is defined such that it increases with an increase in \( T_{ski} \).

\[
F_i = \frac{A \cdot (T_{ski} - B)}{X \cdot (\Delta \pm Q_{ski})}
\]  

If \( Q_{ski} \) has a relatively large influence on the \( OTC \) as compared with \( T_{ski} \), a small value will be allocated to \( \Delta \). If \( Q_{ski} \) has relatively little influence on the \( OTC \) as compared with \( T_{ski} \), a large value will be allocated to \( \Delta \). If an increase in \( Q_{ski} \) produces the same effect as a decrease in \( T_{ski} \), a positive sign will be allocated for \( Q_{ski} \).

The mean value of the function \( F_i \) for the whole body is calculated by Eq. (3).

\[
F_T = \sum_{i=1}^{n} F_i \cdot W_i
\]  

Taking into consideration the two tendencies mentioned above, we expressed the \( OTC \) using two terms, \( \beta \) and \( \chi \), that reflect the first and second tendencies, respectively. \( \beta \) is dependent only on \( F_T \), whereas \( \chi \) is dependent only on the proportion of each \( F_i \) to \( F_T \).

\[
OTC = \beta(F_T) \cdot \chi(F_1/F_T, F_2/F_T, \ldots, F_n/F_T)
\]  

where \( 0.0 \leq OTC \leq 1.0 \)

Eq. (5) is adopted for \( \beta \). \( \beta \) reaches its maximum value, \( \alpha_{fb} \), at \( F_T = \delta 2 \) and changes symmetrically with \( F_T \).
\[
\beta = \alpha_\beta \cdot \frac{F_T^{-mT} \cdot (\delta - F_T)^{mT}}{\left(\frac{\delta}{2}\right)^{2mT}}
\]  

Eq. (6) is adopted for \( \chi \). The sum of all \( W_i : F_i / F_T \) values is always constant at 1.0. \( \chi \) takes its maximum at a fixed ratio of \( W_i : F_i \), i.e., \( W_1 : F_1 : W_2 : F_2 : \cdots : W_n : F_n = m_1 : m_2 : \cdots : m_n \).

\[
\chi = \alpha_\chi \cdot \left(\frac{W_1 \cdot F_1}{F_T}\right)^{m_1} \cdot \left(\frac{W_2 \cdot F_2}{F_T}\right)^{m_2} \cdot \left(\frac{W_3 \cdot F_3}{F_T}\right)^{m_3} \cdots \left(\frac{W_n \cdot F_n}{F_T}\right)^{m_n}
\]  

where \( m_i > 0 \)

From Eqs. (4), (5), and (6),

\[
OTC = \alpha_\beta \cdot \frac{F_T^{-mT}}{\left(\frac{\delta}{2}\right)^{2mT}} \cdot \alpha_\chi \cdot \left(\frac{F_1'}{F_T}\right)^{m_1} \cdot \left(\frac{F_2'}{F_T}\right)^{m_2} \cdot \left(\frac{F_3'}{F_T}\right)^{m_3} \cdots \left(\frac{F_n'}{F_T}\right)^{m_n}
\]  

where \( F_i' = \frac{T_{ski} - B}{A \pm Q_{ski}} \)  

\[
\alpha_\chi = \alpha_\chi \cdot W_1^{m_1} \cdot W_2^{m_2} \cdot W_3^{m_3} \cdots W_n^{m_n}
\]

\[
\delta' = \frac{X}{A}
\]

\[
F_T' = \sum_i F_i' \cdot W_i
\]

This study adopted the expression for the \( OTC \) shown in Eqs. (7), (8), and (11). In Eq. (7), \( F_i' \) is used instead of \( F_i \); this is made possible by the transformation of \( \delta \) to \( \delta' \), as shown in Eq. (10). Henceforth, we refer to \( F_i' \) as the tentative local function. The constants and sign in Eqs. (7), (8), and (11) are explained in Section 4.

### 3.2 \( \text{HDS}_i \) and \( \text{CDS}_i \)

Similar to the method used above for deriving the \( OTC \) expression, we defined a local function \( F_i \), as shown in Eq. (12), for deriving the expressions of \( \text{HDS}_i \) and \( \text{CDS}_i \). The whole body was separated into two divisions, a local area \( i \) and the remaining area \( T - i \). The mean value of \( F_i \) for the whole body, \( F_T \), is calculated by Eq. (13). The influence of \( T_{ski} \) and \( Q_{ski} \) is expected to be different for the thermal state in hot discomfort and that in cold discomfort. Subsequently, the constants \( B \) and \( A \) are set for each thermal state.

\[
F_i = \frac{A \cdot \left(T_{ski} - B\right)}{X \cdot \left(A \pm Q_{ski}\right)}
\]

\[
F_T = W_i' \cdot F_i + W_{T-i} \cdot F_{T-i}
\]

Eq. (14) is adopted for the expression of \( \text{HDS}_i \) or \( \text{CDS}_i \). Here, the terms \( \beta_i \), \( \chi_i' \), and \( \epsilon \) represent
the influence of the local thermal state, the influence of the whole body state, and a threshold, respectively.

\[
HDS_i (or CDS_i) = \beta_i' (F_i) \cdot \chi_i' (F_{T_i}, F_i) - \varepsilon
\]

As shown in Eqs. (15) and (16), we expressed \( \beta \) and \( \chi \) in terms of single variables \( F_i \) and \( F_{T_i}/F_i \), respectively.

\[
\beta_i' = \alpha_{\beta'} \cdot F_i^m
\]

\[
\chi_i' = \alpha_{\chi'} \cdot \left( \frac{F_{T_i}}{F_i} \right)^{m_T}
\]

From Eqs. (12) to (16),

\[
HDS_i (or CDS_i) = \alpha_{\beta'} \cdot F_i^{m_i-m_T} \cdot \alpha_{\chi'} \left( W_i \cdot F_i' + W_{T-i} \cdot F_{T-i} \right)^{m_T} - \varepsilon
\]

Where:

\[
F_i' = \frac{T_{ski} - B}{A \pm Q_{ski}}
\]

\[
\alpha_{\beta'} = \left( \frac{A}{X} \right)^{m_i} \cdot \alpha_{\beta}
\]

This study adopted the expressions of \( HDS_i \) (or \( CDS_i \)) shown in Eqs. (17) and (18). Similar to the expression for the \( OTC \), Eq. (17) uses a tentative local function \( F_i' \) as a variable. The constants and sign in Eqs. (17) and (18) are explained in Section 4.

4. Constants and Sign for Expressions

4.1 \( OTC \)

In order to adequately reflect the influence of anterior-posterior, right-left, and up-down non-uniformities, we adopted seven divisions for the body: head, front torso, back torso, right upper limb, left upper limb, right lower limb and left lower limb. The weighting coefficients \( W_i \) were set based on the skin surface areas (Kurazumi et al 1994). For the seven divisions, the

![Figure 1](https://example.com/figure1.png)

**Figure 1** Calculated \( OTC \) versus measured \( OTC \)
mean skin temperatures and mean sensible heat losses were calculated using the basic experimental data along with weights for measurement points in accordance with the skin areas (Kurazumi et al. 1994). Table 1 shows the data ranges for the OTC for different divisions of the body.

For both positive and negative signs of $Q_{di}$ in Eq. (8), the constants in Eqs. (7) and (8) were first obtained by following the steps [1] to [4] given below. Next, we adopted those values of the constants and sign for $Q_{di}$ corresponding to a lower sum of square errors. The steps [2] to [4] were iterated until the sum of square errors reached a minimum level. When all of the constants $\delta$, $B$, and $\Delta$ are obtained through a trial and error process, it is difficult to fix all the values since any change in the value of $B$ in the numerator will affect the value of $\Delta$ in the denominator. Therefore, we fixed the constant $B$ at 25°C, which is sufficiently lower than the local comfortable skin temperature (Nishi 1996), and obtained the constants $\delta$ and $\Delta$.

[1] Initial values were set for $\delta$ and $\Delta$. Next, the values of $F'_{i}$ and $F_T'$ were calculated.

[2] The values of constants $m_T$ and $\alpha_T$ were set by a regression of $\ln(OTC)$ on $\ln[F_T'(\delta - F_T')]$. Both $m_T$ and $\alpha_T$ are constants in Eq. (5) and express the influence of $F_T$ on the $OTC$.

$$\ln(OTC) = \ln(\alpha_T) + m_T \cdot \ln[F_T'(\delta - F_T')]$$

[3] The values of constants $m_1, m_2, \ldots, m_7, \text{ and } \alpha_{\beta}^{'}$ were set by a multiple regression in Eq. (21). The constants $m_1, m_2, \ldots, m_7, \text{ and } \alpha_{\beta}^{'}$ are used for the term $\chi$ in Eq. (6), which compensates Eq. (5), taking into consideration the distribution of $F'_{i}$.

$$\ln \left( \frac{OTC}{F_i' F_T'} \right)^{\frac{m_1}{\alpha_{\beta}^{'}}} + \ln \left( \frac{F_i'}{F_T'} \right)^{\frac{m_2}{\delta}} + \ln \left( \frac{F_i'}{F_T'} \right)^{\frac{m_3}{\Delta}} + m_4 \cdot \ln \left( \frac{F_i'}{F_T'} \right)$$

$$= \ln (\alpha_T) + m_T \cdot \ln \left( \frac{F_i'}{F_T'} \right) + m_1 \cdot \ln \left( \frac{F_i'}{F_T'} \right) + m_2 \cdot \ln \left( \frac{F_i'}{F_T'} \right) + m_3 \cdot \ln \left( \frac{F_i'}{F_T'} \right)$$

[4] The values of $\alpha_{\beta}, m_T, \alpha_T, m_1, m_2, \ldots, m_7$ were fixed, and then the values of $\delta$ and $\Delta$ were obtained through a trial and error process based on the least square error. After recalculation of $F_i'$ and $F_T'$, the iteration process returned to step [2].

Table 2 shows the constants obtained and the sign for $Q_{di}$. Fig. 1 is a graphical representation of the calculated value versus basic data for the $OTC$, for each temperature difference between air and the radiation panels used while compiling the basic data. In this study, in order to account for the magnitude of a thermal non-uniformity, we focused on this temperature difference. Since the data obtained for each temperature difference is based on a one-to-one relation, the empirical expressions obtained are considered to be reflective of environmental
thermal non-uniformity.

<table>
<thead>
<tr>
<th>Division</th>
<th>Head</th>
<th>Front torso</th>
<th>Back torso</th>
<th>Upper limbs</th>
<th>Lower limbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{da}$ [°C]</td>
<td>34.4–36.4</td>
<td>32.6–36.3</td>
<td>31.6–36.6</td>
<td>31.7–35.7</td>
<td>30.7–34.5</td>
</tr>
<tr>
<td>$Q_{di}$ [W/m²]</td>
<td>16.4–51.7</td>
<td>13.2–48.6</td>
<td>9.8–53.1</td>
<td>15.9–71.4</td>
<td>16.4–57.8</td>
</tr>
</tbody>
</table>

Table 1: Data ranges for the OTC

### 4.2 HDS<sub>i</sub> and CDS<sub>i</sub>

For the divisions of the whole body, i.e., the local area $i$ and the remaining area $T−i$, the weighting coefficients $W_i$ were set based on the skin-surface areas (Kurazumi et al 1994). For these two divisions, the mean skin temperatures and mean sensible heat losses were calculated using the basic experimental data and weights for the measurement points in accordance with the skin areas (Kurazumi et al 1994). Table 3 shows the data ranges for $HDS_i$ and $CDS_i$. For both positive and negative signs of $Q_{di}$ in Eq. (18), the constants in Eqs. (17) and (18) were obtained by carrying out steps [1] to [4]. Then, we adopted those values of the constants and sign for $Q_{di}$, corresponding to a lower sum of square errors. In this case, we fixed the constant $B$ to 28°C and 25°C for $HDS_i$ and $CDS_i$, respectively. Next, the constants $\delta'$ and $\Delta$ were obtained. The steps [2] to [4] were iterated until the sum of the square errors reached a minimum.

- [1] Initial values were set for $\Delta$ and $\epsilon$. Then, the values of $F_i^'$ and $F_{T}^'$ were calculated.
- [2] The constants $m_i$ and $\alpha_{\beta}$ were set by a regression in Eq. (22). Both $m_i$ and $\alpha_{\beta}$ are constants used in Eq. (15), which expresses the influence of the local area on $HDS_i$ or $CDS_i$.

$$\ln \left( H \left( C \right) D S_i + \epsilon \right) = m_i \cdot \ln \left( F_i^' \right) + \ln \left( \alpha_{\beta}^' \right)$$

(22)

- [3] The constants $\alpha_{\chi}$  and $m_T$ were set by a regression in Eq. (23). Both $\alpha_{\chi}$  and $m_T$ are constants used in Eq. (16), which compensates Eq. (15) taking into consideration the thermal state of the whole body.

$$\ln \left( \frac{ H \left( C \right) D S_i + \epsilon }{ \alpha_{\beta} \cdot F_i^{'m_i} } \right) = m_T \cdot \ln \left( \frac{ W_{T-i} \cdot F_{T-i}^' + W_{T-i} \cdot F_{T-i}^{'m_i} }{ F_i^' } \right) + \ln \left( \alpha_{\chi}^' \right)$$

(23)

### Table 2: Constants and sign in Eqs. (7), (8), and (11)

<table>
<thead>
<tr>
<th>$\alpha_{\beta}$</th>
<th>$\delta'$</th>
<th>$B$</th>
<th>$\Delta$</th>
<th>Sign for $Q_{di}$</th>
<th>$m_T$</th>
<th>$\alpha_{\chi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.762</td>
<td>0.0505</td>
<td>25.0</td>
<td>296.4</td>
<td>+</td>
<td>14.84</td>
<td>0.812</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_i$</th>
<th>$W_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Front torso</td>
</tr>
<tr>
<td>5.00</td>
<td>0.110</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$F_i^'$</th>
<th>$F_{T}^'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Front torso</td>
</tr>
<tr>
<td>5.32</td>
<td>5.32</td>
</tr>
</tbody>
</table>

Table 2: Constants and sign in Eqs. (7), (8), and (11)
The values of $\alpha_{\beta}', m_i, \alpha_{\chi}'$, and $m_T$ were fixed, and then the values of $\Delta$ and $\epsilon$ were obtained through a trial and error process based on the least square error. After recalculation of $F_i'$ and $F_T$, the iteration process returned to step [2].

With regard to $HDS_i$, we obtained the values of the constants and the sign for $Q_{ski}$ as shown in Table 4a. However, for $CDS_i$, the constant $\Delta$ increased to more than 1000 during the trial and error process for both positive and negative signs of $Q_{ski}$, any change in $Q_{ski}$ was considered to have little influence on $CDS_i$. This reflected the observation that local discomfort in the foot area was not dependent on the local sensible heat loss but dependent on the local skin temperature (Sakoi et al. 2006). Subsequently, we modified the expression for $CDS_i$, as shown in Eq. (24), in which the local functions $F_i$ depend only on $T_{ski}$. The constants were set by the abovementioned steps [1] to [4], with the exception that the constant $B$ was obtained instead of $\Delta$. Table 4b shows the constants obtained for Eq. (24). Figure 2 is a graphical representation of the calculated value versus basic data for $HDS_i$ and $CDS_i$.

\[
CDS_i = \alpha_{\beta}' \cdot (T_{ski} - B)^{m_i \cdot m_T} \cdot \alpha_{\chi}' \cdot \left[ W_i \cdot (T_{ski} - B) + W_{T-i} \cdot (T_{ski} - B) \right]^{m_T} - \epsilon \quad (24)
\]

Where: $0.0 \leq CDS_i \leq 1.0$
4. Characteristics of the Empirical Expressions

With regard to the OTC, as calculated by Eqs. (7), (8), and (11), since all the multipliers were set to positive values (see Table 2), the expressions obtained are consistent with the assumption that the OTC attains its maximum value at a fixed distribution of the local thermal states and decreases due to deviation from the distribution. The OTC takes its maximum at 0.94, under the conditions of \( F'_T = 0.0253 \) and \( F'_1 : F'_2 : F'_3 : F'_4 : F'_5 : F'_6 : F'_7 = 1.34 : 1.08 : 1.14 : 0.84 : 0.84 : 0.90 : 0.90 \). With regard to the expression for \( HDS_i \) in Eqs. (17) and (18), both multipliers \( (m_i - m_T) \) and \( m_T \) take positive values (see Table 4a). Consequently, an increase in the value of \( F'_i \) increases the value of \( HDS_i \); further, a decrease in the value of \( (F'_i + F'_T) \) decreases the value of \( HDS_i \). With regard to the expression for \( CDS_i \) in Eq. (24), both multipliers \( (m_i - m_T) \) and \( m_T \) take negative values (see Table 4b). Consequently, a decrease in the value of \( F'_i \) increases the value of \( CDS_i \); in addition, an increase in the value of \( (F'_i + F'_T) \) decreases the value of \( HDS_i \). The characteristics of these expressions are in good agreement with the study of Zhang et al. (2004). This indicates that the local thermal comfort in the “hot” or “cold” state is improved by the opposite thermal state, i.e., “cold” or “hot” state for the whole body.

5. Conclusions

The authors obtained empirical expressions for overall thermal comfort, thermal discomfort for hot head and/or hot whole body, and thermal discomfort for cold foot (foot and leg) and/or cold whole body. These expressions pertain to a sitting posture under a steady state, in non-uniform thermal environments, and local skin temperatures and local sensible heat losses were used to derive them.

Acknowledgements

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## References

Sakoi et al. 2006, Thermal Comfort, Skin Temperature Distribution, and Sensible Heat Loss Distribution in the Sitting Posture in Various Asymmetric Radiant Fields, Building and Environment (under submission)


### Nomenclatures

- \( \text{CDS}_i \): Cold discomfort taking account of local segment \( i \) and whole body [N.D.]
- \( F \): Local function, as an indicator of local thermal state [N.D.]
- \( F' \): Tentative local function \([\text{m}^2\cdot\text{ºC})/\text{W}]
- \( \text{HDS}_i \): Hot discomfort taking account of local segment \( i \) and whole body [N.D.]
- \( m \): Constant [N.D.]
- \( OTC \): Weighted overall thermal comfort [N.D.]
- \( RH \): Relative humidity [%]
- \( Q_{sk} \): Sensible heat loss \([\text{W/m}^2]
- \( T_a \): Air temperature [ºC]
- \( T_j \): Temperature of radiation panel \( j \) [ºC]
- \( T_{sk} \): Skin temperature [ºC]
- \( W_i \): Weight for local area \( i \) [N.D.]
- \( A \): Constant [1/ºC]
- \( \alpha_{ij}, \beta_{ij}, \alpha_{i'}, \beta_{i'}, \delta, \varepsilon \): Constants [N.D.]
- \( \beta \): Term expressing influence of mean thermal state for whole body on \( OTC \) [N.D.]

### Suffixes

- \( cal \): Value calculated from obtained expressions
- \( i \): Value for division \( i \)
- \( me \): Measured value
- \( T \): Mean value for the whole body
- \( T-i \): Mean value except for local area \( i \)
- \( n \): Number of division for the whole body
Effect of Functional Sportswear Ensembles on Physiological Responses

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Abstract

Physical parameters that influence sports and leisure activity include air temperature, relative humidity, air velocity, sportswear, other support etc. Nevertheless, not many studies have been carried out to understand the end-user’s evaluation of the performance of functional textile products used during sport and leisure activity. To test the functionality of sport textiles, we measured the physiological responses of seven healthy men wearing two kinds of sport t-shirts in 60%Vo2max conditions. The experiment was done in a climate chamber set at 30±0.5°C temperature and 50±10% humidity. The effect of functional textiles on the human body was evaluated by measuring the oxygen uptake, rectal temperature, skin temperature, sweat rate and heart rate. Skin and rectal temperatures were significantly higher with t-shirts A than with t-shirts B and oxygen uptake was also lower with t-shirts B. These factors must be considered when evaluating sportswear, demands of exercise and the fitness levels of athletes.

1. Introduction

During the past six years in Korea, sports and leisure textiles showed high growth rates by an average of 7.9% and 4.1% of the growth in the sportswear textile
market every year. The required properties of winter motorcycle clothing have been measured (R. I. Woods, 1982) [1] and so have the cooling rates of motorcyclists in their own or some experimental clothing (R. I. Woods, 1983) [2]. The relation between clothing thickness and the cooling rate of a single motorcyclist has also been measured (R. I. Woods, 1986) [3]. Preferences in next-to-skin sportswear made from different types of fibre were also studied (Y. Li et al, 1988) [4]. In a comparative study between swimming in swimwear (control-sw) and swimming in clothes (clothes-sw), oxygen uptake and ratings of perceived exertion were determined (S.W. Choi et al, 2000) [5]. Nevertheless, not many studies have been carried out to understand the end-user’s evaluation of the performance of the functional textile products used during sports and leisure activity. The purpose of the present work was to study the physiological responses of humans wearing functional t-shirts before, during and after exercise.

2. Methodology

2.1 Experimental garments

The experimental garments were 100% cotton knit sportswear (half-sleeved t-shirts and trousers, A) and 100% polyester knit sportswear (half-sleeved t-shirts and trousers, B). The two-kinds of sportswear fabrics were designed to have, as closely as possible, the same mass and thickness, so that they differed mostly in their water vapour and water uptake characteristics due to the different fibres used.

2.2 Subjects

The subjects were seven males who were physically healthy and had exercising experiences over one year. Their average ages were 23.4±1.0 years old, height 175.4±4.2 cm, weight 66.7±6.0 kg and their exercising experiences were 2.9±1.0 years. In order to minimize the interference factors relating to fatigue, the subjects had a sufficient amount of sleep on the night before the experiment and abstained from strenuous exercise, smoking, caffeinated drinks and taking drugs.
2.3 Measurements

Oxygen uptake was continuously monitored during all tests using a computerized metabolic cart with TrueOne 2400 (PravoMedics, USA). Gas analyzers were calibrated with gases of known concentration and the pneumotach was calibrated with a 3-L syringe before and after each experiment. The heart rate was transmitted to, and recorded by the metabolic cart wirelessly (Polar Electro Oy, Pravo Medics, USA). The rectal temperature (Tre) was measured using a thermistor probe inserted 12 cm beyond the anal sphincter. Skin temperatures (Ts) were measured with thermistors taped at seven sites: forehead, forearm, hand, chest, thigh, leg and foot. Localised sweat rate on the back area was recorded using capacitance hygrometry. All parameters were recorded continuously by a pen recorder, and also sampled every 60s by a computer through an A/D converter.

2.4 Environmental Conditions

Experiments were carried out in a climate chamber installed at INHA University. Conditions were chosen with 60Vo2max levels of exercise on a treadmill. The clothing was stored in the climate chamber at an air temperature of 30±0.5°C, and a relative humidity of 50±10% and air velocity of 0.1 m/s for at least 2 hours before the test. After being fitted with transducers and resting for 10 min, the subjects put on one of the sportswear and entered the chamber. The measurements were first made during a rest-time before exercising, and then were made at 1 min interval during 40 min exercise. The post measurements were made at 10 min recovery period after exercising. Each of the subjects participated in the same time periods over 2 days.
3. Results and discussion

**Oxygen uptake and heart rate**

The oxygen uptake during running on the treadmill in wearing t-shirts A was significantly greater (p<0.05) than that wearing t-shirts B (Figure 1). During the excising, compared with before and after, the value was increased more. There were no significant differences in heart rate responses to wearing the two kinds of T-shirts.

**Rectal temperature (Tre)**

Following 40 min of running, $Tre$ reached 38.87 ± 0.36°C, 38.62 ± 0.36°C in wearing the t-shirts A and B, respectively. It appears that the wearers in this investigation, while running moderately hard for a prolonged period, wearing t-shirts B, maintained a safe core temperature through effective thermoregulation. These changes were highly significant (p<0.05) for t-shirts A at the end of 15 min of exercise compared to t-shirts B (Figure 2).

**Skin temperature (Ts)**

With t-shirts B, the mean $Ts$ increased to 35.07 ± 0.76°C. In contrast, performing the exercise while wearing t-shirts A induced a mean increase of 0.5°C which was greater than that observed with t-shirts B, 34.56 ± 0.74°C (Figure 3). In addition, the mean $Ts$ during the exercise was greater than that before and after the exercise.

**Sweat rate (SW)**

Wearing t-shirts A during the exercise caused an increase in sweat rate. At the start of the exercise, the subjects reached a mean $SW$ on the back area ranged from 1.5 mg/cm²·min to 1.8 mg/cm² min when wearing the t-shirts A, compared to only 1.2 mg/cm² min to 1.5 mg/cm² min when wearing the t-shirts B. These changes were highly significant (p<0.05) for t-shirts A at the start of 12 min of exercise compared to the t-shirts B (Figure 4).
Figure 1: Oxygen uptake before, during and after exercising, with t-shirts A and B, 
(*) p<0.05 (◆: t-shirts A, ◇: t-shirts B)

Figure 2: Rectal temperature before, during and after exercising, with t-shirts A and B, 
(*) p<0.05 (◆: t-shirts A, ◇: t-shirts B)
Figure 3  Mean skin temperature before, during and after exercising with t-shirts A and B (◆: t-shirts A, ◇: t-shirts B)

Figure 4  Sweat rate on the back area before, during and after exercising, with t-shirts A and B, (* p<0.05) (◆: t-shirts A, ◇: t-shirts B)

4. Conclusions

The results of the study have shown that running with t-shirts (A and B) in a moderate temperature environment can involve ~ 60% of maximal oxygen consumption. If the t-shirt material and/or design exceed those in this study then core temperature might rise to dangerous levels unless the symptoms and the signs
of heat stress are recognized. Furthermore, when t-shirts A were used during the 40 min exercise, it was perceived that a ‘strong’ and ‘high’ heat strain was imposed on the subjects.

References
Section III
Thermal Comfort Modelling
A Three-dimensional Human Thermal Model for Non-uniform Thermal Environments

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In this study, the authors have proposed a three-dimensional human thermal model for predicting the local values of skin temperature, sweat rate, sensible heat loss and latent heat loss. For this model, a three-dimensional shape of the Smith model (1991) was adopted. The blood flow was not controlled through the dilation and constriction of the vessels of the model, while the blood perfusion rate for the skin tissue was numerically changed under a fixed volume of the vessels, as demonstrated in previous models (Stolwijk 1971, etc). The calculated results were compared with the measured local skin temperatures in a sitting posture under a uniform condition around the neutral state. The local skin temperature calculated around the hand region was lower than the measured value; however, the calculated and measured values in the other local areas agreed as a whole.

Keywords: Thermal comfort, heat transfer; human thermal model, non-uniform thermal environment, local skin temperature, local sensible heat loss, redistribution of body heat, superficial vein
1. Introduction

In this study, the authors propose a three-dimensional human thermal model that can predict local skin temperatures and local sensible heat losses under non-uniform thermal environments and various clothing conditions. Table 1 lists the multi-segmental human thermal models for the entire body. Two methods can be used to assign the core component. In the first (B1 in Table 1) method, only the shell is divided into segments and the core component is common for all the segments (Jones and Ogawa 1992, Kohri and Modhida 2003); in the second (A1) method, each segment has an individual core and shell (Stolwijk 1971, etc). Three techniques are used to yield a variety of compositions. First, the composition is uniform in a segment (Wissler 1961). Second, the composition is approximately divided into two sections—core and shell—for each segment (Werner and Webb 1993, etc). Third, different compositions are assigned according to the types of tissues (Stolwijk 1971, etc). Two procedures can be used for connecting the vessels between the core and tissues perfused by arterial blood. First (B2), the arterial and venous vessels are directly connected by neglecting the routes between the heart (core) and tissues (Stolwijk 1971, etc). Second (A2), the vessels are connected using all the segments along the routes between the heart (core) and tissues (Arkin and Shitzer 1984, etc). Four methods can be used for evaluating the countercurrent heat exchange. The first method (Non) does not take into account this heat exchange (Stolwijk 1971, etc). Second (A3), heat is exchanged only between the arterial and venous vessels perfusing the same tissue (Wissler 1961, etc). Third (B3), heat is exchanged throughout the vascular network of tissues (Arkin and Shitzer 1984, etc). For modelling a vascular network, two methods can be used. First (A4), the vascular network can be modeled on the basis of several blood pools and the heat exchange between blood and tissues is macroscopically evaluated (Wissler 1961, etc). Second (B4), the network was modeled as a network of one-dimensional (1D) blood vessel elements and heat exchange occurs at the walls of the blood vessels of each element (Smith 1991, etc). Further, models exist (Smith 1991, etc) in which the total blood mass varies as a result of vasoconstriction and vasodilation. Vasoconstriction decreases the volumes of the 1D blood vessel elements, thereby decreasing the total blood mass; on the other hand, vasodilation increases the total blood mass. Models with superficial veins (Smith 1991, etc) have been developed. Venous blood has a long residence time when compared with arterial blood, and the temperature of the superficial tissue is lower than that of the deep tissue. Further, the location and heat exchange between blood and tissue exhibits a greater influence on venous blood than that on arterial blood.
### Table 1a: Multi-segmental human thermal models and positioning of our study (first half)

<table>
<thead>
<tr>
<th>Proponent(s)</th>
<th>Year</th>
<th>Assignment of core</th>
<th>Number of compositions</th>
<th>Connection of vessels between core and tissues perfused by blood</th>
<th>System of countercurrent heat exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wissler 1961</td>
<td>A1</td>
<td>Uniform in a segment</td>
<td>A2</td>
<td>A3</td>
<td></td>
</tr>
<tr>
<td>Stolwijk 1971</td>
<td>A1</td>
<td>4 in a segment</td>
<td>B2</td>
<td>Non</td>
<td></td>
</tr>
<tr>
<td>Arkin, Shitzer 1984</td>
<td>A1</td>
<td>4 in a segment</td>
<td>A2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>Wissler 1985</td>
<td>A1</td>
<td>4 in a segment</td>
<td>A2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>Smith 1991</td>
<td>A1</td>
<td>9 in the entire body</td>
<td>A2</td>
<td>B3\textsuperscript{3}\textsuperscript{4}</td>
<td></td>
</tr>
<tr>
<td>Jones, Ogawa 1992</td>
<td>B1</td>
<td>2 (shell in a segment and common core)</td>
<td>B2\textsuperscript{3}\textsuperscript{4}</td>
<td>Non</td>
<td></td>
</tr>
<tr>
<td>Takemori et al. 1994</td>
<td>A1</td>
<td>9 in the entire body</td>
<td>A2</td>
<td>B3\textsuperscript{3}\textsuperscript{4}</td>
<td></td>
</tr>
<tr>
<td>Fu 1995</td>
<td>A1</td>
<td>9 in the entire body</td>
<td>A2</td>
<td>B3\textsuperscript{3}\textsuperscript{4}</td>
<td></td>
</tr>
<tr>
<td>Takemori et al. 1999</td>
<td>A1</td>
<td>8 in the entire body</td>
<td>B2</td>
<td>A3</td>
<td></td>
</tr>
<tr>
<td>Yokoyama et al. 2000</td>
<td>A1</td>
<td>8 in the entire body</td>
<td>A2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>Tanabe et al. 2001</td>
<td>A1</td>
<td>4 in a segment</td>
<td>B2</td>
<td>Non</td>
<td></td>
</tr>
<tr>
<td>Huizenga et al. 2001</td>
<td>A1</td>
<td>4 in a segment</td>
<td>A2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>Tanabe 2004</td>
<td>A1</td>
<td>2 in a segment</td>
<td>A2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>McGuffin et al. 2002</td>
<td>A1</td>
<td>Less than 5 in a segment</td>
<td>A2</td>
<td>B3\textsuperscript{3}\textsuperscript{4}</td>
<td></td>
</tr>
<tr>
<td>Kohri, Mochida 2003</td>
<td>B1</td>
<td>2 (shell in a segment and common core)</td>
<td>B2\textsuperscript{3}\textsuperscript{4}</td>
<td>Non</td>
<td></td>
</tr>
<tr>
<td>Our study 2004</td>
<td>A1</td>
<td>9 in the entire body</td>
<td>A2</td>
<td>B3\textsuperscript{3}\textsuperscript{4}</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

\(\dagger\) Years in which the papers referred to in this study were published. There may be cases wherein the mentioned year is different from the first year the model was published.

\(\dagger 2\) Skin and fat are regarded as different tissues. For their mixed composition, the mean properties in accordance with the weights have been assigned.

\(\dagger 3\) Blood and tissue in the core are considered to be identical.

\(\dagger 4\) Heat is exchanged by the mediation of tissue.
<table>
<thead>
<tr>
<th>Proponent(s)</th>
<th>Year(^{1})</th>
<th>Modelling of vascular network</th>
<th>Dimension of temperature distribution in a segment(^{5})</th>
<th>Change in total blood mass by control of blood flow</th>
<th>Superficial veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wissler</td>
<td>1961</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Stolwijk</td>
<td>1971</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Gordon et al.</td>
<td>1976</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Arkin, Shitzer</td>
<td>1984</td>
<td>A4</td>
<td>2D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Wissler</td>
<td>1985</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Smith</td>
<td>1991</td>
<td>B4</td>
<td>3D</td>
<td>Change</td>
<td>Exists</td>
</tr>
<tr>
<td>Jones, Ogawa</td>
<td>1992</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Werner, Webb</td>
<td>1993</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Takefumi et al.</td>
<td>1994</td>
<td>B4</td>
<td>3D</td>
<td>Change</td>
<td>Exists</td>
</tr>
<tr>
<td>Fu</td>
<td>1995</td>
<td>B4</td>
<td>3D</td>
<td>Change</td>
<td>Exists</td>
</tr>
<tr>
<td>Yokoyama et al.</td>
<td>2000</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Tanabe et al.</td>
<td>2001</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Huzenga et al.</td>
<td>2001</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Tanabe</td>
<td>2004</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Exists</td>
</tr>
<tr>
<td>McGuffin et al.</td>
<td>2002</td>
<td>B4</td>
<td>3D</td>
<td>Change</td>
<td>Exists</td>
</tr>
<tr>
<td>Kohri, Mochida</td>
<td>2003</td>
<td>A4</td>
<td>1D</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>Our study</td>
<td></td>
<td>A4</td>
<td>3D</td>
<td>Non</td>
<td>Exists</td>
</tr>
</tbody>
</table>

Notes: \(^{1}\) Years in which the papers referred to in this study were published. There may be cases wherein the mentioned year is different from the first year the model was published.  
\(^{5}\) 1D: Core ↔ surface, 2D: Core ↔ surface and aspect angle, 3D: Omni-directions

The positioning of our model can be determined from Table 1. The three-dimensional (3D) temperature field, heat conduction, redistribution of body heat by blood circulation, promotion of heat conduction in skin tissue by conduction of blood flow, respiratory heat loss, and sensible and latent heat losses at skin surface are numerically analyzed on the basis of a finite element method. This model employs a 3D shape of the Smith model (1991). Further, the model exhibits the heat transfer characteristics in correlation with the thermal properties of the compositions in this shape. The thermoregulatory mechanism proposed by Yokoyama (1993) has been adopted in order to consider the segmental characteristics of the physiological responses. The blood perfusion rate in the skin varies within a fixed volume of the blood elements.
2. Summary of human thermal model

The human thermal model has two blood circulations: main circulation and pulmonary circulation. Figure 1 shows both the vascular networks. The arterial and venous networks are symmetrical; further, the 3D tissue and the arterial and venous blood pools share the same 3D space at a fixed volume ratio. There are two types of 1D veins: deep veins and superficial veins. The arterial blood flows from the ventricles to blood capillaries of the tissue through 1D deep arteries and 3D arterial pools. Venous blood originating from the blood capillaries of the tissue returns to the atriums through the 3D venous pools and 1D veins. The details of the blood circulations are described in the next section. The boundary conditions for the heat transfer, disappearance of arterial blood, and appearance of venous blood are common to the 1D arteries, 3D arterial pools, 3D tissues, 3D venous pools, and 1D veins. For obtaining the mean values for the entire body, the most suitable values for thermal conductivities, densities, specific heats, volume ratios of arterial and venous blood, basal blood perfusion rates, basal metabolic heat productions, and diameters of 1D arteries and veins are selected from different studies (Smith 1991, Ochi 1990, Yokoyama 1993, Sasaki 1981, Kodansha 1989, Ganong 1973). In this study, for the human thermal model, the body weight is 75.94 kg; surface area, 1.837 m²; total blood volume, 6682 ml; total heart output rate in a thermally neutral state, 5782 ml/min; and basic metabolic rate, 47.8 W/m².

3. Blood Circulations in Human Thermal Model

Equations (1) and (2) are the balance equations for the arterial and venous blood, respectively. Arterial blood flow at a given point is determined by the integrated blood perfusion rates \( \beta(s) \) for the lower current spaces along a streamline and the venous blood flowing at a given point is also determined by the integrated \( \beta(s) \) for the upper current spaces along a streamline; these have been described later.
\[ \nabla \mathbf{u}_B + \beta_{(s)} = 0 \quad (1) \]

\[ \nabla \mathbf{u}_B - \beta_{(s)} = 0 \quad (2) \]

The flow directions in the 1D arteries and 1D veins are shown in Figure 1. Figure 2 shows the blood flow directions in the 3D arterial pools and 3D venous pools. In the human thermal model used in this study, the 3D spaces (shared by the 3D tissue and the arterial and venous pools) are approximately divided into two regions: countercurrent region and one-way region. In the former, the arterial vessels directed toward the tissue are assumed to be countercurrent to the venous vessels returning from the tissue. In the latter, the arterial blood comes from the deep part of the cylindrical segments; after perfusing the tissues, the venous blood returns to the atrium through the superficial veins. The internal organs (including lungs), brain, bones, muscle, subcutaneous fat, and skin on the head and neck regions have been assigned to the countercurrent region, and the skin of the torso, upper arms, forearms, hands, thighs, legs, and feet have been assigned to the one-way region.

As shown in Figure 1, blood in the 1D arteries starts flowing from the ventricles and flows to the terminations at the extremities of the hands, feet, or head (for the main circulation) or upper torso (for the pulmonary circulation) while exuding through the side wall of the 1D elements into the surrounding 3D arterial blood pools; here, the blood flows to the terminations at the outer circumferences of the skin (for the main circulation) or those of the lung (for the pulmonary circulation) along with a reduction in the flow due to absorptions into the capillary beds. In the countercurrent region in the 3D venous blood pools, blood starts...
from the outer circumferences of the region and flows toward the center of the cross-section of the cylindrical segments while absorbing venous blood oriented in the capillary beds. Then, it flows into the 1D deep veins. In the one-way region of the 3D venous blood pool, blood starts from the remotest points of the 1D superficial veins and flows toward these veins while absorbing venous blood oriented in the capillary beds in the skin. Then, it flows into the 1D superficial veins. As shown in Figure 1, blood in the 1D deep veins and 1D superficial veins start from the extremities of the hands, feet, or head (for the main circulation) or upper torso (for the pulmonary circulation) and returns to the atriums while absorbing venous blood from the surrounding 3D venous pools.

4. Heat Transfer Equations

4.1 For Finite Elements

Equation (3) is the heat balance equation for the elements of the 1D arteries and 3D arterial blood pools; Equation (4), for the elements of the 3D tissues; and Equation (5), for the elements of the 1D veins and 3D venous blood pools.

\[
\alpha_{A(r)} \rho_g C_p g \frac{\partial T_{A(r)}}{\partial t} = -\rho_g C_p g \nabla \cdot (u_{n} T_{A(r)}) - h_{\text{ext}(r)} (T_{A(r)} - T) \Delta R_{A(r)}
\]

\[
(1 - \alpha_A - \alpha_T - \alpha_{A(r)} - \alpha_{V(r)}) \rho_T C_p T \frac{\partial T_T}{\partial t} = \lambda_T \nabla \cdot \nabla T_T + \beta_{PA} C_p g (T_A - T_T) + \beta_{PV} C_p g (T_{A(r)} - T_T) + M
\]

\[
- h_{\text{ext}(T)} (T_T - T) \Delta R_{T} - h_{\text{int}(T)} (T_T - T) \Delta R_{T}
\]

\[
\alpha_{V(r)} \rho_g C_p g \frac{\partial T_{V(r)}}{\partial t} = -\rho_g C_p g \nabla \cdot (u_{n} T_{V(r)}) + \beta_{r} \rho_T C_p T (T_T - T_{V(r)}) - h_{\text{int}(r)} (T_T - T_{V(r)}) \Delta R_{V(r)}
\]

Heat exchanges in the body surface and the respiratory system (in section 4.2) are referred to as the boundary conditions and the heat dissipation term with regard to the 3D tissue elements, respectively.
4.2 Heat Loss from Lung and Respiratory Tracts

In order to evaluate respiratory heat loss, a region from the mouth to the alveoli was approximately divided into two spaces: dead space and alveolar space. The volume rate of the lung ventilation $V_{res}$ is set in accordance with Fanger (1972). As shown in Figure 3, one respiration cycle $\Delta t_{res}$ is divided into four processes: inhaling process, resting process, exhaling process, and resting process. In the two resting processes, there are no air movements. A fixed air rate of $(V_{res}/0.34\Delta t_{res})$ is inhaled or exhaled during the respective processes. Equation (6) reveals the heat balance in air in dead space. Equation (7) reveals the mass balance in the humidity for air in dead space.

\[
\rho_{ares} C_{pares} \frac{\partial T_{ares}}{\partial t} \pi_{o}^2 v_{ares} \frac{\partial T_{ares}}{\partial z} = -\rho_{ares} C_{pares} \pi_{o}^2 v_{ares} \frac{\partial T_{ares}}{\partial z} + 2\pi_{o} h_{ares} (T_{s} - T_{ares}) \quad (6)
\]

\[
\frac{\partial W_{ares}}{\partial t} \pi_{o}^2 v_{ares} \frac{\partial W_{ares}}{\partial z} = -\pi_{o}^2 v_{ares} \frac{\partial W_{ares}}{\partial z} + 2\pi_{o} h_{ares} (W_{s} - W_{ares}) \quad (7)
\]

In all the processes, heat and vapor transfers in dead space are calculated according to the convective heat and mass transfer coefficients.

In the inhaling process, air reaching point A is uniformly absorbed into the lung tissues. Air is heated to the temperature of the lung tissue and gets completely humidified.

In the exhaling process, air is released from the lung tissue. This air instantly reaches point A without any heat and vapor exchanges with the surrounding lung tissue.

Figure 3 Modelling of heat and vapour transfers in one respiratory cycle
Equation (8) reveals the heat loss from the lung tissue into air flowing from the termination of the dead space (point A in Figure 4) during the inhaling process.

\[
Q_{\text{lung}~in} = \frac{V_{\text{areas}}}{V_{\text{olung}}} \left( \rho \cdot CP_{\text{areas}} (T_{s} - T_{a,\text{lin}}) + L(W_{s,\text{r}} - W_{a,\text{lin}}) \right)
\]  

(8)

5. Examples of Analysis

The blood perfusion rates for skin, shivering, sweat secretion, and metabolic heat production in the body segments are set in accordance with the formulae given by Yokoyama (1993). We analyzed this human thermal model under two conditions, namely, uniform ambient temperature of 25.5°C and 28.0°C, for a sitting posture (1 met), 16 cycles per min during respiration, only trunks (0.05 clo), still air, 50% RH, and uniform radiant temperature (= air temperature). Figure 4 shows the local skin temperatures of the human thermal model along with the measured local skin temperatures under the same conditions (Sakoi et al. 2006). In the human thermal model, the temperature around the hand region was lower than the measured value. This difference can be attributed to the large difference in the heat transfer characteristics between the complex shape of the actual hands and the simple shape of the cylinder in the human thermal model.

Conclusions

The authors have proposed a human thermal model on the basis of the shape of the Smith model (1991) and the thermal regulatory systems proposed by Yokoyama (1993). This model solves the three-dimensional heat transfer and temperature fields by using inputs of figures and compositions of elements, thermal properties of compositions, and outer conditions. In this model, the composition is changeable for each finite element. The size of finite elements, characteristics of blood perfusion rate in the skin, heat production by action, shivering, and sweat secretion are changeable for each segment. The change in the blood flow is induced under constant volumes of the blood elements.
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at the Osaka Gas Co LTD. for their valuable support and advice for this study.
Nomenclatures

\( AR \) : Effective area per unit volume of tissue for convective heat transfer between tissue and blood \( [m^2/m^3\text{-tissue}] \)

\( Cp \) : Specific heat of composition of body and air \( [J/(kg\cdot{}^\circ{}C)] \)

\( h_c \) : Convective heat transfer coefficient \( [W/(m^2\cdot{}^\circ{}C)] \)

\( h_{vanes} \) : Vapor transfer coefficient between tracheal wall and air in trachea \( [m/s] \)

\( L \) : Heat for the evaporation of water \( (=2406950) [J/kg] \)

\( M \) : Metabolic heat production \( [W/m^3] \)

\( Q_{lung} \) : Heat loss from lung tissue \( [W/m^3] \)

\( r_o \) : Radius of 1D element \( [m] \)

\( t \) : time \( [s] \)

\( T \) : Temperature of compositions of body and air \( [{}^\circ{}C] \)

\( T_{sur} \) : Air temperature of surrounding environment \( [{}^\circ{}C] \)

\( u_B \) : Velocity vector of blood \( [m/s] \)

\( V_{\text{dvol}} \) : Volume of lung tissue \( [m^3] \)

\( v_{res} \) : Velocity of air in trachea \( [m/s] \)

\( W \) : Absolute humidity \( [kg/kg\text{-dry air}] \)

\( W_{at} \) : Absolute humidity of saturated air at temperature of tracheal wall \( T_{at} [kg/kg\text{-dry air}] \)

\( z \) : length coordinate of 1D elements \( [m] \)

\( \alpha_{a(t)} \) : Rates of volume occupied by arterial blood (in pulmonary circulation) \( \text{[N.D.]} \)

\( \alpha_{v(t)} \) : Rates of volume occupied by venous blood (in pulmonary circulation) \( \text{[N.D.]} \)

\( \beta_{a(t)} \) : Blood perfusion rate to body compositions (in pulmonary circulation) \( [m^3/(s\cdot{}m^3\text{-tissue})] \)

\( \Delta_{vanes} \) : Duration of one respiration cycle \( [s] \)

\( \lambda \) : Thermal conductivity \( [W/(m\cdot{}^\circ{}C)] \)

\( \rho \) : Density \( [kg/m^3] \)

Suffixes

\( A_{s} \) : Values for arterial blood (in pulmonary circulation)

\( ares \) : Values for air in trachea or those between tracheal wall and air in trachea

\( aLin \) : Values at termination of the dead space (point A in Figure 3) in respiratory system

\( B \) : Values for blood

\( T \) : Values for tissue or trachea

\( A(s)T \) : Values between three-dimensional tissues and arterial blood (in pulmonary circulation)

\( V(s)T \) : Values between three-dimensional tissues and venous blood (in pulmonary circulation)

\( V(s) \) : Values for venous blood (in pulmonary circulation)
Study on Human Physiological Models for Hot Environments

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Abstract

Recently, the outdoor thermal environment in urban areas has deteriorated during summer. There is a potential for serious consequences, such as “heat disorders”, arising under such harsh hot outdoor environments. Many researchers are seeking to evaluate the thermal environment in urban, outdoor or semi-outdoor areas. These tend to be evaluated as Standard Effective Temperature (SET\textsuperscript{*}), using the 2-Node Model (2NM), Wet Bulb Globe Temperature (WBGT), Predicted Heat Strain Model (PHS Model) and so on. The authors aim to develop an index for hot outdoor environments, and the purpose of this paper is the verification of the 2NM and PHS models. Experiments involving human subjects are performed in a laboratory to understand the physiological response of the human body to heat. The results are understood with the computed values from the 2NM and PHS models. Additionally, the relationship between the metabolic and sweating rates is presented and modification to the sweating model in 2NM is discussed.

1. Introduction

Recently, the outdoor thermal environment in urban areas has deteriorated during summer, increasing the potential for serious ailments, like “heat disorder”, arising in such harsh hot outdoor environments. Fig. 1 shows changes in the number of fatalities ascribed to heat disorder in Japan. The hatched columns indicate
particularly hot years. Their correlation with the increased death toll is evident and demonstrates a chronic surge since 1994. Heat disorders are also certain to rise in future. Accordingly, an appropriate methodology is required in order to account for the risk of such an event.

Many researchers are seeking to evaluate the thermal environment in urban, outdoor or semi-outdoor areas. These tend to be evaluated as New Standard Effective Temperature (SET*) using the 2-Node Model (2NM) proposed by A. P. Gagge et al., Wet Bulb Globe Temperature (WBGT), and so on. However, the physiological response is not examined in any detail in these models under extremely hot environments. On the other hand, the Predicted Strain Model (PHS Model), proposed by J. Malchaire et al. sets out to evaluate the safety of working conditions in hot environments, and is embraced as ISO 7933:2004. WBGT is a physical index, and there is no direct relation between the physical index value and the state of the human body, whereas the 2NM and PHS models represent the human body’s temperature adjustment. The PHS model is an index that introduces a "Virtual load" in terms of the human body. 2NM theoretically calculates the physiological factors based on the mechanism of human body temperature regulation.

The authors aim to develop an appropriate thermal index to evaluate hot outdoor environments. The purpose of this study is validation of the 2NM and PHS models in hot environments. Experiments with human subjects are performed in a laboratory to understand the physiological response of the human body to hot environments. The results, measured as skin temperature, core temperature and sweating rate, are compared with the computed values from the 2NM and PHS models. Additionally, the relationship between metabolic and sweating rates is presented, and modification of the sweating model in 2NM is discussed.

2. Experiment

The aim of these laboratory experiments, involving human subject, is to understand the physiological response of the human body to hot environments. Table 1 presents an outline of the experiment, and Fig. 2 shows the setup for the experiment. This experiment is performed in a test chamber, of which the air temperature and relative humidity can be arbitrarily controlled. The average height and weight of the subjects were 164.8 cm and 57.1 kg, respectively.
Section III: Thermal Comfort Modelling

| Time       | Exp. A: From 1 to 15 August 2005  
|           | Exp. B: From 9 to 23 January 2006 |
| Place      | Ultimate Environment Test Chamber, I.I.S., The Univ. of Tokyo |
| Subject    | 12 men and 13 women in healthy condition, aged 18 to 24 |
| Content    | Measurement of physiological factors |

Table 1: Outline of the experiment

![Figure 2 Photos of the experimental conditions](image)

2.1 Measurement factors

Table 2 presents the measurement items. Core temperature is measured as the tympanic temperature by an infrared radiation sensor. Mean skin temperature is calculated from eight skin temperature sensors (on the forehead, right back, left upper chest, right upper arm, left lower arm, left hand, right anterior thigh and left calf), using weight averaging based on ISO 9886. Sweating rate is calculated from the change of weight (water loss) determined by a precision weighing scale.

<table>
<thead>
<tr>
<th>Item</th>
<th>Place / Method</th>
<th>Equipment</th>
<th>Interval [min.]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental items</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>100 mm / 1,100 mm / 1,700 mm above the floor</td>
<td>T-type thermocouple thermometer and data logger</td>
<td>1</td>
</tr>
<tr>
<td>Wall temperature</td>
<td>4 wall surfaces, 16 points</td>
<td>T-type thermocouple thermometer and data logger</td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>1,100 mm above the floor</td>
<td>Assman psychrometer</td>
<td>1</td>
</tr>
<tr>
<td>Air velocity</td>
<td>1,100 mm above the floor</td>
<td>Hot-wire anemometer</td>
<td>1</td>
</tr>
<tr>
<td><strong>Physiological items</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metabolic rate</td>
<td>Amount of O₂ consumption and CO₂ production</td>
<td>Portable metabolic testing system</td>
<td>Every 3 breaths</td>
</tr>
<tr>
<td>Core temperature</td>
<td>Tympanic membrane</td>
<td>Infrared clinical thermometer</td>
<td>5</td>
</tr>
<tr>
<td>Skin temperature</td>
<td>8 points on the skin’s surface</td>
<td>Handheld temperature logger</td>
<td>1</td>
</tr>
<tr>
<td>Sweating rate</td>
<td>-</td>
<td>Precision weight scale</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2: Measurement items
2.2 Experimental conditions

Table 3 shows the conditions for each case. While the conditions created in the experimental chamber differ from the real outdoor environment in terms of radiation and wind, these conditions were selected as uniform environments in which changes in physiological factors can be measured accurately. Case 1 represents the standard case. Cases 2 and 3 were for the verification of the effect of activity, and Cases 4 and 5 were for the verification of the effect of relative humidity and air temperature, respectively. In Cases 2 and 3, the subjects walk on a treadmill at a speed of 0.9 [m/s] and 1.4 [m/s]. For the safety of the subjects, the experimental period for Cases 2 and 3 was shortened to 45 minutes. Case 3 was carried out during Exp. B; from 9 to 23 January 2006 only. Every subject wore a standard set of clothes in all cases, namely a white T-shirt and white short pants.

<table>
<thead>
<tr>
<th>Case</th>
<th>Environmental conditions</th>
<th>Human conditions</th>
<th>Experimental period [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3: Experimental conditions

3. Results: A Comparison between experimental and computed values

Changes in physiological factors are compared between the experimental values and the computed values are compared using the 2NM and PHS models. 2NM assumes that the human body is composed of two nodes, i.e. a central core and a skin shell, and calculates individual thermal balance equations. The PHS Model predicts transitions in core temperatures with consideration for the required evaporative rate to maintain a steady thermal equilibrium, the response characteristic of evaporation, and thermal storage of the skin. While prediction of thermal physiological responses of an unsteady human body is common to both models, they also have some differences in their basic concept. A comparison of the 2NM and PHS models is described in Table 4. Figs. 3, 4, and 5 present comparisons of the experimental results and computed results with the 2NM and PHS models. The experimental values of each case are the average of all subjects. The vertical lines show the standard deviations in the experiment.
### Section III: Thermal Comfort Modelling

#### 2-Node Model (2NM) Predicted Heat Strain Model (PHS Model)

<table>
<thead>
<tr>
<th>Initial value</th>
<th>Experimental initial values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Convective heat transfer coefficient</strong></td>
<td></td>
</tr>
<tr>
<td>Maximal value of:</td>
<td>Maximal value of:</td>
</tr>
<tr>
<td>$h_c = 5.7 \left(M - 0.85\right)^{0.39} \text{[W/m}^2\text{K]}$ (active in still air)</td>
<td>$h_c = 2.38 \left(T_{sk} - T_{ai}\right)^{0.25} \text{[W/m}^2\text{K]}$ (in still air)</td>
</tr>
<tr>
<td>$h_c = 8.6 V_{walk}^{0.53} \text{[W/m}^2\text{K]}$ (walking in still air)</td>
<td>$h_c = 3.5 + 5.2 V \text{[W/m}^2\text{K]}$</td>
</tr>
<tr>
<td>$h_c = 3.1 \text{[W/m}^2\text{K]}$ (seated with moving air, $0 &lt; V_{air} &lt; 0.2$)</td>
<td>$h_c = 8.7 V^{0.6} \text{[W/m}^2\text{K]}$ (Seated with moving air)</td>
</tr>
</tbody>
</table>

#### Calculation of evaporative sweating rate

**Assume as signal:**

- $\Sigma_{cr, warm} = T_{cr} - 36.8 \text{[-]}$
- $\Sigma_{sk, warm} = T_{sk} - 33.7 \text{[-]}$

**Skin evaporative loss by regulatory sweating $E_{rsw}$**

$$E_{rsw} = 0.68 \cdot 170 \cdot \left(T_b - 36.49\right) \cdot \exp\left(\frac{(T_{sk} - 33.7)}{10.7}\right) \text{[W/m}^2\text{]}$$

**Average body temperature $T_b$**

$$T_b = \alpha T_{sk} + (1 - \alpha) T_{cr} \text{[°C]}$$

**Mass ratio of skin and core $\alpha$**

$$\alpha = 0.0417737 + (0.7451832 / (V_{bl} + 0.5854177)) \text{[-]}$$

**Skin blood flow $V_{bl}$**

$$V_{bl} = 6.3 + 200 \cdot \Sigma_{cr, warm} \text{[L/m}^2\text{h]}$$

**Required evaporative heat flow $E_{req}$ from heat balance of the body**

$$E_{req} = M - W - C_{res} - E_{res} - C - R - dS_{eq} \text{[W/m}^2\text{]}$$

**Required Sweat Rate $S_{req}$ from $r_{req}$**

$$S_{req} = E_{req} / r_{req} \text{[W/m}^2\text{]}$$

**Predicted Sweat Rate at time $t_i$, $S_{p,i}$ from $S_{p,i-1}$ and $S_{req}$**

$$S_{p,i} = e^{(-1/10)} S_{p,i-1} + (1 - e^{(-1/10)}) S_{req} \text{[W/m}^2\text{]}$$

**Predicted evaporative heat flow $E_p$**

$$E_p = r_p \cdot S_{p,i} \text{[W/m}^2\text{]}$$

### Table 4: Comparison between 2NM and PHS Models

Fig. 3 presents a comparison of skin temperatures. In Cases 1, 4 and 5, under low metabolic conditions, 2NM corresponds well with the experimental values. However, 2NM does not agree well with the experimental values in Case 2 under high metabolic conditions. Fig. 4 presents a comparison of the core temperatures. 2NM follows approximately the same trajectory and corresponds well with the experimental values in all cases. The difference between the experimental values and 2NM is within 0.3 deg C. Fig. 5 presents a comparison of sweating rates. In Cases 1, 4 and 5, under low metabolic condition, 2NM corresponds well with the experimental values within 10 g/m$^2$. On the other hand, the results for 2NM are 50 g/m$^2$ lower than the experimental values, while the PHS Model is closer to the experimental values under the high metabolic conditions in Case 2.
Table 5 shows the accuracy of the 2NM and PHS models under low and high metabolic conditions. Overall, the 2NM model corresponds better to the experimental values than the PHS model.

<table>
<thead>
<tr>
<th>State of correspondence</th>
<th>Low metabolic cases</th>
<th>High metabolic case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core temperature</td>
<td>2NM</td>
<td>2NM</td>
</tr>
<tr>
<td>Skin temperature</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Sweating rate</td>
<td>Good</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Table 5: Summary of the comparison
There are some reasons for the difference between the experimental and 2NM results. Firstly, there are the characteristics of the 2NM sweating model itself. Because the model has been developed based on experiments in limited environments, this sweating model might not correspond as well to the physiological response of exercising in hot environments. Secondly, the difference in the sweating characteristics of Caucasian and Mongoloid subjects should be considered. 2NM has been developed based on experiments featuring Caucasians. Mongoloid people are said to have more active sweat glands than Caucasians. Furthermore, there is the possibility that non-contributory sweating occurred during the experiment.

4. Improvement of the sweating model in 2NM

4.1 The present sweating model used for 2NM
In 2NM, equation [1] is used to calculate the sweating rate.

\[
m_{rsw} = 170 \cdot (T_b - 36.49) \cdot \exp\left(\frac{T_{sk} - 33.7}{10.7}\right) \quad [\text{g/hm}^2]
\]  

where \( m_{rsw} \) is the sweating rate, \( T_b \) is the average body temperature and \( T_{sk} \) is the skin temperature. In addition, when \( T_b \) increases by 1.0 deg C, \( m_{rsw} \) increases by 170 g/hm\(^2\) on average.

Eq. [1] is a function of only the core and skin temperatures. Although an increase in metabolism causes an increase in the sweating rate through raised core and skin temperatures, the effect of such metabolism is not directly included in Eq. [1]. On the other hand, there are some reports suggesting that exercise itself stimulates sweating independently based on expectation of the temperature signal.

4.2 Proposal for a new sweating model
Table 6 presents a comparison between the experimental sweating rate value and that computed under high metabolic conditions by Eq. [1]. In order to estimate the accuracy of Eq. [1], the experimental values of the skin and core temperatures are substituted into it.

<table>
<thead>
<tr>
<th>Metabolic rate [met]</th>
<th>2.0</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average sweating rate [g/hm(^2)]</td>
<td>Experimental value</td>
<td>154.2</td>
</tr>
<tr>
<td></td>
<td>Computed value which experimental values of the skin and core temperature are substituted for Eq. [1]</td>
<td>76.7</td>
</tr>
<tr>
<td>Ratio [-]</td>
<td>2.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 6: Variation of the sweating rate as the metabolic rate is changed

The ratio of the sweating rate (the experimental value / the value computed by Eq. [1]) is 2.0 and 2.8 under 2.0 and 3.0 met conditions respectively. Based on this result and the other sensitivity analyses, a new formulation for the sweating model is proposed as Eq. [2].

\[
m_{rsw} = 170 \cdot (T_b - 36.49) \cdot \exp\left(\frac{T_{sk} - 33.7}{10.7}\right)(0.5M + 0.5) \quad [\text{g/hm}^2]
\]  

[2]
where $M$ is the value of the metabolic rate [met].

5. Results of the new sweating model

Figs. 6 and 7 show comparisons of the skin and core temperatures and sweating rates for the experimental and computed results using the existent sweating model (2NM) and the newly developed sweating model (2NMnew). The skin and core temperatures given by the new sweating model were lower and closer to the experimental values than those given by the existent model under both the 2.0 and 3.0 met conditions. This is because the summative sweating rates predicted by the new model are better than those of the existing model (see Figs. 6 c) and 7 c))

![Figure 6 Result of improvement in Case 2 (2.0 met)](image1)

![Figure 7 Result of improvement in Case 3 (3.0 met)](image2)

6. Conclusion

The aim of this study was to develop an appropriate thermal index for evaluating hot outdoor environments and the conclusions drawn are as follows:

1. Experiments were performed to estimate the human physiological response to hot environments.

2. Experimental results were compared with values computed using the 2NM and PHS models. As a first step the accuracy of the present thermal physiological models, such as the 2NM and PHS models, has been examined by comparison with experiments involving human subjects.

3. In low metabolic cases, the 2NM model corresponds well with the experimental results, whereas in the high metabolic case, the sweating rates, computed from
2NM, are lower than the experimental values. Furthermore, the values computed for skin temperature tended to be a little higher than the experimental results.

4. The relationship between sweating and metabolism was investigated, and the sweating model 2NM was improved.

References
Effect of Partly Impermeable Clothing on Thermoregulatory Responses in Hot Environment: a Computer Simulation

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¹International Center for Information Technologies and Systems UNESCO, Kiev, Ukraine.  
²Centre d'Etudes de Physiologie Appliquée (CNRS), Strasbourg, France

Abstract

A major goal of the study is to use a computer model to analyse the effects of partly impermeable clothing on thermal physiological processes and regulatory responses of a human in a hot environment. To achieve this goal, a Computer Simulator is used. Computer Simulators, for predicting human thermoregulatory responses, are derived from the class of multicompartmental thermal models. The mathematical models involve a detailed description of passive and active processes through division into compartments taking into consideration heat flows via blood, by conduction, convection and radiation, skin blood flow and sweating. The Computer Simulator allows the composing of different clothing from available data base of textiles. The results of two computer simulations were compared for the prediction of human thermal processes in a hot environment under two clothing conditions:

1) person wearing full cotton ensemble;
2) person wearing combined cotton clothing, involving an impermeable textile on the trunk. It was found that the thermoregulatory system is highly sensitive to clothing in a hot environment. Partly impermeable clothing increases heat stress. It reduces the time a person can be exposed to the hot environment, increases core temperature, sweat dripping and total water losses.

Keywords: Thermal models; Protective clothing; Body temperature; Dynamic simulation
1. Introduction

Different approaches have been proposed to avoid or reduce heat stress in a person wearing impermeable protective clothing when working in hot environments. Mathematical modelling is one of the effective ways which can be used for predicting the thermal and regulatory responses under different conditions. Although the first such models appeared in the middle of the last century and the modelling development has continued, it has become a tradition to motivate the use of the mathematical models in any concrete case.

The usefulness of models for the development of protective clothing is obvious since it minimises or avoids hazardous effects on the person under extreme conditions. A great advantage of modelling is to gain a preliminary knowledge of the effect of protective clothing on the human being. Models take into consideration human physiological and anthropological data, human muscular activity, environmental characteristics and clothing apparel. Simulation makes it possible to monitor the dynamics of thermal processes, and gain an integral picture which helps to evaluate the advantages and shortcomings of protective clothing.

A major goal of the study is to use computational modelling to evaluate the effect of partly impermeable clothing on thermal physiological processes and regulatory responses of a person in a hot environment.

2. Methods

Modelling was performed using the Computer Simulator for predicting the human thermoregulatory responses. It is derived from the class of dynamic multicompartmental models. As a whole, a mathematical model involves a system of differential and algebraic equations the order of which depends on the approximation of the human body [1]. The modelling approach is a typical evolution of the basic model developed by Stolwijk [2]. The mathematical models involve a detailed description of passive and active processes through a division into compartments, taking into consideration heat flows via blood, by conduction, convection and radiation, skin blood flows and sweating. The Computer Simulator allows different clothing to be composed from available textile data bases. It shows transient and steady state processes of localised temperatures, evaporation heat losses, evaporative and dripping sweat rate and total water losses during the time of the exposure to heat.

This study was performed using a body approximation consisting of 30 compartments: head (brain, head skin), trunk (internal organs, muscles, skin), forearm, arm, hand, thigh, shank, foot (muscle and skin) and blood pool (mixing reservoir). Clothing was modelled as an additional compartment taking into account the air between the skin and textile [3]. The total characteristics involved in the model of a person are weight = 71 kg, body surface = 1.8m$^2$, cardiac output = 320 l/h and initial metabolic rate = 72 kcal/h.
To evaluate the effect of partly impermeable clothing on thermoregulatory responses in a hot environment two variants of computational experiments were performed:

- person wearing clothing made from cotton;
- person wearing combined cotton clothing, involving some impermeable textile on the trunk.

3. Results

In hot environments the main thermoregulatory response is the evaporation of sweat which is the only way to eliminate the additional heat from the organism. The effect of this regulatory response depends on many factors, involving the human thermal state, clothing and environment. The present analysis concentrates on the modelling results related to thermoregulatory sweating.

**Variant # 1 - person wearing clothing from cotton.**

Conditions of computational experiment:

- **CLOTHING:** total permeable, denim, 100% cotton, with intrinsic insulation 0.037 m² °C/W and evaporative resistance 0.0066 m² kPa/W,
- **MUSCULAR ACTIVITY:** 150 W;
- **ENVIRONMENT:** air temperature 40°C, air velocity 0.1 m/sec and relative humidity 50%;
- **EXPOSURE:** 2 hours;
  - Textile characteristics were taken from ISO CD 9920-1.

In the case of a person wearing cotton clothing in a hot environment, core temperatures increased, brain temperature increased by 0.6°C from 36.8°C to 37.4°C, internal organ temperature increased by 0.5°C from 36.9°C to 37.4°C. The dynamics of blood temperature and mean skin temperature are shown in Fig.1. It can be seen that the blood temperature increased by 0.6°C from 36.7°C to 37.3°C and mean skin temperature by 2.6°C from 34.3°C to 36.9°C. At the end of the exposure (2 hours) the difference between core and skin temperatures was only 0.4°C. Heat losses by evaporation are shown in Fig.2.
It can be seen that sweat evaporation started at 0.2h and that heat losses by evaporation increased during exposure and attained 90 kcal/h at the end of exposure.

The accumulation of heat in the body is explained by the fact that not all sweat evaporates. As can be seen in Fig.3 evaporative sweat rate is 157 g/h at 2 hours of exposure but at 1.7 hours part of the sweat is dripping, practically at the same rate. In Fig.5 total water losses including evaporative and dripping sweat, are shown. At 2 hours of exposure, they reached 390 g.
**Variant # 2** - Person wearing combined cotton clothing, involving an impermeable textile on the trunk.

Conditions of computational experiment:

**COMBINED CLOTHING**: trunk is covered by an impermeable textile 100% PVC vinyl, with intrinsic insulation 0.016 m²°C/W, and **evaporative resistance 0.3489 m²kPa/W**; other parts of body in denim (see data in Variant #1);

**MUSCULAR ACTIVITY**: 150 W;

**ENVIRONMENT**: air temperature 40°C, air velocity 0.1 m/sec and relative humidity 50%;

**EXPOSURE**: 2 hours

Textile characteristics were taken from ISO CD 9920-1.

Computational experiments involving a person wearing combined clothing, showed differences in thermoregulatory responses compared to the previous experiment. Core temperatures increased to the end of exposure; brain temperature increased by 1.18°C (initial was 36.8°C) and the internal organ temperature by 1.11°C (initial was 36.9°C) (Compare var. #1). The dynamics for blood and mean skin temperatures are shown in Fig.4.
It can be seen that at 2 hours of exposure, the blood temperature increased by 1.2°C, reaching 37.9°C and the mean skin temperature increased by 3.2°C to reach 37.7°C. The difference between blood and mean skin temperature was reduced to 0.2°C, which is half that observed in the previous case. There is no tendency to a steady-state after 2 hours of exposure to the hot environment. Heat losses by evaporation from the skin were 66kcal/h, which is lower than that in Variant #1, where it reached 90 kcal/h (Fig.2).

The evaporative sweat rate was 114 g/h, and the dripping sweat rate was 600 g/h which was much more than that observed in the previous experiment (150 g/h), with the most sweat dripping from the trunk, 267 g/h (Fig.5).

The total water losses from the organism including evaporative and dripping sweat are shown in Fig.6; at the end of exposure the total of 700g for Variant #2 is twice that of Variant #1. This is not critical for dehydration of the organism.

Modelling results showed that the cardiac output increased to 510 l/h and the heart rate to 98 beats/min (initially 74 beats/min).
4. Discussion and conclusions

Comparisons have been carried out of two computer simulations for the prediction of thermal processes in a hot environment with the aim to evaluate the effects of partly impermeable clothing on the thermoregulatory responses for:

- person wearing only cotton clothing;
- person wearing combined cotton clothing, involving an impermeable textile on the trunk.

Simulation showed that in both cases there clearly was heat stress, although the person wearing only cotton clothing can perform longer in a hot environment without a danger to health.

Even a local limitation of evaporation resulted in significant quantitative changes in the dynamics of physiological processes. It was found that the thermoregulatory responses are extremely sensitive to impermeability, even if the body (e.g. trunk) is only partly covered with impermeable clothing (surface of the trunk is 0.68 m², approximately 38 per cent of the total skin surface). In such a case, the dynamic changes in thermal processes are quicker, the increase in core temperature is greater compared to the total denim clothing and the efficiency of thermoregulatory sweating is less, with a large part of the excreted sweat dripping. Referring to R. Goldman, the difference between core and skin temperatures appears to be the best informative parameter for the evaluation of heat tolerance [4, 5]. In this case, it was divided by 2 compared to Variant 1.

The performance of a human in a hot environment is a very important factor. The main thermoregulatory response is sweating and the efficiency of this regulatory response depends on the amount of sweat that can evaporate. Only evaporation can prevent the organism from overheating. It was shown that any local limitation in sweat evaporation reduces the time a person can perform in a hot environment.

It may be concluded that the thermoregulatory responses are highly sensitive to the impermeability of clothing, in a hot environment. Even partly impermeable clothing can decrease heat tolerance significantly. It reduces the time the person can perform in a hot environment since the core temperature increases intensively. Thermoregulatory sweating is not effective enough, the sweat dripping increases without the possibility of a steady-state.

Results of the study showed that simulation can be applied in practice to determine how long a person wearing protective clothing can perform in a hot environment without a danger to health.
References
5. Pandolf K., Goldman R. Convergence of skin and rectal temperatures as a criterion for heat tolerance. 1975, Aviat. Space Environ, Med.49, 1095-11101
Predictive Model of Human Responses to Local Cooling

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²Department of Building Science, Tsinghua University, Beijing, People’s Republic of China

Abstract

At room temperatures ranging from neutral to warm, three sensitive body parts: face, chest and back were each exposed to local cooling airflow. Dressed in shorts, 30 randomly selected male subjects were exposed to each condition for 30 minutes and reported their local thermal sensations of all body parts, overall thermal sensation and thermal acceptability on voting scales at regular intervals. It was shown that local cooling affected local thermal sensations of the not cooled body parts significantly, based on which a new influencing factor method was proposed. The influencing factor is unaffected by room or cooling air temperatures under steady state and the predictive model of overall thermal sensation for local cooling was obtained. Non-uniformity of thermal sensations was found to affect overall thermal acceptability significantly. Taking the maximum thermal sensation difference between body parts to represent non-uniformity of thermal sensation, a predictive model of percentage dissatisfaction for local cooling was proposed.

1. Introduction

Local cooling is increasingly receiving attention, not only as an alternative to the conventional air conditioning, but also as an advanced technology to provide an acceptable environment while using less energy. The effect of local cooling on overall thermal sensation and acceptability is the key problem in studies on human responses to local cooling.

Weighting factoring is commonly used in the studies of the effect of local cooling on overall thermal sensation, which is defined as the change of overall thermal
sensation when local thermal sensation of a body part changes one unit on a thermal sensation voting scale while others remain constant. Ingersoll et al (1992) proposed the use of the respective surface areas of each body part as its weighting factor to derive whole body thermal sensation. Hagino and Hara (1992) found, however, that the whole body thermal sensation was governed by local thermal sensations of certain small areas of the body that were exposed to direct airflow or solar radiation in the passenger compartment of an automobile. Zhang (2003) found that as local sensation diverged from that of the rest of the body, weighting factor became larger, and certain body segments, such as chest, back and pelvis, had larger weighting factors and dominated the influence on overall sensation, while the hand and foot had small weighting factors. Li (2004) reported that weighting factor changed with the intensity of local stimulus, and the weighting factor of the head was the largest. Weighting factor, as a key index evaluating the effect of local thermal sensation, on overall thermal sensation, has been widely accepted. However, which body part has a large weighting factor and what variables affect weighting factor remain inconclusive.

There have been a number of studies on the effect of local exposure on overall thermal acceptability and comfort, mainly concerned with the negative effect of local exposure while maintaining the whole body thermal neutral (ASHRAE Handbook (2001)), and few having been concerned with the positive effect of local exposure on comfort while the whole body is warm or cold. Studies performed by Melikov et al. (1994), Bauman et al (1998), Brook et al (1999) and Knudsen et al (2005) showed that local heating or cooling could improve a subject’s acceptability of the thermal environment. However, a predictive model for the effect of local exposure on thermal acceptability is not available. Zhang (2003) derived the relationship between local thermal sensation and overall thermal acceptability at different ambient room temperatures, the results being applicable only to the conditions tested and to seat heating or cooling. Zhang (2003) proposed a rule-based overall thermal comfort predictive model using local comfort votes, applying two rules to different conditions, with no consistent model being obtained.

The purpose of the present study is to investigate the effect of local cooling on overall thermal sensation and acceptability systemically and to develop a predictive model of human responses to local cooling.

2. Experimental methods

2.1. Experimental design

The experiment was carried out in the Department of Building Science at Tsinghua University during the period March 2005 to June 2005. A personalised ventilation system was used to supply the local cooling airflow and a set of special clothes was used to fix the cooling body surface area (see Fig. 1). Three sensitive body parts: face, chest and back were selected to be cooled locally in the present study. A climate chamber was used to control the ambient room temperature for local cooling.
The temperature in the chamber and temperature at the outlet of local airflow could be maintained with a precision of ±0.2°C.

Three levels of room temperatures, ranging from neutral to warm, and three levels of local cooling target temperatures (target temperature means the air temperature at the center of cooling body part surface), ranging from neutral to slightly cool, were chosen to be studied (see Table 1).

<table>
<thead>
<tr>
<th>Room temperature (°C)</th>
<th>28, 32, 35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target temperature (°C)</td>
<td>22, 25, 28</td>
</tr>
</tbody>
</table>

Table 1: Experimental conditions

The relative humidity was kept constant at 40% and the air speed was less than 0.1 m/s in the chamber. The air speed at the outlet of the local cooling airflow was maintained at 1 m/s.

2.2. Measurements

Subjects reported their responses twice before local cooling and 16 times while local cooling, occurred at one-minute intervals for six minutes and then at two-minute intervals for fourteen minutes and then at five-minute intervals. Overall thermal sensation and local thermal sensation for each of the body parts (including face, chest, back and lower body part) were reported on the 7-point ASHRAE scale (Fig. 2). A visual-analogue scale indicating acceptability, originally developed to evaluate indoor air quality (Gunnarsen and Fanger (1992)), was used in the present study to assess the whole thermal environment (Fig. 2). The temperature in the room and that at the outlet of the local airflow were measured and recorded every two seconds during each exposure.
Thirty randomly selected Chinese male students, dressed in shorts, with a normal range of age, height and weight, participated in the experiment. Each test consisted of half an hour pre-conditioning and half an hour exposure. The room temperature was maintained constant for each test and no local airflow existed during pre-conditioning. The total duration of each subject’s participation was 27 hours. The sequence of presentation was balanced for each subject using Latin squares. Subjects remained sedentary throughout each exposure. Subjects responding ‘clearly unacceptable’ at any point in time were allowed to terminate the exposure and leave immediately.

3. Results and Discussion

Shapiro-Wilk's W test was applied and the results show that the human responses obtained under all the conditions were normally distributed. They were therefore analysed using repeated measure ANOVA and paired-sample t-tests. It was found that the human responses reached a steady state within 25 minutes during pre-conditioning (p>0.05) and within 20 minutes during local cooling (p>0.05) under all conditions. If not mentioned specifically, all responses reported below are steady state responses.

3.1. Influencing factor method

It can be seen from Figure 3 that when face cooling was applied (7th minute in the figure), not only did the face thermal sensation and overall thermal sensation decrease rapidly, but also the local thermal sensations of the uncooled body parts, including chest, back and lower body part, changed significantly. The responses were tested for significance using paired-sample t-tests and the results show that local thermal sensations of the uncooled body parts changed significantly with local cooling(p<0.05), which indicates that local thermal sensations of all body parts are not independent, but correlated with each other.
The correlation was analysed using co-linearity diagnostics and the results show that high co-linearity exists in most cases (tolerance<0.1). As repeated-measures experimental design, which is often used in thermal comfort experiment, was adopted in the present study, the sphericity assumption was tested and the results show that the autocorrelation in the responses is significant (p<0.05). Co-linearity and autocorrelation violate the independency of the data and may result in unreasonable results using weighting factor method, which can be expressed as:

\[ S_O = w_1S_1 + w_2S_2 + ... + w_nS_n \]  

[1]

where \( S_O \) is overall thermal sensation, \( S_i \) is local thermal sensation of body part \( i \) and \( w_i \) is weighting factor of the body part \( i \).

To solve the problem, a new method was proposed, which can be expressed as:

\[ \Delta S_O = f_{EO}\Delta S_E \]  

[2]

where \( \Delta S_O \) is the change of overall thermal sensation, \( \Delta S_E \) is the change of local thermal sensation of the cooled body part, and \( f_{EO} \) is the regression coefficient.

The effects of co-linearity and autocorrelation are removed using the new method. Here a new term ‘influencing factor’ is proposed for \( f_{EO} \), defined as the change of overall thermal sensation when local thermal sensation of the cooled body part changes one unit on the 7-point ASHRAE scale under the condition of single body part cooling. This influencing factor represents the general effect of local cooling on overall thermal sensation, while the weighting factor represents the importance of the local thermal sensation of a single body part in the process of integration of overall thermal sensation.

3.2. Influencing factor and predictive model of overall thermal sensation for local cooling

The influencing factor for face cooling was analysed using the influencing factor method and the result is shown in Fig. 4. The change of thermal sensation in the figure means the mean thermal sensation vote during local cooling minus the one during pre-conditioning. A straight line passing through the origin fits the data well (\( R^2>0.9 \)) and the slope represents the influencing factor of face on overall thermal
sensation. It can be seen that the influencing factor was unaffected by either cooling air temperature (Fig. 4a) or room temperature (Fig. 4b).

The influencing factors of chest and back on overall thermal sensation and the influencing factors of the cooling body parts on local thermal sensations of the uncooled body parts were analyzed in the same way and the results are listed in Table 2.

<table>
<thead>
<tr>
<th>Cooling body part</th>
<th>Face thermal sensation</th>
<th>Chest thermal sensation</th>
<th>Back thermal sensation</th>
<th>Lower body part thermal sensation</th>
<th>Overall thermal sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face</td>
<td>1</td>
<td>0.54</td>
<td>0.57</td>
<td>0.43</td>
<td>0.61</td>
</tr>
<tr>
<td>Chest</td>
<td>0.16</td>
<td>1</td>
<td>0.4</td>
<td>0.31</td>
<td>0.47</td>
</tr>
<tr>
<td>Back</td>
<td>0.18</td>
<td>0.3</td>
<td>1</td>
<td>0.3</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 2: Influencing factors ($R^2>0.63$)

It can be seen from Table 2 that face cooling affects overall thermal sensation and local thermal sensations of the uncooled body parts more than chest or back cooling. The impact of chest cooling on back thermal sensation is close to the impact of back cooling on chest thermal sensation. However, the impact of chest or back cooling on the face thermal sensation is much less than the impact of face cooling on chest or back thermal sensation.

Based on the influencing factor, a predictive model of overall thermal sensation for local cooling was obtained:

$$S_O = F_{EO}(S_E - S_{EI}) + S_{OI}$$  \[3\]

where: $S_{OI}$ and $S_{EI}$ are, respectively, the initial overall thermal sensation and local thermal sensation of the cooling body part before local cooling, $S_E$ is the local thermal sensation of the cooling body part while local cooling occurs. If the initial whole body thermal state and local thermal sensation of the cooling body part are known, the overall thermal sensation can be predicted using the model. Similarly, the local thermal sensations of the uncooled body parts can be predicted by the corresponding influencing factor.
3.3. Non-uniformity of thermal sensation

Overall thermal sensation is the most important index to evaluate the thermally uniform environment under a steady state. Relationship between predicted percentage of dissatisfaction and predicted mean vote of thermal sensation was derived by Fanger (1970) and thermal neutrality corresponds to 5% percentage dissatisfaction. However, the overall thermal sensation was found to be independent from the percentage dissatisfaction while local cooling was supplied, and percentage dissatisfaction changed from 5% to 40% while the overall thermal sensation remained neutral. Overall thermal sensation is not the sole factor influencing thermal acceptability of a non-uniform environment.

The survey in the experiment shows that most of the subjects perceive obvious non-uniformity of thermal sensation between body parts during local cooling. Under this circumstance, they felt dissatisfied with the whole environment even when they felt neutral in terms of the whole body thermal sensation. Considering the strongest feeling of non-uniformity comes from the difference between the coolest and the warmest body part, the maximum thermal sensation difference between body parts was chosen to represent the non-uniformity of thermal sensation and it can be seen from Figure 5 that the greater the thermal sensation difference, the more people feel dissatisfied. A second-order polynomial curve fits the data well ($R^2=0.88$), regardless which body part is exposed.

\[ y = 12.85x^2 - 3.27x + 5.73 \]

\[ R^2 = 0.88 \]

Figure 5 Percentage dissatisfaction as a function of the maximum thermal sensation difference between body parts while the whole body was close to neutral

3.4. Predictive model of percentage dissatisfaction for local cooling

Subjects evaluate the environment based on their perception of overall thermal sensation and their perception of non-uniformity of thermal sensation between body parts. As the two perceptions are independent, the general percentage dissatisfaction with local cooling can be reasonably expressed as the sum of the effects of the two perceptions:

\[ PD = PD_1 + PD_2 \] [4]
where PD is the general percentage dissatisfaction with a non-uniform environment, PD_1 is the uniform term and PD_2 is the non-uniform term. The uniform term is a function of overall thermal sensation, and the function was obtained by an analogy from the results of uniform environment (ISO, 1994): 

\[ PD_1 = 100 - 95e^{-(0.03353S_O^4 + 0.2179 S_O^2)} \] [5]

The non-uniform term is a function of the maximum thermal sensation difference between body parts S_D, and the function was obtained by regression of the experimental data obtained in the present study (see Figure 5):

\[ PD_2 = 12.85S_D^2 - 3.27 S_D \] [6]

4. Conclusions

The effect of local cooling on human responses was studied in the present experiment and the following conclusions were drawn:

1. A new influencing factor method was proposed based on the fact that local thermal sensations of the uncooled body parts changed with local cooling. The influencing factor of each body part is unaffected by room or cooling air temperatures. Based on the influencing factor, a predictive model of overall thermal sensation for local cooling was obtained.

2. Non-uniformity of thermal sensation between body parts is an important factor affecting percentage dissatisfaction with local cooling. Taking the maximum thermal sensation difference between body parts to represent non-uniformity of thermal sensation, a predictive model of percentage dissatisfaction for local cooling was obtained.

Acknowledgements

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References
Prediction of the Thermal Comfort Range of Handwear by Thermophysiological Simulation

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Abstract

Military glove systems for cold conditions were investigated, using the thermophysiological simulation device “CYBOR” to measure their thermal insulation behaviour and to estimate a temperature limit for the thermal comfort range. A new feature controlling the heat flow into the hand phantom with improved relation to the human physiology was implemented in the CYBOR system.

1. Introduction

Equipping military personnel for out of area operations not only requires a fundamental knowledge about the expected climatic conditions but also about the performance of the clothing to be worn. Thermophysiological simulation helps to make a preselection of garments, which are expected to give optimum thermal comfort in a defined climate. The thermophysiological simulation device “CYBOR“ (Cybernetic Body Regulation) is used for predictions about the climatic wearing comfort of shoes and gloves (Kurz et al., 1999; Uedelhoven, 1994). It has been improved with a new control feature which is intended to give more reliable predictions of the thermal comfort range of handwear systems. The present study provides the first results for different military handwear systems designed for cold environments.
2. Methods

Five different military gloves intended for the use in cold environments were investigated (Table 1). The heat flow of the thermophysiological simulation device into the hand phantom was controlled as a function of the measured “skin” temperature of the hand phantom simulating vasoconstriction. Because of the little local metabolic heat production in the extremities (i.e. hands, feet) their heat balance strongly depends on the continues heat input by warm blood from the body core. To prevent a loss of heat in a cold environment the blood vessels constrict and the blood flow into the extremities is reduced (vasoconstriction). It was shown (Glitz et al., 2005) that the skin temperature is a nearly linear function of the perfusion of the fingers in the skin temperature range of about 31 °C to 15 °C. On the basis of the “skin” temperature of the hand phantom, therefore, the heat flow into the phantom can be controlled with sufficient physiological relevance.

<table>
<thead>
<tr>
<th>Glove</th>
<th>Construction details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regular German combat glove</td>
</tr>
<tr>
<td>2</td>
<td>Five finger German combat glove</td>
</tr>
<tr>
<td>3</td>
<td>Combat glove cold/wet protection</td>
</tr>
<tr>
<td>4</td>
<td>Mitten shell #1</td>
</tr>
<tr>
<td>5</td>
<td>Mitten shell #2</td>
</tr>
</tbody>
</table>

Table 1: Military gloves intended for use in cold environments under investigation

It was found that the perfusion of the fingers is reduced down to about 30 % at 15 °C skin temperature compared to the value at 31 °C (Glitz et al., 2005). The nearly linear decrease of the blood flow in the hand as a function of skin temperature was implemented in the control software of the CYBOR system to enable the control of the heat flow into the hand phantom. Based on the data from the study mentioned above the heat flow into the phantom was decreased gradually in dependence on the measured “skin” temperature T_{skin} (palm region) from 5,1 W at T_{skin} = 31 °C down to a lowest value of 1,5 W for T_{skin} ≤ 15 °C. The chosen value for the maximum heat flow into the phantom of about 5 W (starting parameter at normal skin temperature) corresponds to a medium metabolic rate of the human body. The environmental temperature in the climate chamber was lowered continuously from 0 °C to -40 °C in a period of 120 minutes (cooling rate: 0.33 K/min). The temperature of the climate chamber as well as the skin temperature of the hand phantom were monitored with thermo-sensors and plotted as a function of time.

3. Results and discussion

According to the literature (Heus et al., 1995) a mean finger temperature of 15 °C is said to be the lowest acceptable skin temperature for sufficient manual skills and thermal self-perceived comfort. It should be mentioned, however, that there is a great variation in the values reported in the literature concerning the minimal skin
temperature for the occurrence of pain under cold conditions, these ranging from 10 °C (Hellström, 1965) up to 21 °C (Enander, 1986). Thus, the chosen limit of 15 °C for the skin temperature in this study falls within the range of the reported values in the literature. The lower temperature limit $T_{\text{min}}$ of the predicted thermal comfort range of a defined glove or handwear system can be taken from the plot of skin temperature $T_{\text{skin}}$ as a function of environmental temperature at the point $T_{\text{skin}} = 15$ °C of the phantom (see Figure 1). The handwear systems under test show clear differences with respect to their thermal insulation performance and lower limit of the thermal comfort range.

![Figure 1 Plot of skin temperature $T_{\text{skin}}$ as a function of the measuring time corresponding to the environmental temperature in the climatic chamber (temperature ramp)](image)

Depending on the construction of the glove and the combination of an inner finger glove with a mitten shell, the lower temperature limit $T_{\text{min}}$ varies between -10 °C and about -30 °C. While the environmental temperature limit for the comparatively thin regular German combat glove (glove 1, green curve in Fig. 1) is only about -10 °C the thermal comfort range is extended down to -19 °C for the combat glove especially equipped for wet and cold protection with 3-layer laminate and wadding inside (glove 3, black curve in Fig. 1). The lowest value for $T_{\text{min}}$ (-30 °C) could be measured using a combination of the regular German combat glove (glove 1) with mitten shell #2 (glove 5) – see the magenta curve in Figure 1. This corresponds to the results of a research project of the Oulu Regional Institute of Occupational Health, Finland, in co-operation with the Finnish Defence Forces (Anttonen, 2005). Using questionnaires and physiological measurements, the needs concerning gloves in key military tasks were determined. A combination of an inner glove with a mitten shell seemed to be the most suitable handwear system in a cold environment. The skin temperature can be maintained even under extremely cold conditions, and manual tasks, mostly done barehanded by the soldiers, can be carried out with the inner glove after quickly taking off the mitten.
In conclusion, the described method allows a physiology related and more reliable prediction of the thermal comfort range of handwear systems compared to former measurements with constant heat flow into the hand phantom. The decline of the measured skin temperature with decreasing environmental temperature using the new feature with a controlled heat flow into the hand phantom is much faster compared to former measurements with constant energy input. This leads to significant lower temperature limit values $T_{\text{min}}$ for the thermal comfort range with great relevance for any prediction or advice in this case. The more precise estimation of limit temperatures for the operating range of handwear systems in cold environment can help to avoid serious cold injuries to soldiers in action.

The principle of the method can be used for the investigation of footwear systems in a cold environment as well. The comfortable measurement of $R_c$ values (thermal resistance) for complete hand- and footwear systems is a further application of the thermophysiological device CYBOR using the new feature in the energy control measurement mode.

References
Validation and Comparison of Prediction Models for Dynamic Clothing Thermal Insulation and Moisture Vapour Resistance

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Abstract

This paper reports on the validation of two new prediction models for clothing thermal insulation and moisture vapour resistance recently developed by the authors, using experimental data from both previously published sources and new experiments. These two new models are also compared with existing models in terms of prediction accuracy and suitability of applications. The advantages and limitations of the different models are discussed. With respect to the prediction of clothing thermal insulation, the study showed that, except for the heavy and highly enclosed winter ensembles, the new direct regression model and the new quasi-physical model provide very good prediction with percentage fits of 95% and 94%, respectively. For heavy and highly enclosed clothing ensembles (with static thermal insulation greater than 0.4 m²°C/W or 2.6 clo), Nilsson et al’s model provides better prediction, but improved prediction can be made for the new quasi-physical model by using a model parameter (KVI) which is specific for the heavy and enclosed winter ensembles. As for the prediction of clothing moisture vapour resistance, the new quasi-physical model is the best.

Keywords: clothing thermal insulation, clothing moisture vapour resistance, prediction model, validation, isothermal
1. Introduction

The development of prediction models for clothing thermal insulation and moisture vapour resistance has received attention in the past several decades (Spencer-Smith, 1977a and b; Lotens and Havenith, 1991; ISO 9920, 1995; Holmer et al, 1999; Nilsson et al, 2000). Although the models developed can predict the dynamic clothing thermal insulation and moisture vapour resistance under special conditions, the existing models still have many limitations, particularly with respect to the effects of clothing characteristics, such as fabric air permeability, garment style, garment fit and clothing construction.

Based on an improved understanding of the effects of wind and walking motion on the heat and moisture transfer through clothing, a direct regression model and a quasi-physical model for the prediction of the dynamic clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion from the static values when a clothed person is standing in “still” air have been recently developed by the authors (Qian, 2005). The direct regression model is very simple and effective, but the quasi-physical model has the advantage of incorporating the fundamental mechanisms of heat and moisture transfer and these two models can take into account the effects of clothing characteristics through the model parameters. All the existing models, including the two new models, were developed based on some special clothing ensembles; they should be validated with experimental data from other sources. On the other hand, little attention thus far has been focused on a comparison of the advantages and limitations of the different models.

The aim of this paper is therefore to validate and compare the existing models.

2. Summary of the existing prediction models

Table 1 provides a summary of the existing models for predicting the values of clothing thermal insulation and moisture vapour resistance under body motion and wind from those under standing position with no wind.
Table 1 Published models

<table>
<thead>
<tr>
<th>Source</th>
<th>Model</th>
</tr>
</thead>
</table>
| Spencer-Smith (1977a, 1977b)   | \[
I_{st}/I_t = 1 - 1.2 \times 10^{-4} V_{wind} \sqrt{A_p}, \]
\[
R_{st}/R_t = 1 - 0.024 V_{wind} \sqrt{A_p} \]
| Lotens and Havenith (1991)    | \[
I_{cl}/I_{scl} = e^{-I_{cl} V_{walk}^{0.45}} \times \frac{3 + \sqrt{0.67 V_{walk} + 0.11}}{3 + \sqrt{V_{wind}^2 + 0.67 V_{walk} + 0.11}} \]
| ISO 9920 (1995)               | \[
I_t/R_t = L_R i_m = \frac{I_{st}}{R_{st}} \]
| Holmer et al (1999)           | \[
I_t/I_{st} = e^{(0.043 - 0.398 V_{wind} + 0.066 V_{wind}^2 - 0.378 V_{walk} + 0.094 V_{walk}^2)} \]
I_t/I_{st} = 0.54 e^{(-0.15 V_{wind} - 0.22 V_{walk})} (A_p)^{0.075} - 0.06 \ln(A_p) + 0.5 \]

The two new prediction models developed by the authors are listed in Table 2.

Table 2 The models developed by the author (Qian 2005)

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>The new direct regression model</td>
</tr>
</tbody>
</table>
| \[
I_t = \frac{1}{I_{st}} \left( 1 + K_f (V_{wind} + 1.8 V_{walk} - v_0) \right), \]
| \[
R_t = \frac{1}{R_{st}} \left( 1 + K_R (V_{wind} + 1.8 V_{walk} - v_0) \right) \]
| Average values: \( K_f = 0.27, K_R = 0.32 \)                        |
| The quasi-physical model                                               |
| \[
I_t = m I_c + \frac{1}{KVI (V_{wind} + 2 V_{walk} - v_0) + \frac{1}{(1 - m) I_c + \frac{1}{f_{co}} I_{so}}} \]
| \[
R_t = n R_c + \frac{1}{KVR (V_{wind} + 2 V_{walk} - v_0) + \frac{1}{(1 - n) R_c + \frac{1}{f_{co}} R_{so}}} \]
| Average values: without underwear: \( KVI = 0.88, \)
| \( KVR = 0.0076 \) with underwear: \( KVI = 1.72, KVR = 0.0111 \) |

3. Evaluation of the prediction models

3.1 Database used in the present study

In order to validate and compare the various prediction models, a large database consisting of 453 pairs of experimental data of dynamic clothing thermal insulation and moisture vapour resistance measured with 49 sets of clothing ensembles under different environment conditions, such as typical indoor conditions, very cold conditions or isothermal conditions were used. This database includes two parts, the
one consisting of 84 experimental data with 17 garments comes from published work. Some of these were obtained from measurements on manikins (Hong, 1992; Holmer et al, 1996; Bouskill et al, 2002; Adair, 2005), and some from measurements on human subjects (Nielsen et al, 1985; Lotens & Havenith 1988 listed in Havenith 1990(b); Havenith et al 1990(a) and 1990(b)).

The other part of the database was from measurements (Qian, 2005) on the walkable sweating fabric manikin Walter recently developed by the authors (Fan and Qian, 2004) and involved 32 sets of clothing ensembles. The clothing used for the database included different clothing ensembles, such as tight fitting and loose fitting garments, jackets, shirts, uniforms, formal wear, cold protective clothing and outdoor activity wear with permeable and impermeable outer fabrics.

Since the air permeability values of many clothing assembly reported in the literature are not known, in applying Spencer-Smith and Nilssion et al’s models, the air permeability values of the outer fabrics of different clothing assembly were assumed to be the values with which the models provided the best fit to the experimental data. These air permeability values were derived from non-linear regression of the data. In applying the direct regression model and the quasi-physical model established in the present study, average values of model parameters, i.e. $F_I$, $F_R$, $K_{VI}$, and $K_{VR}$, were used for different clothing assembles.

### 3.2 Comparison and validation of prediction models for clothing thermal insulation

The clothing thermal insulation values predicted using different models are plotted against the experimentally measured values in Figures 1 to 6.

Figure 1 plots the measured thermal insulation against the values predicted using the Spencer-Smith model. It can be seen that there are considerable over estimation for insulation values less than 0.15m²°C/W. This may be because, at high wind velocity, the reduction of clothing thermal insulation is greater than what is predicted by the model, which assumes a linear reduction with an increase in wind velocity.
Figure 2 plots the measured dynamic thermal insulation against the values predicted using the Lotens and Havenith’s model. As can been seen, the predicted values deviate greatly from the measured data. One possible source of errors is the value of $\beta$ (viz. equivalence of walking speed to wind velocity). They used the value of
\( \beta = 0.67 \), which was derived from the reduction of surface thermal insulation by walking motion and wind (Havenith et al 1990a). Our study (Qian, 2005) shows the value of \( \beta \) for the surface thermal insulation is different from that for the clothing thermal insulation, the value of \( \beta \) were found to be 0.45 for surface thermal insulation and 1.8~2.0 for clothing thermal insulation.

The Lotens & Havenith’s model is especially poor for the data of Holmer et al’s 4th and 5th clothing ensembles and Bouskill et al’s 2nd clothing ensemble measured by thermal manikins. Holmer et al’s 4th and 5th clothing ensembles are winter clothing which included a cap and a scarf, and they were tested in the sub-zero climate of -10°C. The static thermal insulation values are 2.55\( \text{clo} \) (0.395 m\(^2\)\( ^\circ\)C/W) and 3.48\( \text{clo} \) (0.539 m\(^2\)\( ^\circ\)C/W), respectively. Bouskill et al’s 2nd clothing ensemble consisted of an air impermeable three-layer overcoat with gloves and a cap. It was tested in the environmental temperature of 10°C, and its static thermal insulation is 2.54\( \text{clo} \) (0.394 m\(^2\)\( ^\circ\)C/W).

Figure 3 plots the measured dynamic thermal insulation against the values predicted using the Holmer et al’s model. This model was based on seven ensembles tested on a “walking” manikin and three ensembles tested human subjects by Havenith (1990a). The range of clothing thermal insulation was 1.33~1.84\( \text{clo} \) (0.206~0.285 m\(^2\)\( ^\circ\)C/W). As can be seen, Holmer et al’s model predicts the clothing thermal insulation quite well both for the data obtained by author on the sweating manikin-Walter and those reported in the literature, with a squared correlation coefficient \( (R^2) \) of 0.91, except for some overestimation for the thermal insulation less than 0.2 m\(^2\)\( ^\circ\)C/W and underestimation for values higher than 0.28 m\(^2\)\( ^\circ\)C/W.

Figure 4 plots the measured thermal insulation against the values predicted using the Nilsson et al’s model. Compared with Holmer’s model, Nilsson et al’s model gives better prediction for clothing ensembles having higher thermal insulation, but worse for clothing ensembles having lower thermal insulation. This is understandable as the model was established based on 10 cold protective work wear, which had relative high thermal insulation.

Figure 5a and b plot the measured dynamic thermal insulation against the values predicted using the new direct regression model developed by author with all database and without the database used to derive the model, respectively. As can be seen, the new direct regression model predicts the measured thermal insulation from both our experiments on Walter and those reported in the literature quite well. There is however some underestimation for clothing ensembles with high thermal insulation, particularly for the two winter ensembles tested by Holmer et al and one winter ensemble tested by Bouskill et al. This may be due to the fact that, in the experimental data used for establishing the new direct regression model, there is no winter clothing ensemble as warm as those two tested by Holmer et al and that tested by Bouskill et al.

Figure 6a plots the measured dynamic clothing thermal insulation against the values predicted using the quasi-physical model developed in the present study. As can be seen, the quasi-physical model predicts the measured thermal insulation from both our experiments on the sweating manikin-Walter and those reported in the literature very well, except for the large underestimation for the two heavy winter ensembles
tested by Holmer et al and one heavy winter ensemble tested by Bouskill et al. These three ensembles were relatively heavy having the static thermal insulation greater than 0.4 m²K/W or 2.6clo. They also consisted of caps, gloves or scarf, making them highly enclosed from air ventilation and penetration. Consequently, the average model parameter ($KVI$), which was averaged from relatively lighter clothing ensembles in our study, would not be appropriate for these three heavy and highly enclosed winter ensembles.

If thermal insulation of these three ensembles is predicted with a special $KVI$ value (0.26), the squared correlation coefficient of the new quasi-physical model are the same as 0.96 for the database which is not used to derive the model, respectively. It is shown as Figure 6b.

From the analysis above, it can be seen that, except for the heavy and highly enclosed winter ensembles as the 4th and 5th clothing ensembles tested by Holmer et al and the 2nd clothing ensemble tested by Bouskill et al, the new direct regression model and the new quasi-physical model provide very good prediction with the squared correlation coefficient ($R^2$) of 0.95 and 0.94, respectively. For heavy and highly enclosed clothing ensembles (with the static thermal insulation greater than 0.4 m²K/W or 2.6clo), Nilsson et al’s model provides the best prediction. Improved prediction by the new quasi-physical model can be achieved by using the model parameter ($KVI$) specific for the heavy and enclosed winter ensembles.

### 3.3 Comparison and validation of prediction models for clothing moisture vapour resistance

Figure 7 plots the measured moisture vapour resistance against the values predicted using the Spencer-Smith’s model. It can be observed that there is a large deviation for the 3rd clothing ensemble tested by Havenith et al using trace gas method on human subjects. This clothing ensemble consists of a rain coverall which is moisture impermeable. There is also some over estimation for the clothing moisture vapour resistance values less than 30 m² Pa/W, probably because the wind induced reduction in moisture vapour resistance is greater than what is predicted in the model.

![Figure 7 Spencer-Smith’s Model](image1)

![Figure 8 ISO9920’s Model](image2)
Figure 8 plots the measured clothing moisture vapour resistance against the values predicted using the model adopted by ISO9920. As can be seen, ISO9920 generally predicts the measured data well except for the impermeable rain coverall tested by Havenith et al and there is some over estimation for clothing moisture vapour resistance less than $30 \text{ m}^2\text{Pa}/\text{W}$.

Figure 9 plots the measured clothing moisture vapour resistance against the values predicted using the new direct regression model. Again, with the exception for the data of the impermeable rain coverall tested by Havenith et al on human subjects using the trace gas method, the new direct regression model provides very good prediction. The squared correlation coefficient of the new direct regression model would be 0.91, if the data of the impermeable rain coverall tested by Havenith et al on human subjects using the trace gas method was omitted in the analysis.

Figure 10 plots the measured moisture vapour resistance against the values predicted using the quasi-physical model. Although there is still a slight overestimation for the impermeable rain coverall tested by Havenith et al, the model provides very good overall prediction with a squared correlation coefficient ($R^2$) of 0.95.

Based on the above analysis and discussion, it is clear that the new quasi-physical model is the best in predicting the dynamic clothing moisture vapor resistance. The reason why all models have difficulty in fitting the data of the impermeable rain
coverall tested by Havenith et al (1990b) using the trace gas method is rather incomprehensible, as the models have no particular problem in fitting the data of similar impermeable ensembles tested by Lotens & Havenith (1988) using the same trace gas method, and similar ensembles tested on sweating manikins.

Figure 11 compares the ISO9920 model, the direct regression model and the quasi-physical model in predicting the dynamic clothing moisture vapour resistance measured under the non-isothermal condition (i.e. 20°C and 50% RH). As can be seen, all three models provide very good prediction.

This however is not the case in predicting the dynamic clothing moisture vapour resistance tested under the isothermal condition (i.e. 35°C and 40% RH). As can be seen from Figure 12, there is a slight overestimation in the values predicted using the direct regression model and the ISO9920 model. The quasi-physical model gives the best prediction. This is because the quasi-physical model considered the change of the resistance of the surface air layer under isothermal condition.

4. Conclusions

With respect to the prediction of clothing thermal insulation, the analysis showed that, except for the heavy and highly enclosed winter ensembles, the new direct regression model and the new quasi-physical model provide very good prediction with the squared correlation coefficient ($R^2$) of 0.95 and 0.94, respectively. For heavy and highly enclosed clothing ensembles (with the static thermal insulation greater than 0.4 $m^2{\cdot}C/W$ or 2.6 clo), Nilsson et al’s model provides better prediction. Improved prediction by the new quasi-physical model can be achieved by using the model parameter ($KVI$) specific for the heavy and enclosed winter ensembles.

As for the prediction of clothing moisture vapour resistance, it can be concluded that the new quasi-physical model is the best in predicting the dynamic clothing moisture vapor resistance. With the data of clothing moisture vapour resistance measured under the isothermal condition and that under the non-isothermal condition, the two are compared.

References:


Section IV
Heat and Moisture Transfer through Clothing
Prediction of Textile Fabric Thermal Conductivity

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Abstract

The main aim of this paper is the prediction of textile fabrics thermal conductivity as a function of material (fibre type) and construction parameters (porosity or packing density). The relations between thermal conductivity and sound velocity or electrical conductivity are mentioned. Some approaches to predict thermal conductivity of multiphase systems with specific geometrical arrangements are given. A measurement of the thermal conductivity is performed by the Alambeta apparatus. A set of plain weave cotton fabrics, varying in the fineness of the weft yarns, is used as experimental material. The relations between total volume porosity and thermal conductivity of cotton weaves are predicted.

1. Introduction

The prediction of the thermal conductivity of fibrous structures is important for design purposes of new fabrics and prediction of their thermal comfort. It is well known that physiological comfort is strongly connected with thermal comfort (Fanger (1970)). There are a number of fabric properties which influence thermal comfort. Thermal insulation properties, characterized by thermal resistance or thermal conductivity, are amongst the most important ones.

There exists various models for the prediction of thermal conductivity of multiphase materials which can be used for the prediction of textile fabric thermal conductivity (see e.g. Hashin and Shtrikman (1962) and Sulaiman et al (2006)). Tai (1976) deduced mathematical expressions for the equivalent thermal conductivity of two- and three-dimensional orthogonally fibre-reinforced composites in a one-dimensional heat flow model. Tai showed that whether a square
slab model or a cylindrical fibre model is used makes little difference to the heat flux; while the fibre volume fraction matters. Transversal heat conductivity of fibrous composites is dependent on the yarn shape (see Tai (1998)) and fabric macroscopic porosity.

Krach and Advani (1996) investigated the effect of void volume and shape on the effective conductivity of a unidirectional sample of a 3-phase composite using a numerical approach consisting of a unit cell. Their findings clearly showed that the influence of porosity on thermal conductivity could not be described solely by the void volume. Other predictions, based on the models of fabric unit cell, were presented by Stark and Fricke J (1993) and Ning and Chou (1995). Militky (2006) used the plain weave cell model for the prediction of fabric thermal conductivity of cotton type fabrics. Application of these models for systems in which the matrix phase is replaced by air phase is complicated by the fact, that during measurement of thermal conductivity, the fabric is deformed, the shape of yarn is not circular and therefore the unit cell is not precisely known. The simpler approach is to use estimated porosity and packing density as characteristics of the fabrics porous structure.

In this work, simple formulae are compared to predict the thermal conductivities of fabrics as a function of effective thermal conductivity of moist fibres and the basic fabric structural parameters. The fabric porosity is computed from various assumptions. The predictive ability of the resulting models is verified on a set of cotton plain weave fabrics with weft yarns varying in fineness.

2. Thermal conductivity

Thermal conductivity \( K \) [W m\(^{-1}\)K\(^{-1}\)] is defined as a factor in the well known Fourier equation describing the steady state of the one directional transport of heat through a body of cross sectional area \( A \) and length \( L \) due to thermal difference \( \Delta T \) (see Fig. 1).

\[
Q = K \times A \times \frac{\Delta T}{L}
\]

where: \( Q \) [W] is heat flow generated by the temperature gradient.

![Figure 1 Thermal transport through a solid body](image)

Thermal conductivity of solid particles \( K \) is about 1-5 [W m\(^{-1}\)K\(^{-1}\)], for water \( K = 0.6 \) [W m\(^{-1}\)K\(^{-1}\)], for ice \( K = 2.24 \) [W m\(^{-1}\)K\(^{-1}\)] and for air \( K = 0.024 \) [W m\(^{-1}\)K\(^{-1}\)]. No adequate theory exists which may be used to predict accurately the thermal transport in polymeric systems. A simple phonon model of thermal conductivity is
described by Van Krevelen (1992). In crystalline solids the thermal conductivity is increased by a concerted action of the molecules. Most of the semi empirical expressions for the prediction of the thermal conductivity $K$ are based on the Debye equation

$$ K = C_p \times \rho \times u \times L $$

[2]

where: $\rho$ is the density, $u$ is the velocity of the elastic waves (sound velocity), $C_p$ is the specific heat capacity and $L$ represents the average free path length (distance between molecules in adjacent layers).

Crystalline polymers show much higher thermal conductivity. For typical PET, with 40% crystallinity, $K = 0.272 \text{[W m}^{-1}\text{K}^{-1}]$. Assuming that $L$ is nearly constant, it may be expected that a direct proportionality exists between $K$ and sound velocity.

The thermal conductivity of textile fibres is generally dependent on their chemical composition, porosity and water content. Haghi (2003) published the thermal conductivity for some typical fibres. For practically nonporous polypropylene fibre he found $K = 0.518 \text{[W m}^{-1}\text{K}^{-1}]$ and for porous acrylic fibre $K = 0.288 \text{[W m}^{-1}\text{K}^{-1}]$.

For hydrophilic fibres thermal conductivity is based on the moisture content, characterized by regain $R$ [%]. For wool fibres the dependence of $K$ on $R$ is described by the following relation (Haghi (2003)):

$$ K = 10^{-3} \times (38.49 - 0.72 \times (R/100) + 0.113 \times (R/100)^2 - 0.002 \times (R/100)^3) $$

[2]

The empirical relation between $K$ and $R$ for cotton fibres has the form (Haghi (2003)):

$$ K_c = 10^{-3} \times (44.1 + 63 \times (R/100)) $$

[3]

For the expression of the thermal conductivity of fabric it is simplest to use a two phase model, consisting of fibres (moist), having a thermal conductivity $K_y$, and air, with a thermal conductivity $K_a$, in serial (lower limit) or parallel (upper limit) arrangements as shown in Fig. 2. The relative portion of the air phase is equal to porosity $P_o$ and the relative portion of the fibrous phase is $1-P_o$.

$$ K_y = P_o \times K_y + (1 - P_o) \times K_a $$

For the serial arrangement, the thermal conductivity $K_s$(lower limit) is defined as:
The actual composition of the fibre and air phases can be presented by a linear combination of parallel and series structures incorporating the thermal resistance of its constituents (Sulaiman (2006)). This might not give an accurate prediction of the fabric thermal conductivity due to the specific orientation the fibres take within the yarns as well as the distribution, shape and size of the pores. However, the parallel/series structure provides a first prediction and would give reasonable prediction accuracy for practical applications due to its simplicity.

A different model, combining the thermal conductivities of air and fibres, and taking into consideration the fibre orientation has the form:

\[
K_b = K_y + \frac{K_a - K_y}{1 + \frac{1 - P_O}{P_O} \left[ 1 + z \frac{K_a - K_y}{K_a + K_y} \right]}
\]

with \( z = 1 \) when all fibres are perpendicular to the direction of heat flow, \( z = 2/3 \) for random fibre orientation and \( z = 5/6 \) for half of the fibres being random and the other half being normal to the direction of heat flow (this value is used in the calculations here).

Hashin and Shtrikman (1962) developed lower \( K_{hl} \) and upper \( K_{hh} \) bounds for the thermal conductivity of the two phase mixture (derived originally for spherical inclusions of one phase in a continuous other phase):

\[
K_{hl} = K_a + (1 - P_O) \left[ \frac{1}{(K_y - K_a)} + \frac{P_O}{(3 * K_a)} \right]
\]

\[
K_{hh} = K_y + P_O \left[ \frac{1}{(K_a - K_y)} + \frac{(1 - P_O)}{(3 * K_y)} \right]
\]

In all of these relations, the thermal conductivity of the fibrous phase can be replaced by \( K_y \) as defined by equation [3]. Then the thermal conductivity is predicted as a function of a suitable definition of fabric porosity \( P_O \).

### 3. Fabric porosity

There exists a number of models characterising the idealised porosity \( P_O \) from certain constructional parameters of textile fabrics (Militký et al (1998)). Classical parameters are weft sett (texture) \( D_C [1/m] \), warp sett \( D_M [1/m] \), weft yarn fineness \( T_C [tex] \), warp yarn fineness \( T_M [tex] \), planar weight of fabric \( W_p [kg \, m^2] \), density of fibres \( \rho_f [kg \, m^{-3}] \) and fabric thickness \( t_f [m] \). For the idealised arrangement of yarns in the fabric \( t_f = d_C + d_M \), where \( d_C \) is the diameter of the weft yarn and \( d_M \) is the diameter of the warp yarn. In the case where \( t_f \approx t_i \) the yarns in the fabric are roughly circular. This type of arrangement is assumed hereafter.

For **idealised circular yarn** with the same packing density it is simple to compute their diameters from the relation:
Section IV: Heat and Moisture Transfer through Clothing

Here \( \rho_C \) and \( \rho_M \) are unknown densities of weft and warp yarns. These densities are combinations of densities of fibres \( \rho_F \) and air \( \rho_A = 1000 \text{ [kg m}^{-3}] \) according to the packing of the fibres in the yarns. For known packing density \( \mu_M, \rho_M = \mu_M \rho_F \) and the same relation is valid for a weft yarn. The values \( \rho_C \) and \( \rho_M \) are therefore a function of twist and the method used to spin the yarn. For a moderate level of twist it has been empirically found that \( \rho_C/\rho_F = \mu_C \approx 0.525 \) and this correction can be imposed on the relations [4] and [5] for the computation of \( d_C \) or \( d_M \). The „density“ porosity of fabrics can be computed from the relation:

\[
P_D = 1 - \frac{\rho_W}{\rho_F}
\]

where \( \rho_W = \frac{m_V}{v_V} = \frac{W_P}{t_W} \).

A second possibility of porosity evaluation is based on the definition of „hydraulic pore“ for filtration purposes (Militký et al 1998). The „volume“ porosity is defined as

\[
P_V = 1 - \frac{\text{volume covered by yarns}}{\text{whole accessible volume}} = 1 - \frac{v_Y}{v_V} = 1 - \frac{v_Y}{t_W}
\]

Where \( v_Y \) is computed from the equation derived by Militký et al (1998). For the case of negligible yarn dimensional changes in fabrics, the porosity \( P_V \) can be expressed by the relation:

\[
P_V = 1 - \frac{[D_C T_C + D_M T_M]}{525 \times 10^3 \times \rho_F \times t_W}
\]

A more accurate determination of volume porosity is based on the idealized fabric surface structure projection shown in Fig. 3.
The unit cell (element of structure) shown within the solid lines contains curved weft and warp yarn portions. The volumes and lengths of these portions are computed from the equation derived by Militký et al (1998). Corrected volume porosity is then defined as:

$$P^*_V = 1 - \frac{\pi}{4*(D_m + D_c)} \left[ d_c^2 * D_c * \sqrt{1.16 * d_c^2 * D_c^2 + 1 + d_m^2 * D_m * \sqrt{1.16 * d_m^2 * D_m^2 + 1}} \right]$$

From a purely geometrical point of view the surface porosity can be defined:

$$P_S = 1 - CF$$

CF is the fabric cover factor defined as $CF = D_c d_c + D_m d_m - d_c d_m D_c D_m$.

4. Experimental

Some 14 different kinds of cotton fabrics suitable for summer clothing were investigated. Details of fabric preparation and constructional parameters are given by Matusiak (2005). These were the plain woven fabrics produced from the same warp: cotton combed yarn of a linear density $T_m = 15$ tex. All fabrics were produced at the same nominal warp density $D_m = 2700 [1/m]$ and at the same nominal weft density $D_c = 1450 [1/m]$. Differentiation of the fabric structure was achieved by the use of different weft yarns: $T_c = 20$ tex, 25 tex, 30 tex, 40 tex, 50 tex and 60 tex. To characterise fabric structural parameters connected with transport properties, the density porosity $P_D$, volume porosity $P_V$, corrected volume porosity $P^*_V$ and surface porosity $P_S$ were computed. The experimental thermal conductivity $K_{ex} [W m^{-1}K^{-1}]$ was measured by means of the ALAMBETA device.
5. Results and discussion

For the prediction of the fabric thermal conductivity, the values of $K_s$, $K_p$, $K_b$, $K_{hd}$ and $K_{hh}$ were computed from the equation defined in section 2. $K_y$ was computed from equation [3] for a regain value $R = 10\%$, and a thermal conductivity of air $K_a = 0.024$. To investigate the influence of the porosity $P_O$ definition on the thermal conductivity, the values of $K_s$, $K_p$, $K_b$, $K_{hd}$ and $K_{hh}$ for the above mentioned surface $P_S$, volume $P_V$, corrected volume $P^*_V$ and density $P_D$ based porosities, were computed. The scatter plot map for porosities is given in Fig. 4a. The very strong linear relation between the porosities is apparent. Larger differences occur in the range and scale of porosity values. Based on the comparison of predicted and measured thermal conductivities, the surface porosity was selected as optimal for prediction purposes (see Fig. 5). The scatter plot map for thermal conductivities (porosity $P_S$) is given in Fig. 4b. The strong correlation between the experimental values $K_{ex}$ and predicted thermal conductivities is clear. The predicted thermal conductivities correlated strongly with each other as well.

![Figure 4 Scatter plot map for a) porosities   b) thermal conductivities (case $P_O = P_S$)](image)

The relation between experimental thermal conductivity, predicted conductivity (porosity $P_S$) and surface porosity $P_S$ shown in Fig. 5, demonstrates good prediction capability and the same trends. The apparent linearity between thermal conductivity and porosity here is due to the relatively small range of porosities covered. The best prediction capability has upper limit $K_p$ corresponding to the parallel arrangement or upper limit $K_{hh}$.

![Figure 5 Experimental and predicted thermal conductivity versus porosity $P_S$](image)
6. Conclusions

On the basis of the present investigations, the thermal conductivity of cotton type woven fabrics can be predicted from the surface porosity \( P_S \) and model the parallel arrangement \( K_P \). Further improvements are obtained by a more precise definition of \( K_S \) and replacing the fibrous phase by a yarn as a composite of fibres and air. For rough prediction purposes this approach is quite sufficient and could be used for design purposes as well. This is the first step to engineer the thermo–physiological features of fabrics by the appropriate designing of fabric structure.

Acknowledgements

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Predicting the Impact from Wind and Activity on Thermal Characteristics of Ensembles

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Abstract

A simulation program has been used to predict the impact of wind and physical activity on the thermal characteristics of ensembles. The computer program is based on general formulae valid for heat and mass transfer and together with a thermal physiology model they constitute a virtual manikin. It has been used to show that the reduction in ensemble total insulation value due to wind can be described entirely from the air flow across a cylinder if the outer material is air tight. Compared with measurements on a static manikin, the difference between the methods is negligible over a wide range of wind speeds. The simulation program has also showed that a walking induced reduction in ensemble intrinsic insulation value can be estimated from convection in ducts. Development of folds forces the enclosed air to move at the pace of walking. The convective heat transfer is governed by the internal air speed, degree of compression and the width of the air layer. The predicted intrinsic insulation values are similar to those obtained from walking manikin measurements. These applications show that the thermal properties of widely differing ensembles can be predicted fairly well without making any physical measurements.

1. Introduction

It is well known that the thermal insulation of an ensemble is reduced by external wind and physical activity. Such effects have been quantified in human calorimetric studies as well as by using movable thermal manikins. However, to assist the user there has been a need to develop mathematical expressions that may predict the (changes) in of static insulation values in a realistic environment including wind and physical activity. The formulae, proposed for inclusion in standards, are expressed as a relation between static and dynamic insulation values, containing a correction factor including air and walking speed as well as air permeability of the fabrics involved. Yet, as the formulae are pure empirical equations they don’t give much
information on the physical mechanisms governing the changes in the insulation value. Altering the composition of an ensemble, or changing the way of wearing it, may give quite a different thermal resistance under dynamic conditions. Such effects can scarcely be derived from the formulae. Nevertheless, if available, this would imply an option that might be valuable. Comprehensive studies in thermal engineering have led to detailed knowledge that is useful in clothing physics. For instance, the airflow pattern around a body and the influence of its characteristic measures on the transportation of heat and mass can be used for prediction of ensemble thermal properties in external wind. The impact of physical activity on the intrinsic insulation value is somewhat more complicated. Fitting, material thickness, and activity rate affect the internal convection between the various clothing layers. Development of folds causes a redistribution of air within the ensemble. However, close to the openings, there is an exchange of air with the environment affecting the thermal resistance by introducing new heat and vapour transfer avenues.

Expressing the heat resistance of an ensemble from general convection expressions makes it possible to estimate the thermal properties of an ensemble under various conditions without making any experimental studies. This has been done and combined with a thermal physiology model a virtual thermal manikin is obtained. Such one (Insula) has been used to predict the impact of external wind and physical activity on the total and intrinsic insulation values on ensembles. The outcome has been compared with data for articulated manikins.

2. Theories, Methods and Techniques

Validation of the theories used was done by measuring convective heat flow and air flow rate, on humans and cylinders of various shapes in a wind tunnel. Special heat flow discs and air speed meters were developed for the measurements (1). Theories and the modelling have been thoroughly presented elsewhere (1, 2).

2.1 Forced convection at an external clothed surface

When air is blowing over a surface the convective heat transfer will depend on a number of factors. Assuming that the airflow is laminar, the heat transfer rate is affected by air speed and the shape and diameter of the object as well as surface characteristics. Furthermore, the convection will depend on the angle to the wind. If the object is adjacent to another body, blocking may change the air flow.

The convection over a cylinder surface can be estimated by using the Nusselt number for a cylinder. It can be written as

\[ \text{Nu} = C_{Re} \cdot \text{Re}^x \cdot \text{Pr}^{1/3} \]  

This empirical correlation is also valid for non-circular cylinders in a cross flow with different values for the constants \( C_{Re} \) and \( x \). For a nude human or a human wearing very tight fitting clothing, standing in a wind, \( C_{Re} \) and \( x \) are 0.61 and 0.71 for the trunk, 0.25 and 0.56 for the leg and 0.19 and 0.59 for the arm, respectively. For the whole body the corresponding values are 0.17 and 0.61. As the values for the whole body are very close to those of a circular cylinder the convection coefficient can be expressed as

\[ h_c = 4.2 d^{0.38} v_0^{0.62} \]  

If the surface is not smooth and/or if there is an object blocking the air flow, the dependence on diameter, shape and speed becomes different. In addition, the influence of angle to the wind will change. Hence, this will also happen at body parts clothed with loose fitting garments. Air flow will also be obstructed e.g. at parts of the body facing another part, between the thighs, between the arm and trunk e.g. Due to increased characteristic diameter, the expected \( h_c \)-value for the clothed part is lower than when nude. This is, however, not always the case. Depending on folds and shapes the \( h_c \)-value can be greater as well as smaller than expected from the diameter. The \( C_{te} \) and \( x \) values for the nude whole body were 0.17 and 0.61 whereas for the clothed human body values of 0.19 and 0.64 are obtained which can be compared with those of the circular cylinder, namely 0.19 and 0.62 respectively. At the various parts of the clothed body, it has been that found that the \( h_c \)-values are related to diameter according to \( d^{-0.04} \) (1). The corresponding value for the nude body is \( d^{-0.33} \), which was fairly close to the \( d^{-0.38} \) for the circular cylinder. The results for the clothed body, \( d^{-0.04} \), indicate that, with a loose-fitting ensemble, the \( h_c \)-values at the various parts of the body are not dependent on the characteristic diameter.

2.2 Convection coefficients within enclosures

During physical activity, the fit of the garment changes and the enclosed air volume is displaced. Development of folds will induce air movement with an associated convection heat transfer, the magnitude of which depends on the air gap width and the activity rate. Natural convection may also contribute to the convection heat transfer. The internal air speed may be affected by activity rate, fitting, external air speed, degree of closure of the apertures etc. However, the impact on the convection coefficient is not that simple as the air exchange and ventilation affects the air and wall temperatures differently. The increase in internal \( h_c \)-values during walking is mainly due to the deformation of the garments and reduced air gap widths. The internal whole-body \( h_c \)-value when walking is almost unaffected by external wind even when the apertures at wrists ankles, waist and neck are open, as long as the material is air-tight. Locally, however there are some effects seen close to the openings, mainly at the waist and ankle. For a given air gap width, the internal convection coefficient is affected mainly by the air layer speed, but is practically unaffected by the size of the air gap or air volume displaced. Then the \( h_c \)-value coincides very well with that of laminar flow in wide channels. Such a condition is valid for the lower part, for example, of e.g. long coats. However, when the air gap changes due to bodily movements, for example, size of the air gap, the enclosed volume and displaced air volume are important factors affecting the convection coefficient. Then convection is similar to undeveloped, laminar flow at an entry length. It can be expressed as

\[
h_c = h_{cN}^{\frac{4}{4}} + (5.1 \cdot \left(\frac{v_i}{(k \cdot 2 \cdot d_{th})^{3/4}}\right) )^{1/4} \tag{3}
\]

where \( k \) is the compression factor and \( d_{th} \) is the air gap width when uncompressed. The internal air speed, \( v_i \), induced in the tight-fitting ensemble is similar to that in a loose-fitting one. Yet, because of the influence of air-gap width and the entry length, the corresponding \( h_c \)-values become greatest in tight fitting ensembles. For the whole body, the compression is about 30% and 40% for the loose fitting and the tight fitting ensembles, respectively. For the individual body parts, the compression ranges from 10% (upper arm, loose fitting) to 65% (thigh, tight fitting). These figures are applicable for walking at various speeds. The relative magnitudes of natural and forced convection differ considerably during the various phases of the
gait. In the tight-fitting ensemble, the natural component is often greater than the forced one, while in the loose fitting ensemble, the natural component only exceeds the forced component when the gap distance is at its minimum. Decreasing the air gap width therefore reduces the importance of the forced convection component (Figure 1.) The greatest reduction in the air-layer insulation value for a one-layer ensemble occurs when the walking speed changes from zero (standing) to a slow walk. Increasing the walking speed further has only a slight effect on the air-layer insulation. So the contribution from a relatively thin fabric layer to the intrinsic insulation value is small when standing, especially if the ensemble is loose-fitting.

When walking, however the fabric thickness becomes more important, especially if the ensemble is tight-fitting. With a thin air layer, the reduction in the air-layer insulation value, due to the compression when walking, is mainly in the natural component of convective heat transfer. The forced component is less important despite the large air layer speed. The mechanisms controlling the convection in a multi-layer ensemble are the same as those in a single-layer outfit. The bodily movements deform the fabric layers, which displaces the enclosed air volumes. However, with several fabric layers the material thickness becomes important, as this changes the air gap width and compression factor.

![Figure 1 The relative importance of natural and forced convection during one walking cadence wearing two ensembles having two fittings](image)

### 2.2.1 Ventilation

During the various phases of physical activity, the air enclosed between the clothing layers is redistributed inside the garment. If the apertures are closed, no ventilation occurs and consequently no air is exchanged with the surroundings. On the other hand, with open apertures, there is a combination of internal redistribution of air and exchange with the environment. Simply, the ventilation is governed by the air speed at the openings and the surface area of the apertures. Based on internal air speed measurements, rough figures have been obtained for various walking speeds, garment fittings and ventilation sites (leg, arm, trunk). A loose-fitting ensemble covering both the upper and lower body parts is associated with a whole-body ventilation rate of 1, 2 and 3 l/s at the walking speeds 0.9, 1.4 and 1.9 m/s,
respectively. The activity induced ventilation is mainly affected by the activity rate whereas the impact of external wind is minor when the outer layer was air-tight. The internal convection coefficient is influenced by the ventilation rate and the fabric insulation value due to the different impact on the fluid and surface temperatures. One consequence is that the greater clothing insulation value the greater is the impact of external air exchange.

2.3 Virtual ensembles
To illustrate the effects of wind and activity on various ensembles Insula has been used to develop virtual ensembles. They are composed of common garments, underwear, shoes, socks, shirt, trousers etc. Depending on the condition discussed, the ensemble with its layers was exposed to external and internal air flow, air exchange, garment compression etc as described above.

3. Results and Discussion

3.1 Static conditions
Havenith and Nilsson (3) discussed the errors that are introduced when comparing results from measurements performed under diverging conditions, such as different “no wind” air speed and covered surface area. Figure 2 (left) shows the reduction in total insulation value due to wind for the windproof virtual ensemble, coverall without gloves and hood, as a ratio to “no wind” condition. The three curves show the results when 0 (still air), 0.15 m/s and 0.4 m/s are used as reference air speeds, respectively. The still air (0 m/s) total insulation value was 0.285 m²K/W. The greatest difference between the curves is obtained for low air speeds and is some 10% when comparing the insulation values when 0 and 0.4 m/s reference values are used. At a wind speed of 18 m/s, roughly 40% of the insulation value remains and the deviation due to ref. air speed is roughly half the value at low air speeds. Figure 2 (right) shows the result for the virtual coverall including gloves and hood covering a greater skin surface area. The estimated total insulation value was 0.309 m²K/W in still air (0 m/s). When the air speed is 18 m/s the predicted insulation value becomes approximately 55% of the calm air value, showing that minor deviations in covered surface area may cause substantial differences, especially under windy conditions. Furthermore, the effect of changing the fraction nude skin area will increase significantly the greater the insulation value is. Figure 2 shows that the effect of using different “no wind” conditions is reduced the greater the covered skin surface area.

Similar results as in Figure 2, right panel, are obtained for heavy winter clothing. Figure 3 shows the effect of wind when the virtual ensemble total insulation value is 0.443 m²K/W (0 m/s). The figure shows also the results of Nilsson et al (4), with the ensembles total, static insulation value ranging from 0.23 to 0.54 m²K/W ($v_{ref} = 0.4$ m/s). The figure indicates that the relative impact of wind is about the same as for the less insulating ensemble (Figure 2) giving a reduction of slightly more than 50% at 18 m/s of wind. The figure also shows that the predicted wind effect very closely coincides with the thermal manikin measurements, producing a deviation of just a few percent over the whole range of air speed. The prediction model does not account for garment compression due to wind pressure. which would work in the
direction of overestimating garment insulation. Thus the close agreement may indicate that the effect on the total whole body insulation is small. Yet, locally this impact might be of significance.

Figure 2  Effect of wind on the static, total insulation value for a virtual coverall (left panel) and coverall with gloves and hood (right panel) when the reference air speed differs between 0, 0,15 and 0,4 m/s.

Figure 3: Effect of wind on static, total insulation value. Filled squares refer to the average value of virtual overall and winter uniform, both with hood and gloves. Open diamonds show the results of the Nilsson et al (2000) study.
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Figure 4: Comparison between measured (4) and predicted (Insula) wind induced effects on total, static insulation values (left). The figure at the right shows the comparison between Insula data and that from Havenith et al (5).

Figure 4 (left) shows the insulation ratios for windy and calm conditions. The Insula predictions are compared with the results of Nilsson et al (4) when exposed to external wind ranging from 0 to 18 m/s. The reference air speed is 0,4 m/s and the outer clothing material is air tight. The results of the virtual ensembles are similar to those of Nilsson et al. (4). The maximum deviation between the two methods is around 2%. Figure 4 (right) shows the results of the Insula predictions compared with those of Havenith et al (5), with the ensembles exposed to an external wind ranging from 0 to 4,1 m/s assuming a reference air speed of 0,15 m/s and air tight outer clothing material. The maximum deviation between the two methods is around 4 %. The virtual ensembles used in the prediction were based on the material data presented by Havenith et al (5).

3.2 Dynamic conditions

Physical activity reduces the intrinsic and external ensemble insulation. For an articulated manikin or walking on a treadmill where there is no external wind, the convection coefficients over the clothed surface deviate slightly from those of the nude body. The difference mainly arises over the swinging limbs where the hₜ values become slightly lower, when dressed, due to a greater characteristic diameter compared with the nude parts. The convection coefficients over the arms and legs are similar to those of a pendulating circular cylinder whereas those over the trunk can be estimated from the relations valid for air flow over a flat plate. However, the activity induced external convection does not differ very much between different types of ensembles when looking at the whole body value. Locally, there might be greater differences due to induced convection, especially if the ensemble is bulky. A condition that is a mix of external and internal convection is walking wearing a coat. The lower part of the garment acts more as a free textile layer hanging in the wind than a closed part (Figure 5). Under standing still conditions the coat acts as a normal insulating layer whereas when walking (no wind) the lower part hardly contributes to the ensemble insulation. Hence, comparing the static and dynamic insulation values for ensembles without coats the correlation is good and linear when the coats are excluded. Including such an item changes the relationship. The activity induced reduction becomes greater than when no coat is worn (Figure 5). Excluding the effect of the coat, the dynamic intrinsic insulation is affected by
activity rate (walking speed), number of clothing layers and fabric thickness and other textile properties. Figure 6 shows that for light ensembles composed of few and thin material layers the dynamic intrinsic insulation value is roughly 65% of that when standing still. The figure shows also that the virtual ensembles coincide very well with the experimental data but that the greatest effect is seen for walking speeds up to about 1 m/s. Higher speeds does not reduce the intrinsic insulation that much except for perhaps the lightest ensembles.

Figure 5  Effect of walking on the static intrinsic insulation value (6). The filled squares denote ensembles without a coat, whereas open circles refer to ensembles with a coat.

If the clothing air layer is reduced because of tighter fitting and/or thicker material layers the difference between static and dynamic insulation values is reduced. The ensemble showing almost the same dynamic as static values was composed of thick fleece layers reducing the air layer to a minimum (Figure 6). Figure 7 shows the results from the measured (6) and predicted impact from walking on the intrinsic insulation values. The virtually ensembles used by Insula were based upon the number of garment layers covering various parts of the body, their material thicknesses, and assumed fitting as they were presented by Kim and McCullough (6). Obviously, the data coincide fairly well over the whole range of types of ensembles and insulation values. The minor deviations may refer to differences in gait pattern (Insula based on human gait) but also how the insulation value of the external air layer is subtracted to give the intrinsic value. Kim and McCullough (6) used data from a nude manikin whereas Insula estimate the contribution based on the air layer surrounding a clothed body.
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Figure 6 Relation between dynamic and static intrinsic insulation values. The virtual ensembles (Insula) are designed to mimic ensembles used by Hong (7). These ensembles are “exposed” to two walking speeds, 0.9 and 1.4 m/s. The other data points (8, 9, 5) refer to a walking speed of about 1 m/s.

Figure 7 Comparison between static and dynamic insulation values by Kim and McCullough (6) (filled squares) and those predicted from Insula (open diamonds).
In the Introduction, it was claimed that using models based on the actual mechanisms describing the heat and mass transfer, in addition to correlation equations, advantages could be obtained in respect of flexibility and general applicability. Figure 8 shows that using the same expressions as those used above but with the exception that the radiation component was excluded and the Lewis relation is used to convert from heat to mass transfer, the water vapour resistance of an ensemble can be estimated. Figure 8 shows one example of this where the static intrinsic water vapour resistances from virtual ensembles are compared with those from a static sweating manikin. It has been shown (10) that the Lewis relation is valid also at very low air speeds. Nevertheless, the relation should work still better at forced convection. On the other hand, the influence of the ventilation rate becomes much more critical compared with when estimating the heat resistance. The declaration of what part of the body is covered becomes also much more important.

4. Conclusions

It has been shown that the thermal properties of a broad range of ensembles, exposed to wind and physical activity, can be predicted using expressions based on general engineering heat and mass transfer models. One obvious advantage of using that approach is that virtual ensembles can be exposed to various environments and easily evaluated in respect of their thermal properties without having access to costly facilities. Nevertheless, it should be pointed out that new materials and special garment designs may not be properly treated without further development of the model.
5. Literature

9. Olesen, B. W. and Nielsen, R., Thermal insulation of clothing measured on a movable thermal manikin and on human subjects. Research No 7206/00/914, Technical University of Denmark, Lyngby, Denmark, 1983.
Heat and Mass Transfer from Clothing Induced by Air Ventilation

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Abstract

Air ventilation can induce heat and mass exchanges between the microclimate within clothing and the environment; the amount of heat and mass exchange being obviously related to the amount of air ventilation. To better understand the effects of body motion, a tracer gas technology was developed and used for investigating the ventilative heat and mass transfer through clothing systems induced by wind and body motion. However, due to the limitation of this method, the effects of moisture condensation and absorption within the clothing cannot be taken into account. Based on the measurements on the fabric thermal sweating manikin – “Walter”, a new algorithm for estimation of the coupled heat and mass transfer induced by air ventilation is reported in this paper. The study showed that the heat and mass transfer induced by air ventilation is linearly related to the sum of double walking speed and wind velocity. The present study also proposed a dimensionless air ventilation coefficient of clothing system \( KV \) for representing the ventilation ability of clothing which is only dependent on the clothing features, such as garment style, fit and properties of garment fabrics.

Keywords: clothing thermal insulation, clothing moisture vapour resistance, prediction model, ventilation, wind
1. Introduction

Clothing is a main determinant of heat transfer between humans and their surroundings. Unless the clothing is skin tight, air gaps exist both between the skin and under clothing and between different layers of clothing, these gaps also vary in size as the wearer moves or the garment flaps. This is referred to as the microclimate in the clothing system. When a clothed person is walking in wind, the loose outer garment may flap, pumping out warm air and moisture vapour from the air gap between the tight-fitting inner garment and the loose-fitting outer garment and replacing it by cooler air from the surrounding environment, and at the same time wind may penetrate through the outer garment to create heat and mass exchange. Obviously the temperature and humidity of the microclimate in a clothing system are very different from that of the surrounding environment. The reduction of the effective insulation caused by the body motion seemed to have been universally accepted and it is attributed mainly to the loss of convective heat by forced exchange of air contained under the clothing with the ambient air. Depending on the construction of the fabrics (such as woven or knitted) and clothing (style), air could be forced through the pores in the fabrics as well as through the openings in the garments. This was named as air ventilation. “Air ventilation” can be further classified into direct ventilation and indirect ventilation. Direct ventilation refers to the exchange of garment microclimate air with ambient air through openings in the garment itself or those which result from the manner in which it is worn. Indirect ventilation refers to the exchange of garment microclimate air that passes through the materials from which the garment assembly is made. That is to say the air exchanges between the microclimate and ambient caused by ventilation is irrespective of the avenue through which it passes (Laing and Sleivert 2002). It is difficult to clearly distinguish between wind or air penetration and indirect air ventilation through clothing systems. The amounts of indirect ventilation may include those of wind penetration.

Crockford et al (1972) first measured the clothing ventilation successfully by means of a trace gas dilution method; two enhanced techniques were further developed by Lotens and Havenith (1988) and Reischl et al (1987) for the purpose. Air exchange characteristics of clothing can be quantified using the Ventilation Index (Birnbaum and Crockford, 1978), which was defined as the rate of ventilation in volume per unit body surface area and per unit time. Clothing ventilation is dependent on many variables such as body movements, wind speed, clothing material and design. Different clothing designs change the microclimate volume. Although the clothing ventilation index is a quantitative, relatively inexpensive, fast, reliable and repeatable measure, due to the limitations of this method, the effects of moisture condensation and absorption within the clothing cannot be taken into account. Furthermore, the effect of microclimate volume on clothing ventilation has not been quantified before, and little is known on how clothing ventilation relates to different environmental and body motion conditions.

Based on the measurements on the fabric thermal sweating manikin – “Walter”, a new algorithm for estimation of the coupled heat and mass transfer induced by air ventilation is reported in this paper. The study showed that the heat and mass transfer induced by air ventilation is linearly related to the sum of double walking
speed and wind velocity. The present study also proposed a dimensionless air ventilation coefficient of clothing system $KV$ for representing the ventilation ability of clothing that is only dependent on the clothing features, such as garment style, fit and properties of garment fabrics.

### 2. Review and re-analysis work

Under body motion and windy conditions, the thermal insulation and the moisture vapour resistance will be reduced due to (1) the increased heat and mass transfer induced by forced convection in the air layer near to the outer clothing surface; (2) the additional heat and mass transfer induced by “bellows” action or clothing ventilation; (3) the additional heat and mass transfer caused by the wind penetration through the fabrics of the clothing. As far as the wind penetration is concerned, although past theoretical analysis showed that the wind induced air exchange is proportional to the square of the wind velocity (Stuart and Denby 1983), there is a distinct difference between the theoretical prediction and experimental results. Since the garment hangs naturally on the body and indefinite vibration is induced by wind, especially when the clothed person is moving, the efficiency of air penetration is reduced. This means the theoretical model tends to overestimate the actual amount of air penetration. Harter (1981) and Danielsson (1993) stated that the rate of air penetration through the clothing assembly is approximately linear with the wind velocity.

After re-examining the results of the ventilation data obtained by Reischl et al (1987), Lotens and Wammes (1993), Havenith et al (1990) and Bouskill et al (2002), we found that the air ventilation and wind penetration also increased linearly with the sum of several times the walking speed and wind velocity. An example of the relationship is shown in Figure 1.

**Figure 1** Relationship between air ventilation and the sum of several times the walking speed and wind velocity (Data from Bouskill et al, 2002)
Since the dry and latent ventilative heat transfer coefficients are linearly proportional to the air exchange, the following empirical equation is proposed to predict heat and mass transfer coefficients by air ventilation and wind penetration for a clothed person walking under windy conditions:

\[
\begin{align*}
    h_{dv} &= KVI(V_{wind} + \beta_V V_{walk} - v_0) \\
    h_{ev} &= KVR(V_{wind} + \beta_V V_{walk} - v_0)
\end{align*}
\]

where, \(KVI\) and \(KVR\) are constants, which depend on garment(s) fit, styles of design and construction of the clothing ensemble. \(V_{wind} + \beta_V V_{walk} - v_0\) is an equivalent wind velocity taking into account the effect of walking speed, \(\beta_V\) is an equivalent air velocity factor for “walking” motion on heat and mass transfer induced by air ventilation. \(v_0\) is the air current in the “still air” condition. (In any climate chamber, even at “still air” condition, there is air current. This is essential for the operation of the air conditioning system in the chamber). In our study, \(V_0=0.22\,\text{m/s}\). By definition, under the “still air” condition, when there is no air exchange by wind and walking motion, \(h_{dv}=h_{ev}=0\).

### 3. Method and Experiments

According to the conservation law, the heat transfer coefficient induced by air ventilation can be expressed as:

\[
\begin{align*}
    h_{dv} &= \frac{1}{I_t} - \frac{1}{I_c + I_{oa}/f_c} \\
    h_{ev} &= \frac{1}{R_t} - \frac{1}{R_c + R_{oa}/f_c}
\end{align*}
\]

The surface thermal insulation and moisture vapour resistance of a clothing system can be estimated by the equations (Qian and Fan, 2005):

Fifteen sets of clothing ensembles were tested in the present study, which included one-layer tight and loose fitting jackets with permeable and impermeable fabrics. These clothing assemblies were tested on the walk-able sweating manikin-Walter (Fan and Qian 2004) in a climate chamber at 20°C and 50% RH. Each of the clothing ensembles was tested under six different levels of wind velocity with the manikin in a standing position. At the wind velocities of 0.22 and 2.48 m/s, the clothing ensembles were also tested at four levels of walking motion. Thus for each clothing ensemble, there were 12 cases investigated. The static total thermal insulation and moisture vapour resistance of the clothing ensembles ranged from 1.13~1.41clo (0.175 ~0.219m²oC/W) and from 30.07 ~ 38.98 m²pa/W, respectively.
4. Evaluation of the heat and mass transfer coefficients \((h_{dv} \text{ and } h_{ev})\) induced by air ventilation

4.1 Determination of the value of equivalent wind velocity coefficient \(\beta_v\)

With the thermal insulation and moisture vapour resistance values of a clothed person standing in windy condition, the values of \(h_{dv}\) and \(h_{ev}\) can be calculated by the above equations. Hence, \(KVI\) and \(KVR\) for each clothing ensemble can be obtained by linear regression. By applying these values of \(KVI\) and \(KVR\) under walking motion and windy conditions, \(\beta_v\) can be obtained by fitting equations 1 and 2 to the experimental data. It was found that: \(\beta_v = 2.0 \quad (R^2 = 0.95)\)

The examples of dry heat and latent heat transfer coefficients \(h_{dv}\) and \(h_{ev}\) induced by air ventilation are plotted against the equivalent wind velocity \(v_v\) in Figures 2 below:

![Figure 2 Examples of the effect of equivalent wind velocity on dry and latent heat transfer coefficient](image)

It can be seen that the values of \(h_{dv}\) and \(h_{ev}\) were approximately linearly related to the equivalent air speed \(v_v\).

4.2 Relationship between \(KVI\) and \(KVR\) and the clothing fit index, the air permeability and the fabric thickness of outer clothing

With the values of \(I_{tdyn}, I_{oa}, I_{ci}\) and \(I_c\) and \(R_{tdyn}, R_{oa}, R_{ci}\) and \(R_c\), by means of the nonlinear regression, the value of \(KVI\) and \(KVR\) can be obtained by fitting equations (3) and (4) for different clothing ensembles. By applying the nonlinear regression, the following relationships can be derived to predict \(KVI\) and \(KVR\) of clothing ensembles consisting of jackets and pants without underwear.

\[
KVI = 0.0649 \ln \left( \frac{Fit \sqrt{ap}}{th} \right)^2 + 0.5897 \quad R^2 = 0.84 \quad (5)
\]
\[
KVR = 0.0006 \ln \left( \frac{Fit \sqrt[3]{ap}}{th} \right)^3 + 0.0036 \quad R^2 = 0.81 \quad (6)
\]

where, \(Fit\) is the value of the clothing fit index defined as the area weighted average of the percentage difference between the inner circumferences of different parts of the garment and the corresponding circumferences of the body., and \(th\) is the fabric thickness of the jackets measured using ASTM D737-96, \(ap\) is the air permeability of the shell fabric measured using the FAST system.
Figures 3 shows the correlations of the calculated $KVI$ and $KVR$ using Equations (5) and (6) with those obtained by direct regression using measured data in the equations (1), (2), (3) and (4).

![Figure 3](image)

**Figure 3 Correlations of $KVI$ and $KVR$ between predicted value and measured values**

### 4.3 Relationship between $KVR$ and the air ventilation index

The latent ventilation heat transfer $H_{ev}$ can be expressed as

$$H_{ev} = \lambda \cdot A \cdot U_{vent} \cdot (\rho_a - \rho_i) = \lambda \cdot A \cdot f_c \cdot \frac{(p_c - p_v)}{R_v}$$  \hspace{1cm} (7)

where, $\rho_a$ and $\rho_i$ are the moisture vapour concentration of the environment in g/m$^3$ and the mean moisture vapour concentration within the clothing microclimate in g/m$^3$, respectively, $\lambda$ is the evaporative heat of water in J/g ($\lambda = 2419$ j/g at 35°C), $U_{vent}$ is the ventilation index (the rate of ventilation in volume per unit body surface area and per unit time); $R_v$ is the equivalent air ventilative moisture vapour resistance.

According to the basic principle of thermodynamics:

$$U_{vent} = \frac{KVR}{\eta} (V_{wind} + 2V_{walk} - 0.22) \hspace{1cm} m/s$$  \hspace{1cm} (8)

where, $\eta = \frac{\lambda}{9RT} = 17.5 \left(\frac{J}{m^2 \cdot p_a}\right)$

Defining $KV = \frac{KVR}{\eta}$ as the air ventilative coefficient, it is a dimensionless coefficient of the clothing system. The air ventilation index $U_{vent}$ varies not only with the clothing features but also with wind velocity and body motion. The dimensionless $KV$ is only dependent on clothing features, such as garment style and fit and the properties of the garment fabrics and can be used as an index to represent the ventilation ability of clothing.
5. Conclusions

Air ventilation can induce heat and mass exchanges between the microclimate within clothing and the environment. Based on the re-analysis of previously published experimental data, it has been found that the heat and mass transfer coefficients induced by air ventilation increased linearly with the sum of several times the walking speed and wind velocity. This was also confirmed in the present study. The effect of walking speed on the heat and mass transfer induced by air ventilation is double that of wind velocity.

The parameters $KVI$ and $KVR$ were found to be dependent on the garment characteristics. If the garment style and dressing mode are not changed, the values of $KVI$ and $KVR$ can be predicted from the fit index of the garment, the air permeability and fabric thickness of the outer garments.

The present study proposed a dimensionless air ventilation coefficient $KV$ of the clothing system to represent the ventilation ability of clothing that is only dependent on the clothing features, such as garment style and fit and the properties of the garment fabrics.

References


Clothing Ventilation Estimates from Manikin Measurements

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Abstract

Clothing ventilation air exchange can be deduced from energy balance results of clothing insulation studies on dry and sweating thermal manikins over a range of air speeds. This paper demonstrates that energy balances at the skin of the clothed dry heated manikin operating in a 20°C 50% RH environment can determine the energy carried away by ventilation air. The volume flow rates are calculated assuming intrinsic insulation is unchanged by air speed and that the ventilation air leaves the clothing system at skin temperature. Similarly energy balances on the clothed sweating manikin operating in a 35°C 50%RH environment (air temperature=skin temperature) can determine the latent energy carried away by the ventilation air assuming the ventilation air leaves saturated. Clothing ventilation rate estimates at three air speeds determined on the dry and sweating manikin are compared. Demonstration is conducted on military clothing with and without body armour and on fuel handler’s protective coverall.

Introduction

The quantification of clothing ventilation is useful for estimating the dose of airborne contaminants contacting the skin, for estimating the effects on fabric and skin moisture mechanisms and for other exposure and thermal issues of clothing design and its application. Clothing ventilation air exchange is often measured by tracer gas methods but clothing air exchange can also be estimated from the energy balance results of clothing insulation measurements routinely done on dry and sweating thermal manikins.

Partitioned energy balances at the skin of a clothed dry heated manikin, operating at steady state conditions at several wind speeds, can determine the energy (qvent) carried away by ventilation air as shown in Figure 1. In the figure, qskin represents...
the power input to maintain the manikin’s skin temperature (Tsk) in steady state environmental conditions of air (Ta) and radiant (Tr) temperature, humidity (RH) and wind speed (V), qcl is the energy flow through the clothing and its boundary layer resistance.

![Figure 1 Schematic of energy flow paths from the thermal manikin skin](image)

The energy flows depicted in Figure 1 are applicable to dry and sweating manikin operations. For dry manikin skin conditions, the ventilation air is assumed to leave the clothing with a temperature equal to Tsk. For sweating manikin conditions, the ventilation air is assumed to be saturated air at Tsk. The ventilation analysis described here requires measurements over a series of different wind speeds including a low speed (V=vo) where the ventilation is assumed to be zero. Also the analysis assumes the clothing’s dry thermal resistance (Rcl) and vapour resistance (Rclp) to be unaffected by wind speed and have values evaluated at the low speed where ventilation is assumed zero. To demonstrate the ventilation estimation process, calculations were done on previous measurements on a static stationary sweating thermal manikin wearing: 1) a battle dress uniform (BDU) consisting of trousers, t-shirt and long sleeved shirt worn outside of the trousers, 2) a BDU plus body armour (BDU+ armour) and 3) a fuel handlers protective coverall over shorts and a t-shirt (FPC).

### Methods

#### Dry Manikin

Measurements were made in a climate chamber at 20°C and 50%RH with the manikin skin dry and its skin temperature (Tsk) maintained at 35 °C. The measurements were made following the procedures of ASTM F12912 at 3 horizontal wind speeds, with the manikin facing into the wind. Assuming the ventilation air leaves at skin temperature, the mass and volume flow rates can be calculated from the following energy balance.

\[ q_{vent} = q_{skin} - q_{cl} \]  
\[ q_{cl} = \frac{(Tsk-Ta)}{(Rcl+Rb)} \]  
\[ Rb = \frac{1}{(fcl \cdot (hr+hc))} \]

Where \( Rb \) is the boundary layer resistance between the clothing’s outer surface and the ambient, \( hr \) and \( hc \) are heat transfer coefficients for radiation and convection, respectively\(^1\). The clothing surface area relative to the manikin’s skin area (fcl)
effective for heat transfer was estimated from an iterative process\(^1\) at \(V=V_0\). At \(V=V_0\), where no ventilation is assumed, \(R_{cl}\) is evaluated as \(R_{cl}=R_{cl,t}-R_{b}\), where \(R_{cl,t}\) is the total thermal resistance from skin to ambient calculated from manikin data. \(R_{cl}\) is assumed to be unchanged at higher wind speeds.

Then, in terms of ventilation air (Vent) flowing under the clothing next to the skin:

\[
q_{vent} = \text{Vent} \cdot c_{pa} \cdot \frac{(T_{sk}-T_a)}{\nu} \tag{4}
\]

where Vent is the flow of ventilation air, \(c_{pa}\) is the specific heat of air (\(j/(g \cdot ^\circ C)\)) and \(\nu\) is the specific volume of air (\(L/g\)). The Vent calculations for the dry manikin wearing the BDU is summarized in Table 1.

<table>
<thead>
<tr>
<th>Wind (m/s)</th>
<th>q_{skin} (w/m²)</th>
<th>R_{cl,t} (Cm²/w)</th>
<th>h (w/m²)</th>
<th>f_cl</th>
<th>R_{cl,v} (Cm²/w)</th>
<th>R_{cl} (Cm²/w)</th>
<th>q_{cl} (w/m²)</th>
<th>q_{vent} (w/m²)</th>
<th>Vent (L/(s m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42</td>
<td>76.4</td>
<td>0.196</td>
<td>5.45</td>
<td>4.47</td>
<td>1.22</td>
<td>0.114</td>
<td>0.196</td>
<td>76.4</td>
<td>0</td>
</tr>
<tr>
<td>1.26</td>
<td>98</td>
<td>0.151</td>
<td>9.82</td>
<td>4.47</td>
<td>1.22</td>
<td>0.114</td>
<td>0.171</td>
<td>87.7</td>
<td>10.3</td>
</tr>
<tr>
<td>2.1</td>
<td>114</td>
<td>0.132</td>
<td>12.89</td>
<td>4.47</td>
<td>1.22</td>
<td>0.114</td>
<td>0.161</td>
<td>93.2</td>
<td>20.8</td>
</tr>
</tbody>
</table>

Table 1: Summary of ventilation estimate calculations for BDU clothing on dry manikin

**Sweating Manikin**

Similarly energy balances at the skin under the clothed sweating manikin operating in a 35°C 50%RH environment (\(T_a=T_{sk}\)) can determine the latent energy carried away by the ventilation air. Assuming the skin of the manikin is 100% wet and that the ventilation air leaves saturated, the mass and volume flow rates can be determined. The measurements made in compliance with ASTM F2370\(^3\) were at chamber conditions of \(T_a=T_r=35^\circ C, 50\%RH\), and three wind speeds. The sweating energy balances are similar to the dry manikin equations 1, 2 and 3 except vapour resistances (\(R_{clp}, R_{bp}\)) and torr terms replace thermal resistances (\(R_{cl}, R_{b}\)) and \(^\circ C\) and \(q_{skin}\) and \(q_{cl}\) are followed by a p.

\[
q_{vent} = q_{skinp} - q_{clp} \tag{5}
\]

where

\[
q_{clp} = \frac{(P_{sk}-P_a)}{(R_{clp}+R_{bp})} \tag{6}
\]

and

\[
R_{bp} = \frac{1}{(fcl\cdot he)} \tag{7}
\]

where the evaporative heat loss coefficient (he) equals \(LR\cdot h_c\)\(^1\) and the Lewis ratio \(LR = 2.2 \; ^\circ C/\text{torr}\). As in the estimate for a dry manikin, at \(v=v_0\), where no ventilation is assumed, \(R_{clp}\) is evaluated as \(R_{clp} = R_{cltp} - R_{bp}\). \(R_{cltp}\) is the total parallel vapour resistance from skin to ambient and \(R_{clp}\) is assumed to be unchanged at higher wind speeds.

The ventilation air (Vent) flowing under the clothing next to the skin is calculated:

\[
q_{vent} = \text{Vent} \cdot h_{fg} \cdot \frac{(W_{sk}-W_a)}{\nu} \tag{8}
\]

where \(h_{fg}\) is the latent heat of vaporization and \(W_{sk}\) and \(W_a\) are humidity ratios of ventilation air. A summary of the Vent calculations for a 100% wet sweating thermal manikin wearing the same BDU is summarized in Table 2.
Table 2: Summary of ventilation estimate calculations for BDU clothing on sweating manikin

<table>
<thead>
<tr>
<th>V (m/s)</th>
<th>qskinp (w/m²)</th>
<th>Psk (torr)</th>
<th>Pa (torr)</th>
<th>Rclp (w/m²)</th>
<th>he (torr m²/w)</th>
<th>Rclp_vo (torr m²/w)</th>
<th>qclp (w/m²)</th>
<th>qvent (w/m²)</th>
<th>Vent (L/(s m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36</td>
<td>107</td>
<td>42.2</td>
<td>21.2</td>
<td>0.196</td>
<td>10.65</td>
<td>0.123</td>
<td>0.196</td>
<td>107</td>
<td>0</td>
</tr>
<tr>
<td>1.15</td>
<td>148.3</td>
<td>42.2</td>
<td>21.4</td>
<td>0.14</td>
<td>19.62</td>
<td>0.123</td>
<td>0.163</td>
<td>127.5</td>
<td>20.8</td>
</tr>
<tr>
<td>1.94</td>
<td>179.9</td>
<td>42.2</td>
<td>21.6</td>
<td>0.115</td>
<td>25.9</td>
<td>0.123</td>
<td>0.153</td>
<td>134.5</td>
<td>45.4</td>
</tr>
</tbody>
</table>

Results

Clothing ventilation rates (L/(s m²)) at 3 air speeds from energy balances on the dry manikin and those found from latent energy balances on the sweating manikin are displayed in Figures 2, 3 and 4 for the BDU, BDU+ armour, and fuel handlers protective clothing respectively.

![Figure 2 Ventilation estimates (Vent) for BDU (long sleeved shirt, t-shirt and trousers) at several wind speeds (V)](image-url)
Figure 3 Ventilation estimates for BDU plus body armour

Ventilation estimates for fuel handler’s protective clothing.
Figure 5 Comparison of regression results through ventilation estimates of BDU, BDU+ armour and fuel handlers’ protective coverall over -shirt and shorts

Discussion and Conclusions

The estimates of clothing ventilation developed from dry and sweating manikin clothing insulation test data for three different clothing systems increased consistently with wind speed. The ventilation estimated from the dry manikin data was generally greater than the ventilation estimated from the sweating manikin data. The comparison of regression results for the three clothing systems in Fig 5 shows the ventilation decreased when heavy body armour was added and decreased further for the fuel handler’s protective clothing. The fuel handler’s protective clothing is similar to chem-bio clothing but made from water vapour semi-permeable fabric.

The energy balance ventilation estimates are a straightforward calculation procedure on manikin clothing insulation test data and the data may already exist as in this study. The ventilation estimates are useful to compare clothing systems ventilation capabilities. The estimates as done here depend on a number of assumptions, such as ventilation air leaving in equilibrium with skin temperatures and vapour pressure, no ventilation at the low wind speed (vo) and unchanging intrinsic clothing insulation (Rel and Relp) with wind speed. As a result of the assumptions, the energy balance method may underestimate the ventilation found by tracer gas techniques. However, clothing ventilation can be repeatably estimated from energy balances using the data from standard clothing insulation measurement tests. The ventilation estimates found are useful to compare ventilation capabilities of clothing systems and may be useful for design and application.
Disclaimer

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References


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Forced Ventilation of Protective Garments for Hot Industries

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Abstract

The performance of a battery powered, forced air distribution system for ventilation under protective clothing (torso body armour) was evaluated on a sweating thermal manikin in a 35°C and 50% RH environment. The ventilation system, delivering 9 L•s\(^{-1}\) of ambient air, increased the heat loss from the manikin by 45 W. Measurements made on the manikin indicated that the ventilation decreased the dry thermal resistance and the vapour resistance of the clothing system by 17 and 20 %, respectively.

1. Introduction

Heavy protective garments necessary for some industries and military situations insulate the body and reduce body heat loss. In hot environments, the garments can impose significant physiological thermal and cardiovascular strains on the wearer. Forced air flow, under such heavy protective garments, can increase body cooling by improving the evaporation of sweat thereby reducing the physiological strain for the wearer. Without forced ventilation, the sweat secreted under protective garments is often not evaporated and drips off the skin, wasting the cooling potential. Testing with a sweating manikin enables the cooling effect of a forced ventilation system to be evaluated and quantified.

This paper evaluates the application of a battery powered ventilation system (BVS) for military body armour (BA). The BVS delivered ambient air to a fabric manifold distribution system which encircled the waist and routed the air to a vest attached to
the inside of the torso body armour (Figure 1). The fan was located at the lower back waist area.

![Figure 1 Schematic of ventilation system as worn, side view](image)

### 2. Methodology

The cooling capacity of the BVS was measured on a sweating thermal manikin according to ASTM F2371\(^1\). The torso body armour with attached BVS was worn over a Desert Battle Dress Uniform (DBDU). The static manikin was in a climate chamber in a 35°C 50%RH environment with the manikin facing a uniform 0.4 m\(\cdot\)s\(^{-1}\) wind (Figures 2 and 3). The manikin’s surface temperature was controlled at 35°C.

![Figure 2 Front view of manikin wearing desert battle dress uniform, body armour with the battery powered BVS, standing in the climate chamber.](image)

The ventilation flow rate was determined from the fan inlet area (80 cm\(^2\)) and the average intake air speed. The average air speed was calculated from measurements made with a hot bead anemometer over a 12 element grid placed across the inlet area. The calculated inlet flow rate was 9 L\(\cdot\)s\(^{-1}\).
The garment cooling capacity with the BVS was determined by measuring the power input to the manikin with the fan OFF and ON. With the fan OFF after the manikin had reached steady state, the power input to the manikin was recorded for 60 minutes. The fan was then turned ON and the manikin was allowed to run until steady state conditions for two hours. Ventilation cooling was calculated by subtracting the average OFF steady state power average from the average ON steady state power. 120 minutes of power input at steady state were recorded. The test was then repeated.

The total thermal and vapour resistances of the BVS ensemble were also measured with and without the fan. The total dry thermal resistance was measured on a dry manikin in a 20°C 50%RH environment at wind speeds of 0.4, 1.2 and 2.0 m\textsuperscript{s}\textsuperscript{-1}, following the procedures of ASTM Standard F1291\textsuperscript{3}. The total vapour resistance was measured on a sweating thermal manikin in a 35°C 50%RH environment at the same air speeds, following the procedures of ASTM Standard F2370\textsuperscript{2}.

3. Results

The power inputs to the sweating manikin recorded with the ventilation OFF and ON are displayed in Figure 4. Subtracting the average power input with the fan OFF from the average with it ON results in an average cooling capacity of 45.1W associated with the 9 L\textsuperscript{s}\textsuperscript{-1} of ventilation. Though untested, the cooling capacity would be expected to increase at a lower ambient humidity.

In terms of clothing insulation results, the total dry thermal resistance decreased by a nominal 17% from 0.225 m\textsuperscript{2}\textdegree\textsuperscript{C}\textsuperscript{W}\textsuperscript{-1} at a 1 m\textsuperscript{s}\textsuperscript{-1} wind speed with the fan ON and the total vapour resistance decreased by 20%.
4. Conclusions

Forced ventilation under a heavy, torso body armour increased the evaporation of sweat and its cooling effect by 45 W. This demonstrates the benefit of clothing ventilation as a simple, economical, light weight method to efficiently improve personal cooling in hot environments. The evaluation of clothing ventilation systems cooling potential and insulation parameters using sweating thermal manikins is accurate, time efficient and very repeatable. In addition, manikin testing reduces the cost and health risks of human testing.

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References
Section V
Development of Manikins
Current Development of Thermal Sweating Manikins at Empa

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Abstract

Over the past two decades, Empa has developed heated sweating body parts and a whole-body sweating thermal manikin (Sweating Agile thermal Manikin, SAM). These manikins are used in clothing research to measure the insulation and water vapour resistance of clothing under steady-state conditions as well as to study the effects of clothing, wind, posture, body movement and climate on the local heat flux from different areas of the body.

At present, two sweating manikins are being developed further to enable the thermo-physiological behaviour of the human to be simulated. This is being achieved by coupling the control software of each sweating manikin to a multi-node thermo-physiological model. The first manikin being coupled is the heated sweating cylinder which is designed to simulate the torso of an adult human. Good agreement between initial results from the coupled torso and human thermal responses is observed.

Work is now in progress to achieve a similar coupling to the more sophisticated Sweating Agile thermal Manikin SAM using the same physiological model. In order to achieve this goal, further development to optimise and extend the control of SAM is being carried out in parallel.
1. Introduction

Determination of the wear comfort and protective properties of clothing is one of the main focuses of the Laboratory for Protection and Physiology at Empa. This is facilitated by investigating the transport of body heat and sweat through clothing under steady-state and dynamic conditions, which includes determination of the dry and wet thermal insulation and evaporative resistance of individual clothing layers and complete clothing systems. The term wet thermal insulation refers here to the total thermal insulation when sweating. To this end a series of thermal manikins have been developed to simulate the heat and moisture production of the human body and parts of the body. These manikins are listed chronologically in Table 1, according to when they were first taken into operation. Also the number of separately-heated segments, the physical clothing properties measured and references to previous publications are indicated.

<table>
<thead>
<tr>
<th>Manikin</th>
<th>Operation al since</th>
<th>Segments</th>
<th>Physical properties measured</th>
<th>References / Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweating guarded hot plate</td>
<td>1985</td>
<td>2</td>
<td>Dry thermal insulation and water vapour resistance of single and multiple horizontal layers</td>
<td>(EN 31092/ISO 11092, 1993)</td>
</tr>
<tr>
<td>Heated hand</td>
<td>1989</td>
<td>1</td>
<td>Dry thermal insulation of gloves</td>
<td></td>
</tr>
<tr>
<td>Sweating arm (with 90° movement of lower arm)</td>
<td>1993</td>
<td>5</td>
<td>Dry thermal insulation and water vapour resistance of sleeves without / with lower arm movement</td>
<td>(Weder et al., 1995)</td>
</tr>
<tr>
<td>Torso (Cylinder representing a ¼ of the total adult body surface)</td>
<td>1995</td>
<td>3</td>
<td>Dry and wet thermal insulation of bedding and upper body garments</td>
<td>(Zimmerli and Weder, 1996)</td>
</tr>
<tr>
<td>Sweating head ALEX</td>
<td>1999</td>
<td>3</td>
<td>Dry and wet thermal insulation of helmets</td>
<td>(Brühwiler, 2003)</td>
</tr>
<tr>
<td>SAM (Sweating Agile thermal whole-body Manikin)</td>
<td>2001</td>
<td>30</td>
<td>Dry and wet thermal insulation and evaporative resistance of complete clothing systems without / with body movement</td>
<td>e.g. (Richards and Mattie, 2001a) / (ISO/FDIS 15831, 2003; ASTM F 1868-02, 2005)</td>
</tr>
</tbody>
</table>

Table 1: Development of heated sweating body parts and a whole-body manikin
All of these systems have been in operation for five or more years. They have proven to be reliable instruments with little need for maintenance. During a series of measurements each manikin is left on, heated at a controlled temperature between experiments to enable steady-state conditions to be regained quickly following change of clothing and/or conditions.

This paper presents an overview of some of the work presently being undertaken to advance two of the above manikins, namely Torso and SAM. Presently the control software for these two systems is being coupled to a multi-node model of the human thermal system. Conceptually similar work led to the development of a manikin specifically designed with thermo-physiological control in mind (Burke and McGuffin, 2001). The present work presents the results of an alternative strategy of modifying existing thermal manikins to gain such control.

2. Modelling Work

Heat loss and thermal comfort of the human body are dependent on many factors, including the clothing being worn. The evaporation of sweat is an important means of body heat loss when a person is physically active or in a hot environment. Consequently, most heat budget models and thermal comfort indices require values of the thermal insulation and evaporative resistance of clothing. To determine these values accurately for manufactured clothing ensembles, life-sized thermal manikins must be used (Richards and McCullough, 2005).

An alternative approach, which can enable the thermo-physiological response of the human to be predicted more accurately under defined conditions, is to use a multi-node model of the human thermal system e.g. (Fiala et al., 2001; Huizenga et al., 2001; Stolwijk, 1971; Tanabe et al., 2002; Wissler, 1985).

One of the most advanced of these models which Empa has compared with human subject trials is the IESD-Fiala model (Fiala et al., 1999; Fiala et al., 2001). Validation work, presented at the previous manikin meeting 513M, demonstrated the predictive accuracy of the IESD-Fiala model for fire-fighters under hot stressful conditions (Richards and Fiala, 2004). For this work, the physiological responses of fire-fighters to exercise and asymmetric infrared-radiation were investigated at Empa (Richards, 2000). SAM was used to measure the thermal insulation and evaporative resistance of the different fire-fighting clothing worn. These values were input into the IESD-Fiala model, and the dynamic thermo-physiological behaviour of the fire-fighters was predicted. The predicted physiological responses generally agreed well with the wear trial data.

As part of the ongoing validation of the IESD-Fiala model, predicted responses are now being compared with a large range of human data under normal and extreme conditions within COST action 730 (www.utci.org) in which a Universal Thermal Climate Index is being developed.
3. Sweating Heated TORSO

The sweating heated TORSO (Zimmerli and Weder, 1996) consists of a cylinder with outer diameter of 30cm, divided into two guard sectors at the ends and a measurement section in the middle. Each sector is controlled with either constant temperature or constant power. Water used to simulate sweat is supplied at a controlled rate through 54 sweat outlets distributed over the surface of the measurement sector. When operated under constant power mode, the surface temperatures of the guards follow the surface temperature of the measurement cylinder to minimise the lateral heat exchange between guards and measurement cylinder.

4. Coupling the TORSO to the IESD-Fiala Model

Our goal in coupling the control software of the TORSO to the IESD-Fiala model is to simulate the thermo-physiological behaviour of the human in real time. At present the Torso surface temperature and sweat rate are controlled with the mean skin temperature and sweat rate of the whole human body, respectively. Forthwith this coupled system is referred to as the Fiala-Torso.

One example of the initial results of coupling the Fiala-Torso system is shown in Fig. 1. The simulated mean skin temperature actually followed by the Fiala-Torso system is compared to that determined under cool exposure using subjects (Wagner and Horvath, 1985). The experimental conditions under both the simulation and the human experiments were an ambient temperature of 20°C, relative humidity (rh) of 40%, air velocity of 0.1m/s and metabolic rate of 55 W/m². For the human experiments, only briefs were worn (0.216 clo) whereas the Fiala-Torso was unclothed.

![Figure 1 Initial results of the Fiala-Torso system response compared to the mean human response](image_url)

Generally very good agreement is seen between the Fiala-Torso system and human results. During the first half-hour of exposure, the human demonstrates a cooler...
mean skin temperature than the Torso. This initial discrepancy is due to the fact that under these conditions, the human skin cools down very rapidly (Wagner and Horvath, 1985) whereas the Torso responds more slowly due to the thermal mass of the shell part materials. Nevertheless, after this initial period the Torso surface temperature catches up with the true average human response. This cooling response is faster than for a human exercising and/or wearing more clothes and the authors expect that under warmer conditions or with more clothing less discrepancy shall be observed.

5. Preparations to couple SAM to the IESD-Fiala model

Work is now in progress to couple the model to SAM. The Sweating Agile thermal Manikin (SAM) has 26 separately-heated body sectors, 125 sweat outlets and is capable of performing realistic body movements (Richards and Mattle, 2001b). This manikin provides detailed information about the clothing worn, dependent on the climate and sweat rate used. The climatic chamber used provides a well-controlled environment with a wide range of temperatures (-30 to 40°C), humidities (20 to 90% rh) and wind speeds (0.2 to 40 m/s). For standard operation, the surface temperature is controlled homogeneously at 34.0 ±0.1°C. With the model coupled to SAM, the local skin temperatures shall be controlled heterogeneously according to the model.

The present 36 internal sweat-distribution valves are to be replaced with 144, so that each sweat outlet shall have its own dedicated valve. Also the hands and feet, which are presently non-sweating and used as heat guards for the limbs, shall gain sweat outlets and thus the ability to sweat. This shall be a significant advancement, as these body parts are very important in the thermal regulation of the human. Furthermore, it is proposed to replace the present shell parts of SAM with new shell parts (under development) better suited to thermo-physiological control.

6. Conclusions

In addition to measurements of physical properties of clothing materials and the possibility of using these properties to simulate the human response indirectly, the thermo-physiological response (mean skin temperature and mean sweat rate) of the human can now be simulated directly using the sweating cylinder Torso. During next year it is planned to be able to simulate the thermo-physiological response of the human directly in more detail (local skin temperature and local sweat rate) using SAM for a given clothing and climate.

Acknowledgements

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Research (SBF/SER) for funding the latter part of this work as part of COST action 730 under project C06.0023.

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How to Build and Use a Virtual Thermal Manikin Based on Real Manikin Methods

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Abstract

It has always been valuable to be able to make early decisions in thermal climate investigations. The development of virtual thermal manikins (VTM) and computer simulated persons (CSP) has become an important complement to traditional evaluation of the thermal environment. This paper describes how to build a VTM within a commercial computational fluid dynamics code (CFD). The methods are based on human experiments and real thermal manikin measurements.

Unfortunately, too few of the theories behind thermal manikin simulations are available in the public domain. Many researchers and companies still use several in-house codes for all or essential parts of their calculations. This paper provides information on how to build the geometry of the manikin in three different commercial CFD codes (CFX®, Star-CD® and Fluent®). More information and descriptions are also given on how to connect the VTM to the CFD calculations and make the system interact in real time throughout the full iteration process.
The level of thermal comfort is highly dependent on the local environment. Human beings respond differently to local heat exchange in different parts of their bodies. It is therefore suggested that results from manikins should be presented in clothing independent comfort zone diagrams. The results are consequently presented not only as whole body mean influence, but also as local information on how the thermal climate varies over the human body. The main idea is to focus on people. It is the comfort requirements of occupants that decide what temperature and what airflow will prevail. It is therefore important to use comfort assessment methods that originate from people, not just temperatures on surfaces and air.

1. Introduction

Early numerical manikins, for assessment of indoor thermal comfort, were made with a mostly rectangular geometry. Some of the models where calculating whole body indices others were used to evaluate personal exposure to a contaminant source in a velocity field. The numerical manikin heat flux was often fixed (Gan, 1994, Brohus et. al. 1996 and Kato et. al. 1996). Later the manikins became more detailed. The modelling also becomes more advanced, with physiological modelling of the different thermal transport processes and by simulating the combined effects of airflow, radiation, moisture transport, etc (Maue et. al. 1997, Murakami et. al. 1997, Currle et. al. 2000 and Bjørn et. al. 2000).

Many of the VTM models today use one code (CFD) to predict the airflow and air temperature distributions and sometimes a second code to calculate the solar load and radiation view factors. These values are later used as boundary condition input for a third code that simulates the occupant with a human physiology model. The human physiology model computes the surface temperatures of the simulated occupant and sends these back to the CFD code so that the flow and temperatures can be recomputed again. This exchange of data occurs many times during the full analysis (Huizenga et. al. 2001, Tanabe et. al. 2002, Buxton et. al. 2003 and Huang et. al. 2005).
The VTM described in this paper (Nilsson, 2004) is built with an active heat flow interface to the CFD code. This method uses much less time for calculations and does not need grid refinement or the use of special wall functions, two factors that significantly speed up the working and iteration process. The surface temperature of this numerical thermal manikin is actively regulated during the iteration of the fluid domain, using the adaptive boundary conditions. Another feature are the virtual calibrations made to get the right computational equivalent temperature heat transfer coefficient.

<table>
<thead>
<tr>
<th>Zones</th>
<th>No</th>
<th>Name</th>
<th>A (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Scalp</td>
<td>0.100</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Face</td>
<td>0.080</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Chest</td>
<td>0.225</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>BackU</td>
<td>0.065</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>ArmLU</td>
<td>0.065</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>ArmRU</td>
<td>0.065</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>ArmLL</td>
<td>0.070</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>ArmRL</td>
<td>0.070</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>HandL</td>
<td>0.035</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>HandR</td>
<td>0.035</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>ThighL</td>
<td>0.140</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>ThighR</td>
<td>0.140</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>CalfL</td>
<td>0.080</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>CalfR</td>
<td>0.080</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>FootL</td>
<td>0.070</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>FootR</td>
<td>0.070</td>
</tr>
<tr>
<td>17</td>
<td>17</td>
<td>BackL</td>
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<tr>
<td>18</td>
<td>18</td>
<td>Seat</td>
<td>0.095</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1.605</td>
</tr>
</tbody>
</table>

Table 1.1 L= Left, R= Right, U= Upper, L= Lower.

Figure 1.1 The zone area

2. Building the VTM – pre processing

Today several commercial CFD codes are available on the open market. Building a VTM requires some kind of user programming possibilities. This leaves the choice of code to basically three major CFD packages; FLUENT® (Fluent Inc. 2004), STAR-CD® (Computational Dynamics, 2001) and CFX® (Ansys Inc. 2000). These three suites are all quite similar.

First they all use a pre-processor to set up the problem (FLUENT-Gambit, STAR-CD-Prostar and CFX-Build). This program contains tools for creating the computational mesh to represent the flow domain, as well as specifying the
thermophysical properties of the fluid. It also specifies the different boundary conditions and finally writes all of this to appropriate data files.

They secondly have a *flow analysis* part (FLUENT-Fluent, STAR-CD-Star and CFX-Solver). This code consists of means for reading the input data previously created and also ways for judging the quality of the progress of the run by monitoring and analysing various output data and solution statistics.

Finally they have a *post-processing* part to visualise and analyse the calculated results (FLUENT-Fluent, Star-CD-Prostar and CFX-Visualise). This involves the display and manipulation of output data created by the flow analysing code, using facilities for a multitude of different plot options with vectors, fields and tracks as well as movies. This work reported here has been done with CFX v5.4, Star-CD v3.100B and Fluent v6.2.9.

2.1 **Design and dimensions of the VTM using the pre-processor**

This VTM is formed with the same size, areas and number of zones as real manikins. It does not have the highest detail in body shape reconstruction. However, it is found that the most important factor is to have the body parts at the same position. The VTM corresponds well with real manikins in that respect. The way the surface temperature of the VTM is regulated/calculated, with the use of prescribed boundary conditions to the first grid cell, also makes the interface between the VTM and the air a little bit fuzzy. This fact evens out the geometrical shape differences. Moreover, a manikin with thousands of patches uses considerably more computer power to calculate the equivalent temperatures, a fact that has to be avoided in real life. In order to build your own manikin download macro or journal files for CFX®, Star-CD® and Fluent® from the Thermal Manikin Network site (Nilsson, 1999) choose Virtual Thermal Manikins.

2.2 **Clothed manikin heat transfer model**

The near surface flow field around a heated body is characterised by a combination of natural, free and forced convection. The restricted validity of the heat transfer models often used originates from the assumptions that have been made to solve special boundary layer flows, for instance in pipes. One way of achieving adapted convective heat transfer is to adjust the node distance in the grid layout in order to get the same convective heat transfer as in a test case. Another way is to adjust the thermal conductivity or the dynamic viscosity at the first grid cell to achieve a similar result. A higher conductivity increases the heat transfer indirectly. Both these methods unfortunately result in a “catch-22” situation. You want to make a simulation before measurements but have no measured data to run the simulation.

In the method described here the homogeneous climate at three different temperatures (19, 24 and 28 °C) are used to develop convective heat transfer functions between the manikin and the environment. Normally when convective
(\(q'^c\)) and radiative (\(q'^r\)) heat transfer modes are present simultaneously, the total zone heat flux (\(q'^T\)) is the sum of components:

\[
q'^T = q'^c + q'^r = f_{cl} \cdot h_c \cdot (t_{cl} - t_a) + f_{cl} \cdot h_r \cdot (t_{cl} - t_r) = h_{cal} \cdot (t_s - t_{eq}) \quad \text{[Equation 2.1]}
\]

Where:
- \(q'^T\) Total heat transfer (W/m\(^2\))
- \(q'^c\) Convective heat transfer (W/m\(^2\))
- \(q'^r\) Radiative heat transfer (W/m\(^2\))
- \(h_c\) Convective heat transfer coefficient (W/m\(^2\)K)
- \(h_r\) Radiative heat transfer coefficient (W/m\(^2\)K)
- \(h_{cal}\) Calibration heat transfer coefficient (W/m\(^2\)K)
- \(t_a\) Ambient air (adjacent fluid) temperature (°C)
- \(t_r\) Mean radiant temperature (°C)
- \(t_s\) Manikin surface temperature (°C)
- \(t_{eq}\) Equivalent temperature (°C)
- \(A_u\) Surface area unclothed manikin (m\(^2\))
- \(A_{cl}\) Surface area clothed manikin (m\(^2\))
- \(f_{cl}\) Clothing area factor, \(A_{cl}/A_u\) (n.d.)

The clothing area factor (ISO 9920, 1995) is defined as the surface area of the clothed body divided by the area of the unclothed body. The convective heat transfer coefficient \(h_c\) determining the heat flow between the wall and the ambience is given by:

\[
h_c = \frac{q'^c}{f_{cl} \cdot (t_{cl} - t_a)} = A \cdot v_a + C \cdot (t_{cl} - t_a) + D \quad \text{[Equation 2.2]}
\]

Where:
- \(A\) Seated, constant from Silva et al. 2002 (W/m\(^2\)K)
- \(C, D\) Seated, constants from unclothed calibration (@ 19, 24, 28(°C)) (W/m\(^2\)K)
- \(v_a\) Air velocity (m/s)
Regulated “active” manikin heat transfer interface

In order to get good results from the numerical simulation, the knowledge of the wall heat transfer from the calibrations with no clothes are used. Modified wall boundary conditions during the iteration procedure are then introduced in the CFD calculations with the results of the flow field as input. Subroutines for calculation of new surface temperature of the VTM can subsequently be written, calculating new surface temperatures depending on the present heat flow from each of the zones of the manikin (Figure 2.1).
C**************************************************************
C Regulated "active" manikin heat transfer interface
C Code example in FORTRAN 77 by Håkan O. Nilsson
C**************************************************************
C U(I,J) I-th Cartesian velocity component in cell
ICLMAP(J)(m/s).
C T(I,1) Temperature in cell ICLMAP(I) (K)
C A, B SEATED, Silva et. al. 2002
C C, D SEATED, Nilsson Calibration @19,24,28(C)
C FCLR SEATED, (ND) Ar/AD, de Dear et. al. 1997
C FCLC SEATED, (ND) Nilsson Calibration Winter/Summer @21,25(C)
C RCL SEATED, (m2K/W) Nilsson Calibration Winter/Summer
@21,25 (C)
C HTEQ SEATED, (W/m2K) Nilsson Calibration Winter/Summer
@21/25 (C)
C HCAL SEATED, (W/m2K) Virtual Calibration, Saved as HTEQ
C E Emissivity (ND)
C S Stefan-Bolzmann constant (W/(m2K4)
C TS Virtual thermal manikin surface temperature (K)
C----- Iteration for TCL (C)
WHILE (TCL(IR).GE.(TS-RCL(IR)*QT(IR)))
IF (TCL(IR).GE.(TS-RCL(IR)*QT(IR))) THEN
TCL(IR)=TCL(IR)-0.01
ELSE
TCL(IR)=TCL(IR)+0.01
ENDIF
B=C(IR)*(TCL(IR)-TA(H(IR)))+D(IR)
HC(IR)=A(IR)*VA(H(IR))+B
HR(IR)=4*E*S*FCLR(IR)*((273.15+(TCL(IR)+TR(H(IR)))/2)**3
QT(IR)=FCLC(IR)*(HC(IR)*(TCL(IR)-TA(H(IR)))+
&HR(IR)*(TCL(IR)-TR(H(IR))))
TEQ(IR)=TS-QT(IR)/HTEQ(IR)
HCAL(IR)=QT(IR)/(TS-TA(H(IR)))
ENDDO
90 CONTINUE
C----- New manikin surface temperature (C) calculated for all regions
IF(LEVEL.EQ.2) THEN
C----- Called at the END of each iteration
OPEN(87,FILE='CFDout.tab', STATUS='unknown')
WRITE(87,*) 'ITER  IREG  HEIGHT  Va  Ta  Tr
&Tcl  QT  Hc  Hr  (Hcal) Teq'
DO 100 R=1,18
WRITE(87,200) ITER,R,H(R),VA(H(R)),TA(H(R)),TR(H(R)),
&TCL(R),QT(R),HC(R),HR(R),HCAL(R),TEQ(R)
100 CONTINUE
200 FORMAT(3I4,F6.3,8F7.2)
C----- Rewrite OUT file
CLOSE(87)
C----- Open and write new values to TCL file
OPEN(88,FILE='tcl.dat',STATUS='unknown')
DO 110 IR=1,18
WRITE(88,*) TCL(IR)
110 CONTINUE
C----- Rewrite TCL file
CLOSE (88)
ENDIF
RETURN
END

Figure 2.1 The subroutine calculates and saves new manikin boundary data every iteration
2.4 The virtual $t_{eq}$-calibration

In a similar manner as with the full-scale manikin heat transfer coefficient calibration ("$t_{eq}$-calibration"), the VTM also needs adjustment of the heat transfer coefficients. The method is based on the fact that the equivalent temperature is defined to be the temperature of a room with air temperature ($t_a$) equal to mean radiant temperature ($\bar{t}_r$, usually 21 or 24°C) and low air velocity ($v_a$, normally about 0.03 m/s). The heat transfer coefficient in the homogeneous environment is given by the following relationships:

$$h_{cal} = \frac{q_{T,cal}''}{(t_s - t_a)} \quad \text{[Equation 2.3]}$$

which gives in the simulated environment ($h_{cal}$ saved as $h_{eq}$)

$$t_{eq} = t_s - \frac{q_{T,cal}''}{h_{eq}} \quad \text{[Equation 2.4]}$$

Where:

- $q_{T,cal}''$: Calculated manikin heat loss during the actual conditions (W/m$^2$)
- $q_{T,cal}''$: Dry heat loss for the homogenous, standard environment (W/m$^2$)
- $h_{cal}$: Dry heat transfer coefficient, determined in a standard environment (W/m$^2$K)
- $t_s$: Manikin surface temperature (°C)
- $t_{eq}$: Equivalent temperature of the uniform, homogenous environment. (°C)

The virtual calibration is carried out with the computational VTM positioned a fictitious calibration chamber with the dimensions of 2 x 2 x 2 m. The incoming air at 0.03 m/s is entering through the floor, except right under the manikin (centred 0.7 x 0.95 m, 0.5 m from the back wall), and exits through the full roof area. This arrangement gives an ideal calibration environment, where the heat from the manikin is removed swiftly, with as little as possible influence on the calibration itself. The sensors are always positioned at the specified levels (0.1, 0.6, and 1.1 m) to the right of the VTM.
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<table>
<thead>
<tr>
<th>Heat transfer coefficients</th>
<th>((h_{cal} = h_{eq}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W/m²K)</td>
<td>s w s w</td>
</tr>
<tr>
<td>Zone</td>
<td>real real cfd cfd</td>
</tr>
<tr>
<td>Scalp</td>
<td>3.49 3.78 3.47 3.71</td>
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<tr>
<td>Face</td>
<td>8.25 8.19 8.12 8.12</td>
</tr>
<tr>
<td>Chest</td>
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<tr>
<td>BackU</td>
<td>5.79 3.4 5.38 3.35</td>
</tr>
<tr>
<td>ArmLU</td>
<td>4.26 2.37 4.23 2.34</td>
</tr>
<tr>
<td>ArmRU</td>
<td>4.69 2.44 4.31 2.39</td>
</tr>
<tr>
<td>ArmLL</td>
<td>5.22 3.47 5.12 3.4</td>
</tr>
<tr>
<td>ArmRL</td>
<td>5.13 3.4 4.96 3.33</td>
</tr>
<tr>
<td>HandL</td>
<td>8.6 6.98 8.35 6.87</td>
</tr>
<tr>
<td>HandR</td>
<td>8.49 6.7 8.62 6.62</td>
</tr>
<tr>
<td>ThighL</td>
<td>4.96 4.71 4.8 4.6</td>
</tr>
<tr>
<td>ThighR</td>
<td>4.82 4.76 4.76 4.65</td>
</tr>
<tr>
<td>CalfL</td>
<td>5.11 4.98 4.92 4.88</td>
</tr>
<tr>
<td>CalfR</td>
<td>4.83 4.9 4.82 4.8</td>
</tr>
<tr>
<td>FootL</td>
<td>3.63 4.32 3.73 4.24</td>
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<tr>
<td>FootR</td>
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<tr>
<td>BackL</td>
<td>3.11 2.44 3.24 2.38</td>
</tr>
<tr>
<td>Seat</td>
<td>4.59 5.05 4.56 4.94</td>
</tr>
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</table>

Table 2.2 The heat transfer coefficient in the different environments. real = measured with the real manikins, cfd = calculated with CFD simulated data input.

Figure 2.2 The VTM and three sensors inside the virtual calibration cube.

These calibrations are subsequently made in order to get the right computational \(h_{cal}\) for the simulations. The calibrations made are the situations when the VTM is clothed in the same clothing that was used with the real manikins. Results from calibrations with summer (s) and winter (w) clothing show very consistent results as shown in table 2.2.

3. Modelling the environment – flow analysis

In order to design a comfortable indoor environment with the virtual manikin, it is important to get relevant input data of the airflow pattern, velocity, and temperature around the VTM. The majority of flows in the indoor environment are turbulent. Unfortunately no turbulence model exists for general use. Every model must be employed with care and its results treated with caution (Sørensen et al., 2003). When the details of the turbulence are not so important, rather the general mixing behaviour, then it is often possible to use a constant turbulent (eddy) viscosity \(\mu_t\) instead of the molecular viscosity (Nielsen, 1998). This turbulence model is called the zero-equation model and uses a constant or an algebraic function to express the turbulent viscosity. It does not require the solution of any additional differential equations beyond the Navier-Stokes equations. This turbulence model calculates the turbulent viscosity empirically by:
\[ \mu_t = 0.04 \cdot \rho \cdot u_0 \cdot H \]  

[Equation 3.1]

Where:
- \( \mu_t \)  Turbulent (eddy) viscosity (Pa s)
- \( \rho \)  Fluid density (kg/m\(^3\))
- \( u_0 \)  Characteristic velocity, inlet velocity (m/s)
- \( H \)  Characteristic length, inlet min length (m)

The length scale is a characteristic length; in this paper the case specific min length of the inlet is used. In the same way the inlet velocity is used as the characteristic velocity for each case. The empirical constant suitable for different indoor airflows is a number around 0.040. This model is often sufficient for predicting the total characteristic of a turbulent flow; it may not always be appropriate for predicting local details. One benefit of this method is that the time used for calculations with the zero-equation model is much less compared to the more complicated models. Furthermore the use of this turbulence model does not need grid refinement a factor that significantly speeds up the working process. Consequently the computer power needed to calculate indoor airflow is less and can be realised in real time with a personal computer.

The modelling has steady state characteristics and is aimed at the assessment of human thermal comfort. Under-relaxation is used in the iterative steady-flow calculations with SIMPLE (Semi-Implicit Method for Pressure Linked Equations) solution algorithms. Second order discretisation schemes are used in all these calculations. Due to the buoyant flows involved the correction term for the buoyancy force is applied. No grid adaptation is used, as this mostly increases the number of cells and hence the calculation time.

Figure 3.1 The computational manikin positioned in the simulated flow, radiation and temperature field.
4. Examining the results – post processing

In order to make the local comfort evaluation clothing independent, the construction of new comfort zone diagrams have been made by inserting any seated total insulation available. Equation 4.1 shows how a relationship between the equivalent temperature level and MTV can be established for each manikin body part. The heat loss corresponding to a certain level of comfort, or discomfort, in the diagram is consequently considered to be the same. The shape of the zones is, however, changed according to the clothing used.

\[ t_{eq,\text{zone}} = t_s - R_T \cdot (a + b \cdot MTV_{\text{zone}}) \]  

[Equation 4.1]

Where:

- \( t_{eq,\text{zone}} \): Equivalent temperature in the zone [°C]
- \( t_s \): Manikin surface temperature (here 34°C) [°C]
- \( R_T \): Total insulation, seated [m²K/W]
- \( a, b \): Linear regression constants [W/m²]
- \( MTV_{\text{zone}} \): Mean Thermal Vote in the zone [n.d.]

The equation is valid for an interval of seated whole body total insulation (\( I_T \)) between 0.9 and 1.9 clo. With equation 4.1 it is for the first time possible to make a comfort zone diagram (Figure 4.1) that applies to a specific clothing combination used in a given situation. Now \( t_{eq,\text{zone}} \) can be calculated for the four borders of the three shaded comfort zones (blue – green – red) for all zones and the whole body. The result, plotted in a diagram, forms the evaluation background in the clothing independent comfort zone diagram. This is only done once for each clothing combination, and reflects the insulation distribution of the clothing used. Your own clothing independent comfort zone diagrams are made easily by downloading a MS Excel® spreadsheets from the Thermal Manikin Network site (Nilsson, 1999), select Virtual Thermal Manikins.

4.1 Clothing independent comfort zone diagram evaluation output

These methods are the subject of International Standardisation work “EN ISO 14505, Ergonomics of the thermal environment - Thermal environment in vehicles”. The comfort zone diagrams shown in the figure below refer to summer or winter conditions corresponds to figures D1 and D2 in the proposed standard (prEN ISO 14505-2, 2006).
5. Conclusions

Comfort votes from subjective panels and measurements with full-scale thermal manikins have been used to develop a new type of virtual thermal manikin (VTM) actively connected to CFD simulations. The surface temperature of the computational manikin is regulated continuously through the iteration process. This procedure, together with a new model for virtual calibration, forms the basis of this new numerical manikin concept. These computer simulations as well as measurements are visualised in clothing independent comfort zone diagrams, showing how an average human being would perceive not only the whole body mean but furthermore the local climate situation.

Today CFD calculation methods have developed further and a growing field of research is working to establish the methods for simulation of the human thermal environment. Taking this into account, there are still many unexplained differences in the results within and between simulation methods, pointing out new research areas for CFD-methods. There is consequently a need for continued validation of CFD-results with real life measurements as well as benchmark tests.

6. Acknowledgement

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7. References


Female Torso Mannequins with Skeleton and Soft Tissue for Clothing Pressure Evaluation

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²Department of Mechanical Engineering, Dong Hua University, Shanghai, China

Abstract

The female torso mannequin combines the advantages of live model and dress stand, which are the two methods of evaluating the clothing fit currently. In our study, several soft mannequins have been developed with full torso dimensions of real female models. Each mannequin contains a full-size bone skeleton and imitation soft tissue and skin. The Young’s modulus of the soft mannequin falls within the range of the Young’s moduli of different body toros parts of 20 female subjects. Since a skeleton is placed inside the mould, the foam thickness at various parts of the mannequin is similar to the thickness of human soft tissue. Test results also showed that the pressure values measured from the subject are highly correlated with those obtained from the mannequin.

The size and shape of the live model was measured by a TecMath 3D body scanner. From the 3D data file, a mould of the mannequin has been developed with the same dimension as the human model. The novel feature of the proposed mannequin is that the mechanical structure and material simulate the composition of the human female body with various sizes of breasts and abdomen. Attached to the chest region is an adapter, through which different cup sizes of breasts can be exchanged.

The soft mannequin can be applied as a novel tool for evaluating the realistic performance of clothing fit on a human body. It is immediately useful for foundation garments, such as panty girdle, bra and medical pressure garment. Using the soft mannequin, clothing fit and pressure measurement will be more standardized, accurate, reliable, consistent and less costly.
1. Introduction

The pattern development and assessment of fit in the apparel industry always represents a difficult and complex process. It is a fact that designer, pattern maker and customers may have different perceptions and tools in assessing fit. When a technical designer translates the conceptual fashion sketches to real body measurements, a live model having a representative figure of the target size group is hired and used in wear trials for fit assessment. However, the sizes and shapes of such models only approximately match the industrial size chart whereas those with exactly matching figures are rarely available. As a result, a dress stand is commonly used as a tool for pattern development and garment fitting. This paper reviews the deficiencies of the live model and dress stand, and then proposes new methods to develop a soft mannequin that works more effectively, particularly for intimate apparel fitting.

2. Live models

When using a live model in garment fitting, the designer needs to understand the measurement discrepancy of the model and adjust the pattern accordingly. As the live model breathes and moves, her body postures affect how the garment fits. Moreover, the live models have psychological mood changes which can also affect their comments on fit and comfort. Even professional models cannot control their own body size and shape over time. In most cases, they usually work for different employers in fre-lance basis. Hence, their availability is sometimes uncertain and limited. Particularly in the intimate apparel industry, it is very difficult to get a female subject having the specified size and who is willing to work as a live model due to the associated embarrassment. As Hong Kong manufacturers produce apparel products mainly for the US and European markets, the required large-size models are even harder to recruit. While manufacturers are working on the basis of imagination and experience without an accurate model to test the fit, communication among the supply-chain partners becomes very inefficient and ineffective.

3. Dress stands

As an alternative to a live model, a dress stand is commonly used for garment fit assessment. Traditionally, the shape of the mannequin is developed by a gypsum sculpture. Any amendments are done by hand. Once the size and shape are approved, the prototype is transferred to a metallic mould for the manufacture of the core rigid body using glass fibre or expanded polystyrene (EPS). Then it could be lined with cotton, linen or wool fabric to protect the surface. To reduce the weight, polyurethane (PU) foam might be used for the padding.

Since the apparel designers would use pins to fix the fabric on the mannequin during product development and evaluation process, padding with a minimum thickness of 5mm needs to be attached to the mannequin surface. When the garment sample is on the mannequin, designers can amend the poorly fitting areas by adding or removing
ease, pivoting or adjusting the darts, using scissors and pins. Then the pattern will be revised based on some erasable markings. However, these conventional dress stands are expensive, the dimension and softness are hardly reproducible, become soiled and damaged easily, heavy to transport, and in some cases not good for pinning.

It was believed that national size surveys were crucial in the development of sizing standards. Mannequins should be made to achieve the proportions of the key measurements. Liu et al. compared the popular mannequin with the China National Standard of garment sizing system GB/T 1335.1 and found that the mannequin’s back is too thick and too straight. In addition, its back curvature is too sharp vertically but insufficient horizontally. Proportions of shoulder width, neck girth, hip girth and bust girth are also incorrect. The China population is divided into A, B and Y shapes, but only A-shape mannequins are available in the market.

Indeed, for any individual brand, a specific size chart is developed for the target group of customers. The national sizing standard may be considered as a reference rather than the absolute. Industrialists measure their models in determining the size and shape of their unique mannequins. As the mannequin is developed manually based on a set of linear measurements and designer’s perception, it is hard to get two mannequins made consistently with an accurate size and shape. Manufacturers tend to do their own patching and padding on the mannequin to achieve the shape required by the buyers. Certainly, anthropometric details are not easily obtained by sculpture and patching. Therefore, standardisation of mannequins is vitally important to ensure that the buyers and manufacturers assess fit using the same tool.

Sophisticated body scanning technologies are now available for obtaining detailed 3D dimensions of a model for fitting. Alvanon uses a body scanning technique to capture the spatial data of a live model, transforms it to a polyfoam prototype and finally to the fibre-glass form of a mannequin covered with linen cloth. Tukatech also uses laser body scanners to capture the 3D image of the customer’s models. The data is then modified to the acquired 3D geometry. Once approved, the data file is used to machine a prototype form by milling. This stage allows for discrete shaping and sculpting as requested by the clients. In both cases, shape modification and approval are quite time consuming before creating a metallic mould for the production of a durable and repeatable mannequin.

4. Development of 3D soft mannequins

Over the years, industrialists and researchers have desired to develop a mannequin with the softness of the human soft tissue. Earlier developments of soft mannequin were mainly from Japan. The first patent relevant to soft mannequin was published in 1975. For the simulation of human soft tissue, 10-35% ethylene-vinyl acetate copolymeric with an elastic modulus of 500 – 10 kg/cm², was used. However, such material was too rubbery to maintain the right shape of the form. A more rigid layer, having a Young’s modulus of 2000 to 50000 kg/cm², was used in the cavity of the mannequin.
Section V: Development of Manikins

To simulate the human body, a 4-layered mannequin was invented in 1999, using elastic outer skin, soft body wall, hard body core and soft breasts in the structure. The resilience was achieved by elastic gel materials with a specific ratio of OH/NCO functional groups in the polymer mixtures. The outer skin is silicone having a thickness of 50-500μm and torsional rigidity of 100-1100kgf/cm². The elastic gel had a modulus of 250-750g/cm² for the body wall and 50-350g/cm² for the breasts. This material was formed by reacting an alkylene oxide chain-containing polyol liquid at a normal temperature, that create an organic dispersion medium for raising the gel elasticity.

A Japanese patent suggested using the vulcanizing silicone rubber to fabricate the mannequin’s skin by mould casting. Another patent used flexible polyurethane foam for the muscle, and for the skin it used silicone, thermoplastic elastomer, vinyle and flexible urethane. In 2003, Wacoal also developed a soft dummy using silicone for the product evaluation of junior bras.

The above-mentioned mannequins used various types of soft materials with the aim to simulate the human body covered with muscle and skin. Common materials were silicone and polyol, which were heavy. They could achieve a certain degree of softness, yet the realistic range of Young’s modulus of human skin, muscles and breasts were still unclear. The thickness of soft tissues of different body parts were also not considered. The similarity of the soft mannequin and the human model was also not reported.

Starting from 1999, we first attempted to develop a soft mannequin simulating the lower torso of a female subject. The purpose was mainly for the fit assessment of girdle pressure. The mannequin consisted of a fibreglass "skeleton", PU foam "soft tissue" and silicone rubber "skin".

A volunteer underwent a process of medical gesso moulding over her torso from the upper waist to the lower thigh. The 3D body shape obtained, was then cast into a fibreglass -reinforced plastic mould for the manufacture of a “skin mould”. Another mould, 5 mm smaller all-around, was cast as a "tissue mould". The gap between these two moulds were prepared for the manufacture of simulated soft tissue. Firstly, the bone skeleton was fixed inside the tissue mould. Then we mixed the polyol and
additive liquids to a specific weight proportion to achieve the required softness of PU flexible foam to simulate the human soft tissue’s elastic modulus. As the human abdomen is softer than other body parts, a lower density foam material was made for the abdomen area. To hide the foam holes on the surface, silicone rubber was employed to make a smooth skin over the surface of the so-called "soft tissue". After comparing the detailed dimensions of the mannequin with those of the human model, we found that their overall structure and physical dimensions were almost the same.

In 2004, this approach has been further applied to develop a full-torso soft mannequin which is now 'patent pending'xi. The size and shape of a young model of bra size 70B were measured by means of a TecMath 3D body scanner. From the 3D data file, we trimmed the head, limbs and breasts. A prototyping mould was then developed based on a reconstruction of the body cross-sections without the breasts. For the mannequin’s body to mimic the resilient human tissue, we measured the thickness and stiffness of the soft tissue at the breast, waist and hip areas of 20 females using Tissue Ultrasound Palpation System (TUPS). The average Young’s moduli at different body parts were obtained, which facilitate the selection of foam materials that was made within the range of the required Young’s moduli\textsuperscript{xii}. The soft mannequin contains a full-size tailored fit bone skeleton which is placed inside the mould (Figure 2a) with hanging fixture and stand support, before pouring the polyurethane liquid into the mould for the blowing process. Therefore, the foam thickness at various parts of the mannequin is similar to the thickness of human soft tissue. Attached to the chest region is a magnetic adapter, through which different cup sizes of breasts can be attached, detached and position-adjusted. For the surface skin, microfine stretchy fabric was used to develop the skin-garment using the 3D modelling method and to thermoform the breast shape by bullet moulding (Fig. 2b). The overall feel of the mannequin simulates the touch of human skin covering muscles, soft tissues and skeleton. Similar methods have been used to make another soft mannequin of bra size 80B for research purposes.

---

Figure 2  Our development of the soft mannequin

In 2004, this approach has been further applied to develop a full-torso soft mannequin which is now 'patent pending'\textsuperscript{xii}. The size and shape of a young model of bra size 70B were measured by means of a TecMath 3D body scanner. From the 3D data file, we trimmed the head, limbs and breasts. A prototyping mould was then developed based on a reconstruction of the body cross-sections without the breasts. For the mannequin’s body to mimic the resilient human tissue, we measured the thickness and stiffness of the soft tissue at the breast, waist and hip areas of 20 females using Tissue Ultrasound Palpation System (TUPS). The average Young’s moduli at different body parts were obtained, which facilitate the selection of foam materials that was made within the range of the required Young’s moduli\textsuperscript{xii}. The soft mannequin contains a full-size tailored fit bone skeleton which is placed inside the mould (Figure 2a) with hanging fixture and stand support, before pouring the polyurethane liquid into the mould for the blowing process. Therefore, the foam thickness at various parts of the mannequin is similar to the thickness of human soft tissue. Attached to the chest region is a magnetic adapter, through which different cup sizes of breasts can be attached, detached and position-adjusted. For the surface skin, microfine stretchy fabric was used to develop the skin-garment using the 3D modelling method and to thermoform the breast shape by bullet moulding (Fig. 2b). The overall feel of the mannequin simulates the touch of human skin covering muscles, soft tissues and skeleton. Similar methods have been used to make another soft mannequin of bra size 80B for research purposes.
In 2005, a new design of the skeleton was developed for more affordable and versatile use. The widths of shoulder, chest and hip are adjustable so that it saves the time and cost to build tailor-fit skeletons for mannequins of different sizes. In addition, a new way to cover the foam cellular surface was found. We sprayed plastic paint onto the inner surface of the mould, so that the surface of the mannequin is smooth, elastic and pinable (Fig. 2c). The process is easy and it eliminates the need of fabric skin, which requires a high skill to drape the 3D surface, and additional step of fabric moulding.

5. Pressure Evaluation

Up to the present, we have developed five versions of soft mannequins. Test results also showed that the pressure values measured from the subject are highly correlated with those obtained from the mannequin. In 2002, we published the relationship between the pressure obtained from the mannequin and that from the human model, regression equations were established for the prediction of garment pressure at 10 different body positions covered by a panty girdle. A typical example is presented in Fig. 3.

![Figure 3 Relationship between x, pressure on the subject (Ps) and y, pressure on the mannequin (Pm), at point E (Inguinal canal). All units are in mmHg.](image)

In 2005, we conducted pressure tests using the NOVEL pliance-x/E pressure sensing system on 5 commercial girdles worn on the soft mannequin (Fig. 4) and the live model separately. It was found that the pressure trend at 10 different measuring positions on the soft mannequin (Fig. 5) can be useful for the prediction of the pressure sensation on the live model.

![Figure 4 Pressure test of power girdle on the soft mannequin of size 80A](image)
6. Conclusions

For evaluating garment fit, a live model is expensive and varies in size and shape over time. Whereas a dress stand won’t change in shape, it is too rigid for intimate apparel fitting. The proposed female torso mannequin combines the advantages of live model and dress stand, but we have to make it as soft as the human body with various sizes of breasts. Using the soft mannequin, garment fit and pressure measurement will be more standardized, accurate, reliable, consistent and save costs. It is immediately useful for testing foundation garments, such as panty girdle, bra and medical pressure garments. The change of body shape and pressure produced by a garment can be accurately measured by means of the mannequin, which replaces the expensive live model and unrealistic wooden dress stand.

By reducing the subjective perception of the various players in the design and manufacturing process, objective assessment tools and a common yardstick can improve efficiency and reduce the sample development cycle. Brand designers can review the design and fit on the mannequin, compare the body lines and measurements, and then give comments in quantitative format that facilitates communication. Major problems can be identified and interpreted without any confusion. The product development process will be more efficient and effective.

Acknowledgements

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References


Recent Developments and Applications of Sweating Fabric Manikin-“Walter”

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Abstract

Due to its unique features, “Walter” is relatively inexpensive, but achieves high accuracy. This paper reports on the recent improvements on the sweating fabric manikin-“Walter” in terms of hardware and software, further validations of the manikin in terms of reproducibility and relevancy to subjective comfort sensations, as well as its applications in apparel product development and functional clothing testing.

Keywords: sweating, perspiration, manikin, thermal comfort, clothing, environmental ergonomics

1. Introduction

Since the development of the first thermal manikin by the US army during the Second World War, it is estimated that there are now over 100 thermal manikins in the world [Holmer 2004]. Some of the most advanced recent manikins are divided into many sections and the temperature of each section is controlled independently so as to achieve a distribution similar to that of the human skin. Sweating is simulated by supplying water through the tiny tubes to the holes distributed at the manikin surface. Such manikins are very costly due to the complicated control systems for heating and water supply. The simulation of sweating in such manikins is also limited by the practically manageable number of water supplying tubes and holes, which are far fewer than the approximately six million sweating glands on a human. Besides, they are not very accurate because of the difficulty in maintaining consistent sweating and in accurately determining the humidity at the skin surface.
[Fan and Chen 2002]. They also have very different thermal properties to those of a human body.

Inspired by the thermoregulation system of the human body, “Walter” is the first thermal manikin made mainly of water and high strength breathable fabric. Due to its unique features, Walter is relatively inexpensive, but achieves a high accuracy.

2. Key Features of Sweating Manikin-“Walter”

“Walter” consists of the following sub-systems:
- Water circulation system.
- System for the simulation of “Walking” Motion
- Online water supply system.
- Control and measurement system

Figure 1 shows the front view of the standing “Walter”. The main dimension of “Walter” are listed in Table 1.

Table 1: Dimensions of Walter

<p>| | |</p>
<table>
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<tr>
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<tr>
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<tr>
<td>Hip Circumference</td>
<td>100 cm</td>
</tr>
<tr>
<td>Surface Area</td>
<td>1.79 m²</td>
</tr>
</tbody>
</table>

In summary, “Walter” has the following unique features:
- Sweating is simulated by a waterproof, but moisture permeable, fabric 'skin' that holds the water, but allow moisture transmission from the manikin's insides through the millions of tiny pores in the skin.
- Walter simulates human thermal physiology. The core temperature of Walter's body is controlled at 37 °C and the body temperature regulation is achieved by regulating the rate of the pumps which supply warm water from the core region to the extremities.
- Simultaneous heat loss and evaporative water loss from the manikin are measured accurately, hence it takes only one step to measure the two most important parameters - thermal insulation and moisture vapour resistance.
The arms and legs of “Walter” can be motorized to simulate walking motion. The perspiration rate can be regulated by changing the skin temperature and having a fabric skin of different moisture permeability. Since it consists mainly of water, it has a similar weight and heat capacity to a human body, which is also composed mainly of water.

3. Recent Improvements

3.1. DC Pumps for Internal Water Circulation

Just like human body’s blood circulation system, “Walter” has a water circulation system which distributes the heat produced in the core region of the head, arms and legs. Temperatures at extremities depend on the water flow rates into them. The water flow rates can be adjusted by altering the five valves connecting to the head, arms and legs regions and the four small valves at the ends of the legs and arms. The five valves connecting to the head, arms and legs regions should be pre-adjusted, but the four small valves at the ends of the legs and arms can be adjusted during operation. The skin temperature can be further regulated in real time by control software, which adjusts the rate of the pumps. AC pumps were initially used and the pumping rate was regulated by adjusting the AC frequency of the pumps. However it was found that the regulation of the AC frequency could interfere with the signals of temperature measurements and the use of 220V AC pumps causes the safety concerns. Based on such considerations, we replaced the AC pumps with DC pumps, the pumping rate of which can be adjusted by regulating the DC power supply.

3.2. Improved Online Water Supply and Measurement System

The water in the fully filled body of “Walter” maintains the body shape, skin temperature and the water evaporation from the skin of “Walter”. Due to the large amount of water evaporated from “Walter” during its relatively long measurement cycle, an online automatic water supply system is necessary to compensate the water loss from “Walter”, and to keep “Walter” under consistent working conditions. This system is also critical to achieving the online measurement system of “Walter”.

Figure 2 illustrates the original online water supply and measurement system of “Walter”. The water level in the water container is the same as that in the “Walter”’s body at any time because of a siphoning action. Therefore, the water in the water container can automatically flow into “Walter” to compensate the water loss from “Walter”, this amount of water being used to calculate the evaporative rate of water from the skin of “Walter”.
The system illustrated in Fig. 2 still has drawbacks: the water level in the manikin decreases as the water evaporates (although the reduction is small compared with the total height of the manikin) and a calibration equation is required [Qian 2005] to calculate the evaporation rate from the measurement of the electronic balance. An improved system has therefore been developed. The new system, shown in Fig. 3, consists of two water reservoirs: A and B. The water reservoir B is used to maintain a constant water level corresponding to the top of manikin. A separator in the water reservoir B sets the upper limit water level, so that any additional water coming from the water reservoir A through the water pump will lead to an overflow and thus, it will flow back to reservoir A via the tube due to gravity. Apart from flowing back to reservoir A, the water in water reservoir B will also flow to the manikin automatically through tube 3 due to a siphoning action when the manikin is sweating. As a result, the amount of water lost in water reservoir A is equal to the evaporation rate from the manikin. For measuring the changing weight of water reservoir A precisely, tube 1 and 4 must be in a suspension state and have no contact with water reservoir A.

3.3. “Walter” in Seated Posture

“Walter” in a seated posture has also been developed. Details of the development are reported in a separated paper in the proceedings of this conference.

3.4. Software improvements

The PID control has been fine tuned. The manikin can now achieve equilibrium within two hours. This greatly speeds up the measurements. Software called “Walis” has also been developed to predict the comfort level of a wearer in a particular circumstance from the thermal properties of the clothing, which can be measured using “Walter”. This is based on ISO standards, ISO 7730, ISO7933 and ISO11079.
4. Further Validations of “Walter”

4.1. Effect of Water Pressure on the Water Loss from the “Skin”

One question is frequently asked, that is whether the difference in the water pressure between the top and the bottom of the manikin can affect the water vapour transmission through the fabric “skin”. An experiment was therefore conducted to examine this. The experimental setup is shown in Fig. 4. The entire setup was weighed on an electronic balance in a controlled atmosphere of 20 °C and 50% RH. As can be seen from the results shown in Fig. 5, the water loss is linear with time. Or in other words, the reduction of water level in the tube (a measure of water pressure on the fabric “skin” has no effect of water loss from the surface of fabric “skin”.

![Figure 5 Effect of water pressure on water vapour transmission from fabric “skin”](image)

4.2 Inter-laboratory comparison

“Walter” participated in ASTM round robin trial led by McCullough in accordance with F1291- Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin and F2370-Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin. The results are listed in Table I and II. As can be seen, for the nude manikin and when wearing the same fireman uniform, the results from “Walter” are close to the mean values.
Table I: Comparison of thermal insulation values obtained in different labs

<table>
<thead>
<tr>
<th>Labs</th>
<th>( R_{at} ) (Nude) (Clo)</th>
<th>( R_t ) (Clo)</th>
<th>( R_{cl} ) (Clo)</th>
<th>( I_t ) (clo)</th>
<th>( I_{cl} ) (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. TIAx</td>
<td>0.129</td>
<td>0.239</td>
<td>0.133</td>
<td>1.54</td>
<td>0.86</td>
</tr>
<tr>
<td>2. NCTRF</td>
<td>0.083</td>
<td>0.167</td>
<td>0.099</td>
<td>1.08</td>
<td>0.64</td>
</tr>
<tr>
<td>3. ARIEM 1</td>
<td>0.111</td>
<td>0.213</td>
<td>0.122</td>
<td>1.37</td>
<td>0.79</td>
</tr>
<tr>
<td>4. ARIEM 2</td>
<td>0.102</td>
<td>0.202</td>
<td>0.118</td>
<td>1.30</td>
<td>0.76</td>
</tr>
<tr>
<td>5. NCSU</td>
<td>0.083</td>
<td>0.178</td>
<td>0.110</td>
<td>1.15</td>
<td>0.71</td>
</tr>
<tr>
<td>6. KSU</td>
<td>0.104</td>
<td>0.217</td>
<td>0.132</td>
<td>1.40</td>
<td>0.85</td>
</tr>
<tr>
<td>7. HK (Walter)</td>
<td>0.101</td>
<td>0.210</td>
<td>0.127</td>
<td>1.35</td>
<td>0.82</td>
</tr>
</tbody>
</table>

“Walter” has also been used to test the cold protective clothing for a EU project led by Holmer [Gao et al 2006]. The results are comparable to those from other labs, and any differences can be explained.

4.3 Reproducibility over time

The high accuracy and reproducibility of “Walter” have been validated and reported in the past [Fan and Chen 2002, Fan and Qian 2004, Fan 2006]. However, a further concern is that the performance of “Walter” may change over time. In order to examine this issue, the results of the nude manikin tested over last two years are compared and shown in Table III. It can be seen, that for the tests conducted under
the same conditions in January 2005 and September 2006, the results are very reproducible.

Table III: Surface thermal insulation and moisture vapour resistance of the nude manikin tested at different time.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Insulation Rt (m²°C/W)</td>
<td>0.101</td>
<td>0.095</td>
<td>0.101</td>
<td>0.093</td>
</tr>
<tr>
<td>Moisture Vapour Resistance Re (M² Pa/W)</td>
<td>15.4</td>
<td>11.5</td>
<td>13.0</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Note: The test in Sept. 2004 was conducted at 18 °C and 72% RH in a testing lab. The tests in Jan., 2005 and Sept., 2006 were conducted under the same conditions 20 °C and 50% RH in the same Climate Chamber.

5. Some Recent Applications of “Walter”

“Walter” has been used by a garment manufacturer in their product development process to compare the comfort properties of T-shirts having different finishing treatments or materials. In one testing lot, it was found that their Teflon finished cotton T-shirts tended to have lower moisture vapour resistance than cotton T-shirts with nano-care and wrinkle-free finishes. The testing helped them to explore ways to improve the finishing processes.

Another manufacturer has used “Walter” to compare two designs of fireman uniforms. The two designs were the same except for the construction of the insulation layers. The thermal insulation and moisture vapour resistance of the two uniforms as measured on “Walter” were similar. However, the one uniform’s inner layer was dry, whereas that of the other was wet, indicating a difference in the location of moisture accumulation. It is believed that the uniform having the wet inner layer may be less comfortable to wear.

Another example of “Walter’s” application was to compare the performance of two army uniforms, one made of micro-fibre polyamide fabric and the other made of traditional T/C fabric. The results clearly showed that the micro-fibre polyamide uniform was more permeable in terms of moisture transmission.

“Walter” has been used to compare the cooling efficiency of Personal Cooling Garments containing Phase Changing Materials. The increase in the input power to the manikin could be used as a measure of the cooling efficiency of such garments.

Together with Morden Testing Service Ltd, we have also used “Walter” to test the moisture permeability of surgical gowns made from different non-woven fabrics.
REFERENCES


Development of Seated Sweating Thermal Manikin

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Abstract

Nowadays, there are approximately 100 thermal manikins around the world (Holmer 2004). Sweating thermal manikin is a useful tool for obtaining the total clothing thermal insulation value and moisture vapour resistance. Both of the parameters are essential for evaluating thermal comfort of clothing ensembles. However, most of the seated thermal manikins are non sweating. The seated sweating thermal manikins are very scare and expensive. Pass researches indicated that the test results of standing and seated thermal manikin were not same and related to the weight of garments. However, the finding was only based on the test results of non sweating thermal manikin. In this paper, a newly developed low cost seated sweating thermal manikin with direct sweating rate measurement system will be introduced. For testing the accuracy and reproducibility of the manikin, nude state and three clothing ensembles are tested for four times. In addition, the three clothing ensemble also are tested by a standing sweating fabric manikin ‘Walter’ with same conditions and procedures so as to make a comparison.

1. Introduction

Most of the advanced sweating rate measurement systems were developed based on standing manikin and thus, they were not applicable to seated thermal manikin for simulating sweating, especially for the method required to measuring the weight of manikin. In addition, pass researches indicated that the test results of standing and seated thermal manikin were not same and related to the weight of garments. However, the finding was based on the non sweating seated thermal manikin. Therefore, there is significant value to develop a seated sweating thermal manikin with a new sweating rate measurement system to fill the gap.
2. Sweating rate measurement system

2.1. Drawbacks of existing sweating rate measurement system

For measuring the sweating rate of sweating thermal manikin accurately, most of the sweating manikins required to measure the weight of manikin since not all the water supplied to manikin would evaporate through the porosity layer of manikin skin. In fact, the porosity layer under the manikin skin would store a certain amount of water. The manikin ‘Coppelius’ was an example, which can measure the sweating rate accurately by measuring the weight change of water reservoir and manikin. However, the sweating rate calculation method was not applicable to sitting posture as the manikin must be in hanging state for measuring the weight of manikin by an electronic balance. Actually, touching any object other than the electronic balance would make measurement impossible.

Fan and Qian (2004) released a sweating fabric thermal manikin ‘Walter’ which utilized siphon action as a means of real time measurement of sweating rate without the needs of measuring the weight of manikin. This method was accurate, simple and applicable to sitting posture as it did not require measuring the weight of manikin. However, the method still had a room for improvement. The change of the weight of water in the water reservoir is not identical to the water loss of manikin and thus, ‘Walter’ required a coefficient of calibration to calculate the sweating rate.

Apart from measuring the sweating rate, some sweating thermal manikins used cotton or hydrophilic skin with two step measurements for avoiding measuring the sweating rate. The method was based on the assumption of Woodcock (1962) that the dry heat loss and evaporative heat loss were independent of each other and can be measured separately. However, in fact, heat and moisture transfer happened at the same time and would affect each other. The condensation in clothing would affect the thermal properties of clothing and thus, the dry heat loss measured on non sweating thermal manikin would not identical to that of sweating thermal manikin.

2.2. A newly developed sweating rate measurement system

A direct sweating rate measurement system was developed without the necessity of measuring the weight of manikin. The basic rationale of direct measurement system was based on siphon action. An electronic balance with precision of 0.1 gram and maximum capacity of 12000g was used for measuring the water loss of a water reservoir.

Figure 1 shows the new sweating rate measurement system. The water reservoir B is used to maintain a constant water level corresponding to the top of manikin. A separator in the water reservoir B sets the upper limit water level, so any additional water came from water reservoir A through a water pump will lead to overflow and thus, it will flow back to reservoir A via Tube 4 due to gravitation. Apart from flowing back to reservoir A, the water in water reservoir B also will flow to the manikin automatically through Tube 3 due to siphon action when the manikin is sweating. As a result, the losing amount of water in water reservoir A is identical to the sweating rate of manikin. For measuring the changing weight of water reservoir...
A precisely, the tube 1 and tube 4 must be in a suspension state without any contact to water reservoir A.

![Figure 1 Sweating rate measurement system](image)

3. Sweating mechanism of the newly developed seated sweating thermal manikin

The sweating mechanism of the newly developed sweating thermal manikin was based on breathable fabric skin, which was same as the manikin ‘Walter’. The breathable fabric skin was a three layer laminated fabric. The middle layer of the three layer laminated fabric was a microporous polytetrafluoroethylene (PTFE) Gore-Tex membrane. In every square centimeter of Gore-Tex membrane, there are 1.4 billion tiny micropores, which are 20000 times smaller than a drop of liquid water, but are 700 times larger than a vapour molecule. Therefore, the micropores are too small for liquid water passing through, but are large enough to let water vapour pass through.

4. The accuracy and reproducibility of the newly developed seated sweating thermal manikin

For assessing the accuracy and reproducibility of the newly developed seated sweating thermal manikin, a series of tests of total thermal insulation and moisture vapour resistance were conducted in a climate chamber. The wind speed of the climate chamber was set to still air condition, which was equal to 0.22m/s. The environment temperature and environment relative humidity were set as 22.5°C and 55% respectively.

4.1. Nude test

A nude test of the seated sweating manikin with sitting posture on a chair was
conducted for four times. The mean value of the total thermal insulation and moisture vapour resistance were equal to 0.117 \( ^\circ \text{C} \, \text{m}^2/\text{W} \) and 18.27 P am\(^2\)/W respectively. The reproducibility of total thermal insulation was very high as the standard deviation was very low, which was only 0.0021 with a coefficient of variance of 1.78\%, whereas that of total moisture vapour resistance also was very high since the standard deviation was very low with a coefficient of variance of 1.51\%. Table 1 shows the details of the test results. The nude results of the newly developed seated sweating thermal were higher than that of sanding manikins because of the additional insulation of chair. Past research Havenith (1990) and Nishimura (1994) reported that the nude state total thermal insulation value of non-sweating seated sweating thermal manikin insulation was 14\% to 20\% higher than that of standing thermal manikin. However, there was no publication record for moisture vapour resistance comparison between seated sweating thermal manikin and standing sweating thermal manikin. For the comparison of nude state total thermal insulation value, the newly developed seated sweating thermal manikin was 20.1\% higher than that of the mean value of the standing manikin in table 2, which was consistent to past research results.

Table 1: Testing result of the seated sweating thermal manikin in nude status

<table>
<thead>
<tr>
<th>Nude Test</th>
<th>Repeat 1</th>
<th>Repeat 2</th>
<th>Repeat 3</th>
<th>Repeat 4</th>
<th>Mean</th>
<th>STDEV</th>
<th>CV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_t )</td>
<td>0.114</td>
<td>0.117</td>
<td>0.119</td>
<td>0.116</td>
<td>0.117</td>
<td>0.0021</td>
<td>1.79</td>
</tr>
<tr>
<td>( R_{st} )</td>
<td>18.276</td>
<td>17.945</td>
<td>18.232</td>
<td>18.62</td>
<td>18.268</td>
<td>0.2758</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Table 2: The nude results of other manikins around the world

<table>
<thead>
<tr>
<th>Standing Manikin</th>
<th>NCTR</th>
<th>ARIEM1</th>
<th>ARIEN2</th>
<th>NCSU</th>
<th>KSU</th>
<th>HK (Walter)</th>
<th>Mean</th>
<th>STDEV</th>
<th>CV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nude ( I_t ) ( \text{m}^2/\text{W} )</td>
<td>0.083</td>
<td>0.111</td>
<td>0.102</td>
<td>0.083</td>
<td>0.104</td>
<td>0.101</td>
<td>0.097</td>
<td>0.0116</td>
<td>11.96</td>
</tr>
</tbody>
</table>

4.2. Test results of three clothing ensembles by the seated sweating thermal manikin

Three clothing ensembles were tested at same condition for four times. The coefficients of variance of each clothing ensemble were lower than 2\%, so the reproducibility and accuracy level of the newly developed seated sweating thermal manikin was very high.

Table 3: The test results of the three clothing ensembles

<table>
<thead>
<tr>
<th>Ensemble 1</th>
<th>Ensemble 2</th>
<th>Ensemble 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_t ) Mean</td>
<td>0.242</td>
<td>0.173</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.0023</td>
<td>0.0024</td>
</tr>
<tr>
<td>CV %</td>
<td>0.95</td>
<td>1.42</td>
</tr>
<tr>
<td>( R_{st} ) Mean</td>
<td>51.563</td>
<td>32.331</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.358726</td>
<td>0.1686</td>
</tr>
<tr>
<td>CV %</td>
<td>0.70</td>
<td>0.52</td>
</tr>
</tbody>
</table>

In terms of accuracy, it can differentiate the differences among the three clothing ensembles. The upper garment of clothing ensembles 2 and 3 were the same garment, whereas the only difference was the trousers. The manikin can differentiate the
difference between clothing ensembles 2 and 3 in terms of total clothing thermal insulation and moisture vapour resistance. The total moisture vapour resistance of clothing 3 was higher than that of clothing ensemble 2. The result was accuracy and consistent as the trousers of clothing ensemble 3 was made up of waterproof but moisture vapour permeable fabric. By contrast, the trousers of clothing ensemble 2 was made up of cotton.

The total thermal insulation of and moisture vapour resistance of clothing ensemble 1 was highest among of all clothing ensembles. The result was accuracy and consistent. The first clothing layer of upper garment for the three ensembles was identical and only clothing ensemble 1 had second clothing layer, which was a thick coat. Therefore, the $I_t$ and $R_{et}$ of clothing ensemble 1 must be highest.

5. Comparison of the results of the seated sweating thermal manikin and standing sweating thermal manikin “Walter”

The three clothing ensemble also were tested by Walter with same procedures and conditions at the same time. Table 4 shows the results from standing manikin “Walter”. Havenith (1990) showed that the nude value of total clothing thermal insulation of seated thermal manikin was higher than that of standing manikin, whereas with increasing weight of garment, the differences would decrease and eventually, the total thermal insulation value of seated manikin would lower than that of standing with increasing weight of garment. In this paper, the test results of newly developed seated sweating manikin and standing sweating thermal manikin ‘Walter’ also showed similar finding as Havenith (1990). In addition, Havenith (1990) indicated that the total standing clothing thermal insulation 1.2 Clo (or 0.186 °C m²/W, as 1 Clo equal to 0.155 °C m²/W) was a watershed since higher than it, the total clothing insulation value of seated thermal manikin was higher than that of standing, and vice versa. In this paper, the watershed value was 0.115 Clo, which was very close to the value obtained by Havenith (1990). The watershed value was calculated by the regression model ($y = -164.87x + 129.26$, $r^2 = 0.8992$) obtained based on the scatter diagram of figure 2. Figure 3 shows the total clothing thermal insulation value of the newly developed seated sweating thermal manikin as a percentage of standing sweating thermal manikin of ‘Walter’.

### Table 4: Testing results of standing manikin “Walter”

<table>
<thead>
<tr>
<th></th>
<th>Ensemble 1</th>
<th>Ensemble 2</th>
<th>Ensemble 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_t$</td>
<td>0.284</td>
<td>0.19</td>
<td>0.188</td>
</tr>
<tr>
<td>CV %</td>
<td>2.6455</td>
<td>0.23</td>
<td>0.0026</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.0075</td>
<td>0.0004</td>
<td>0.0026</td>
</tr>
<tr>
<td>$R_{et}$</td>
<td>50.916</td>
<td>29.07</td>
<td>30.382</td>
</tr>
<tr>
<td>CV %</td>
<td>2.00435</td>
<td>0.96</td>
<td>0.1361</td>
</tr>
<tr>
<td>STDEV</td>
<td>1.0205</td>
<td>0.2787</td>
<td>0.1361</td>
</tr>
</tbody>
</table>

Regarding the total clothing moisture vapour resistance, the testing results showed that the total clothing moisture vapour resistance results of standing manikin were all lower than that of seated manikin with a decreasing manner. The results could not demonstrate the total clothing moisture vapour resistance results of standing...
manikin would be lower than that of seated sweating thermal manikin since the simple size was not large enlarge for including thicker and heavier clothing ensembles. In addition, there was lack of data from publications for comparison. Figure 3 shows the total clothing moisture vapour resistance ($R_{cv}$) value of the newly developed seated sweating thermal manikin as a percentage of standing manikin of “Walter”.

Figure 2 Scatter diagram of the total clothing thermal insulation ($I_d$) value of the newly developed seated sweating thermal manikin as a percentage of standing manikin of “Walter”

Figure 4-6 Scatter diagram of the total clothing moisture vapour resistance ($R_{cv}$) value of the newly developed seated sweating thermal manikin as a percentage of standing manikin of “Walter”
### Table 4: The details of clothing ensembles being tested

<table>
<thead>
<tr>
<th>Clothing Ensemble 1</th>
<th>Trousers</th>
<th>Long sleeves T-shirt</th>
<th>Coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Black</td>
<td>Blue</td>
<td>Blue</td>
</tr>
<tr>
<td>Content</td>
<td>98% Cotton; 2% lycra</td>
<td>100% cotton</td>
<td>80% nylon; 20% polyester</td>
</tr>
<tr>
<td>Weight</td>
<td>488g</td>
<td>230g</td>
<td>832g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clothing Ensemble 2</th>
<th>Trousers</th>
<th>Long sleeves T-shirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Black</td>
<td>Blue</td>
</tr>
<tr>
<td>Content</td>
<td>98% Cotton; 2% lycra</td>
<td>100% cotton</td>
</tr>
<tr>
<td>Weight</td>
<td>488g</td>
<td>230g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clothing Ensemble 3</th>
<th>Trousers</th>
<th>Long sleeves T-shirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Black</td>
<td>Blue</td>
</tr>
<tr>
<td>Content</td>
<td>Goretex PTFE</td>
<td>100% cotton</td>
</tr>
<tr>
<td>Weight</td>
<td>331g</td>
<td>230g</td>
</tr>
</tbody>
</table>

### 6. Conclusion

In conclusion, the newly developed seated sweating thermal manikin utilized a simple and effective way to measure the sweating rate without any compromise of accuracy and reproducibility. The coefficient of variance of each clothing ensemble and nude test were around 2% only. In terms of seated and standing thermal manikin comparison, most of the pass researches were based on non sweating thermal manikin. By contrast, the findings of this paper all were based on sweating thermal manikin with the consideration of coexistence of heat and moisture transfer. However, the simple size of this paper was not large enough to include thicker and heavier clothing ensembles for establishing a significant relationship between seated and standing sweating manikin in terms of moisture vapour resistance, nevertheless, the data were still useful for future comparison as there was lack of that kind of publication.

### References


Development of a Virtual Manikin Head for Designing Bicycle Helmets

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Abstract

Understanding the dynamic variations at different positions of the 3D head is necessary in the development of a virtual thermal head for designing bicycle helmets. In this research detailed measurements were carried out of temperature, sweat rate, relative humidity and air velocity with nine test subjects wearing a standard helmet while riding an ergometer at two effort levels, 100 and 150 Watt, respectively. Temperatures under the helmet were found to have a significant variation, with the temperature at the inlet showing that the head alters the microclimate under the head. Temperatures at the back of the helmet showed a significant (p > 0.1) difference with temperatures at the front of the helmet for most test subjects. Large variations (p > 0.0001) between air temperatures under the helmet and temperatures of the skin suggest that air stream makes a major contribution to the thermoregulation of the air under the helmet. The occipital region produced significantly (p > 0.1) more sweat than the frontal region.

These results suggest that in helmet design more attention should be paid to heat production at the frontal and at the occipital to maintain thermal comfort. And that additional impact protection at the temporal region is not in conflict with the thermal
demands in helmet design. The reported research is the first step in the interdisciplinary development of a virtual head model that will allow the simulation of thermal and mechanical responses of a human head wearing a helmet.

1. Introduction

Thermal comfort is a key factor in human behaviour and influences human safety. Every year, many cyclists die as a consequence of an unfortunate tumble or a traffic accident in which they suffer from a severe head injury. It is estimated that most of these head injuries could be avoided or strongly reduced by wearing a cyclist crash helmet [Burke 1988]. However, a lot of cyclists still do not like to wear a crash helmet because of the thermal discomfort that comes along with wearing it, especially in the summertime when cycling is popular [Wardle and Iqbal 1998]. The human head plays an important role in the thermoregulation of the body. Up to 50% of the latent and sensible heat produced is transferred via the head, causing high temperatures and sweat production on the head [Rasch et al 1991]. This has to be taken into account during headgear design. Research has shown that, on the whole body scale, the amount of sweat production differs from body part to body part [Kuno 1956 and Johnson et al 1997] and that the distribution of the total amount of latent heat losses changes with changing effort level and environmental conditions [Adams et al 1992; and Desruelle and Candas 2000]. It is expected that latent and sensible heat losses differ from region to region on the human head. Understanding the behaviour of the thermal responses of the head is important to design helmets with optimal thermal comfort.

This research aims at quantifying local temperature gradients and sweat rates under a bicycle helmet while cycling. More specifically, local sweat production on the head, skin temperature under the helmet, air temperature under the helmet, relative humidity and heart rate were measured at varying effort levels with a constant air velocity. These measurements will be used to verify and specify current models about thermoregulation of the head which will be used as boundary conditions in a virtual head in the next steps of the development of a virtual head.

2. Materials and Methods

2.1. Test installation

Figure 1 shows the test setup as it was used by nine test subjects. The test setup consisted of an ergometer, placed in a small wind tunnel in a climatic chamber. Five subjects were male and four were females. Average age was 26.7 years (SD 3.5).
The test setup consisted of three basic units: the room, the ergometer and the sensors. The room had two units: climate control and wind tunnel. Six types of sensors were used: sweat measurement, thermocouples, humidity transmitters, air velocity sensors and a heart rate sensor. Four rows, each with three fans, were used as the actuators for wind speed (Fancom type 1435/L7-588 fans). Each fan has a ventilation rate of 3000 m$^2$/h. A gauze structure was used to obtain a quasi laminar flow within the open-loop wind tunnel. The wind tunnel had a height of 2.1 metres, a length of 2.3 metres and a width of 1.5 metres. The climate chamber had a height of 5 metres, was 4 metres wide and had a length of 12 metres. Climate control between 10 and 50°C was possible at the air inlet of the climate chamber with a ventilation rate between 0 and 2700 m$^2$/h.

Sweat measurement was made using a SKINOS SKD-4000. The device offered four probes for sweat measurements (mg/min, cm$^2$). Two of them were attached to the skin by means of standard skinos stickers, two were pressed against the head because of the hair. Twenty thermocouples, type T, were used to measure temperature distribution under the helmet and on the body (°C). Five humidity transmitters Vaisala HMP 140 were used to measure relative humidity between the head and the helmet and around the helmet (%). These sensors also measured temperature (°C). Three Dimed air velocity sensors were used. One air velocity sensor was used to measure the air velocity (m/s) before the helmet. The other two measured air velocity at the rear of the helmet. Heart rate measurement (BPM) was measured using a polar T 31 chest strap and read with the Tunturi T300 hardware. A Tunturi T300 was used as ergometer for the bicycle test. The ergometer allowed the control of the effort level (Watt) from a PC outside the climate room. A decathlon helmet type sport 900 was used for the test. The helmet is the successor of the helmet that was identified as a “best buy” by the Belgian consumer organisation “test aankoop” in 2005.

Figure 2 shows the position of the thermocouples measuring skin temperature relative to the head. Figure 3 shows the position of the thermocouples measuring air temperature relative to the head. Thermocouples B-1, 3, 5, 6 and 7 were positioned on the inner surface of the helmet. Thermocouple B-0 was positioned slightly in front of the helmet, thermocouples B-4 and B-8 were positioned on two openings at the back of the helmet. Thermocouple B-2 was positioned in an air hole at the top of the helmet. Figure 4 shows the position of the sweat sensors.
2.2. Experiments

Ambient air temperature was set at 20°C and air velocity was set at 2.5 m/s at 50 mm in front of the test subject. Two effort levels were used during each test. A first period (low level 1) of twenty minutes was set at 100 Watt for men, 80 Watt for women with normal physical condition and 50 Watt for women with a physical condition below average. The second period (high level) of twenty minutes was set at 150 Watt for men, 120 Watt for women with a normal physical condition and 100 Watt for women with a physical condition below average. The settings of the first period were also used for the third period (low level 2) of twenty minutes. As a result, each test lasted 60 minutes. Each of the nine test subjects performed the test three times, resulting in 27 tests in total.

2.3. Statistical analysis

Statistical analysis was performed using ANOVA. Skin temperatures were analysed using ANOVA for three periods; as the mean of the measurements from minute 15 till minute 20, from minute 35 till minute 40 and from minute 55 till 60. This corresponded with the last five minutes of each effort level. This was performed for three positions as can be seen in Fig. 2. Air temperatures were analyzed using ANOVA for nine positions as can be seen in Fig. 3. Significant variance between temperatures under the helmet and on the skin were also analysed using ANOVA. H0 indicated that there was a significant difference between the two groups under investigation (f.e. Tskin1 versus Tkin2). All temperature positions were analyzed for significance ($\alpha = 0.05$ or $\alpha = 0.1$) with each other. The variances were analyzed for each test subject. The analysis was performed with the differences in temperatures between sensor 0 and all other. Sweat was measured at four positions, as can be seen in Fig. 4. Eight measurements were accepted by sensors one and two, 27 were accepted for sensors three and four. The mean of each test subject was calculated to overcome this problem and the various means for each sensor were analyzed for variance. An unbalanced ANOVA test was performed between the sensors for the whole population at once. This test was performed with the mean values of each of the three steady state levels. These steady state levels...
corresponded with the variation in effort level. H0 indicated that there was a significant difference in sweat production between the measured zones.

3. Results and Discussion

3.1. Skin temperatures

Each sensor attached to the skin was compared with each other for the three effort levels using ANOVA. Table 1 shows the results of this analysis. The position of the sensors can be seen in Fig. 2.

<table>
<thead>
<tr>
<th>Test Pers.</th>
<th>P-value Sensor Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sensors 1 - 2</td>
</tr>
<tr>
<td>1</td>
<td>0.692</td>
</tr>
<tr>
<td>2</td>
<td>0.616</td>
</tr>
<tr>
<td>3</td>
<td>0.244</td>
</tr>
<tr>
<td>4</td>
<td>0.017 a</td>
</tr>
<tr>
<td>5</td>
<td>0.435</td>
</tr>
<tr>
<td>6</td>
<td>0.921</td>
</tr>
<tr>
<td>7</td>
<td>0.559</td>
</tr>
<tr>
<td>8</td>
<td>0.297</td>
</tr>
<tr>
<td>9</td>
<td>0.258</td>
</tr>
</tbody>
</table>

A significant difference (p < 0.1) was seen between sensors A-1 and A-3 for six test subjects at a high effort level and low effort level 2. Only one test subject indicated a significant difference (p < 0.1) between sensors A-1 and A-2 at both low effort levels. Three test subjects indicated a significant difference between sensors A-1 and A-2 at a high effort level. Four test subjects indicated a significant difference between sensors A-2 and A-3 at low effort level 1. Three test subjects reported a significant difference (p < 0.1) between sensors A-2 and A-3 at a high effort level and low effort level 2.

This indicates that temperatures in the area of sensor A-2 (parietal region, see Fig. 4) were more similar to temperatures in the area of sensor A-1 (frontal region) than to temperatures in the area of sensor A-2 (temporal region). Spatial temperature variations were, besides for the variation between sensors A-2 and A-3, more pronounced when effort levels were high.

Table 2 shows the mean temperature deviation of each sensor with the reference temperature outside the helmet. Sensor A-1 had an average of 10°C above the temperature of the air inlet for all effort levels. Sensor A-2 had an average of approximately 9.2°C and sensor A-3 had averages between 5 and 6°C. The
temperature declined for sensor A-2 (parietal region, sagittal suture) at a high effort level and for sensor A-3 (temporal region) at low effort level 2, suggesting that sweat production could overcool the temperature of the skin. Few inclination of skin temperature was observed under the helmet during the duration of the test.

The results indicate that the area around sensor A-3 (temporal region) was the coldest for six test subjects (p < 0.1) at a high effort level, and that the area of sensor A-1 (frontal region) was the warmest for six test subjects (p < 0.1) at the high effort level and low effort level 2.

<table>
<thead>
<tr>
<th>Table 2: Mean temperature differences between skin and inlet</th>
</tr>
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<tbody>
<tr>
<td>mean temperature differences between skin and inlet</td>
</tr>
<tr>
<td>low level 1</td>
</tr>
<tr>
<td>mean</td>
</tr>
<tr>
<td>sensor 1, frontal</td>
</tr>
<tr>
<td>sensor 2, parietal</td>
</tr>
<tr>
<td>sensor 3, temporal</td>
</tr>
</tbody>
</table>

**Air temperatures**

Visual inspection of the 27 time series for air temperatures under the helmet did not show any response to an increase in effort level for any of the test subjects. Nor could there be found pronounced temperature variations between the beginning of the test and the end. Therefore, air temperatures were investigated as the mean of the last five minutes of the test.

Table 3 shows the number of test subjects for which the comparison of sensors had a significant variance, for air temperatures. Column one shows the sensor pairs that were compared, column two shows the results for $\alpha = 0.05$, column three shows the result for $\alpha = 0.1$ ($\alpha$ = level for which difference between sensors is significant). The position of the sensors can be seen in Fig. 3.

Temperatures at the inlet (sensor B-0) of the helmet were significantly lower for five and up to seven test subjects (p < 0.1) depending on the sensor pair. These findings indicate that the microclimate under the helmet was altered by the thermo-regulative response of the head.

Gradients in air temperature at various positions under the helmet were more difficult to see. A total
of 15 sensor pairs were analyzed (differences between sensor B-1, 2, 3, 5, 6 and 7). The differences were significant ($p < 0.1$) for either none or a maximum of two test subjects for four of these sensor pairs, indicating that there is little variation between these sensor pairs (sensor pairs B1-2, B2-8, B3-6, B3-7, see Fig. 3). The differences were significant for five or more test subjects for four sensor pairs, indicating that there is a large difference between these sensor pairs (sensor pairs B1-5, B1-8, B2-7, B3-5, see Fig. 3).

If one compares the physical placement of the sensors with the differences between these sensors, one sees that sensor three only had a significant difference with sensors seven and six for one test subject ($p < 0.1$), while a significant difference ($p < 0.1$) can be seen for five test subjects for sensor B-5 and for four test subjects ($p < 0.1$) for sensor B-1. Sensors B-3 and B-7 are at the back of the helmet. Sensor B-6 is positioned in the middle of the helmet, while sensors B-5 and B-1 are at the front of the inner helmet surface. Sensor B-5 has a significant variance with sensor B-1 for seven test subjects ($p < 0.1$). Sensors B-1 and B-5 are both at the front of the helmet, suggesting that the differences can be explained by the geometry of the ventilation holes, since their variation cannot be explained by the geometrical position of the sensors.

Table 4 shows the average differences in temperatures between the sensors under the helmet and the one in front of the helmet. Sensors B3, B-6 and B-7 showed higher differences than sensors B-1 and B-5, while the mean of sensor B-5 indicated it to be in a warmer area. Previous analysis (see Table 3) showed the significance of these differences, supporting the idea that a temperature gradient can be seen over the head while wearing a bicycle helmet.

<table>
<thead>
<tr>
<th>sensor 1</th>
<th>sensor 2</th>
<th>sensor 3</th>
<th>sensor 4</th>
<th>sensor 5</th>
<th>sensor 6</th>
<th>sensor 7</th>
<th>sensor 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.758</td>
<td>0.653</td>
<td>2.394</td>
<td>0.663</td>
<td>1.845</td>
<td>2.254</td>
<td>2.885</td>
</tr>
<tr>
<td>SD</td>
<td>0.708</td>
<td>0.433</td>
<td>1.765</td>
<td>0.367</td>
<td>2.021</td>
<td>1.707</td>
<td>2.405</td>
</tr>
</tbody>
</table>

Grouping sensors B-1, B-3, B-5, B-6 and B-7 measuring air temperature under the helmet and comparing these results with the grouped data from the sensors measuring the skin temperature resulted in $P = 0.0001$. This showed that the air temperatures near the head are far below the skin temperatures.

### 3.2. Sweat production.

The four sensors were analyzed against each other for significant variance for three steady state levels that correspond with the three effort levels. The data in Table 5 shows a significant variance ($p < 0.1$) between sensors C-2 and C-4 for all effort levels. The position of the sensors can be seen in Fig. 4.
Sensor C-4 is placed at the frontal region, while sensor C-2 is placed at the parietal region. Table 6 shows the mean sweat production. We see that sweat production is higher at the high effort level and that the mean sweat production at sensors C-1 and C-2 is higher for the high effort level compared to sensor C-3 and C-4. The ANOVA test revealed that the variation in sweat production between sensors C-2 (parietal region) and C-4 (frontal region), was significant (p < 0.1) for all effort levels. This could be caused by the temperature at the back of the head, which proved to be the warmest zone under the helmet for most test subjects indicating that more heat dissipation is required in this position. Sweat production was, as expected, higher for all sensors when effort levels were raised. However, current analysis is not able to quantify these effects, indicating that a dynamic analysis is necessary to study sweat production in more detail.

Table 6: Mean sweat production, for each sensor at three steady state levels.

<table>
<thead>
<tr>
<th>Sensor 1, parietal region</th>
<th>Sensor 2, parietal region (sagittal suture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Low level 1</td>
<td>0.445</td>
</tr>
<tr>
<td>Low level 2</td>
<td>0.525</td>
</tr>
<tr>
<td>Low level 1</td>
<td>0.593</td>
</tr>
<tr>
<td>Low level 2</td>
<td>0.351</td>
</tr>
<tr>
<td>High level</td>
<td>0.525</td>
</tr>
<tr>
<td>High level</td>
<td>0.593</td>
</tr>
<tr>
<td>High level</td>
<td>0.351</td>
</tr>
</tbody>
</table>

4. Conclusions

The mean temperature difference between the air inlet and skin temperatures was found to be 10.38°C (SD 3.52) at the low effort level 1 at the frontal region (see Fig. 2), 11.54 (SD 3.79) at the high effort level and 10.38 (SD 3.63) at low effort level 2. Mean temperature at the temporal region was 5.82 °C (SD 3.07) at the low effort level 1, 6.07 (SD 3.41) at the high effort level and 5.08 (SD 3.30) at the low effort level 2. The variations in skin temperature under the helmet were significant for seven out of the nine test subjects, proving that skin temperatures under the helmet were not uniform. More detailed measurements (more zones on the skin) should provide more accurate information about the temperature distribution under the helmet, in both time and space.
The mean temperature variations between the inlet and air temperatures under the helmet were 0.76 °C (SD 0.71) for sensor B-1 (see Fig. 3), 2.37 °C (SD 1.76) for sensor B-3, 1.85 °C (SD 2.02) for sensor B-5, 2.25 °C (SD 1.71) for sensor B-6 and 2.89 °C (SD 2.41) for sensor B-7. The variations between inlet and air temperatures under the helmet were significant (p < 0.1), showing that the head alters the microclimate under the helmet. However, significant variances (p <0.1) between the skin temperatures and that of the thermocouples under the helmet indicated that the air stream could have a major contribution in the thermal reaction of the air under the helmet.

Mean sweat production at the parietal region was 0.54 g/min.cm² (SD 0.27) at low effort level 1, 1.12 g/min.cm² (SD 0.57) at the high effort level and 0.71 g/min.cm² (SD 0.39) for low effort level 2. At the frontal region we found a sweat production of 0.94 g/min.cm² (SD 0.42) at low effort level 1, 1.90 g/min. cm² (SD 0.72) at the high effort level and 1.29 g/min.cm² (SD 0.49) for low effort level 2. These variations between the sensors C-2 and C-4 (see Fig. 4) were significant (p < 0.1) for all effort levels. However, sweat measurements at sensors one and two were disturbed by the presence of hair, a problem that should be solved for the next batch of measurements.

High temperatures in the frontal region indicate that the investigated helmet should provide better cooling in this region, while more humidity should be transported to the outside of the helmet at the occipital region. Relative low skin temperatures and sweat production at the temporal region provided no evidence (for this test setup) to reject the concept of extra impact support of the temporal region [Bart Depreitere et al 2004] from a thermal point of view.

A first analysis was made in the development of a virtual thermal manikin head. Validation and optimization of current heat transfer models of the head with current and scheduled measurements with respect to the effort levels, while cycling, is a next step. These models will be used as an input for the virtual manikin head, enabling a thermal response of the virtual head that is specific for each virtual helmet design that is placed on top of the virtual manikin head.
5. References


Passive and Active Water Supply to Perspiring Manikin

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Abstract

Several kinds of perspiring manikin have been developed in the world, including the famous “Coppelius”, “SAM”, “Walter” etc. Nevertheless, they have different perspiring functions according to their different perspiring designs. With respect to perspiring, the water supply system is important in terms of carrying water to the perspiring skin and it can be considered as two categories, namely: Active water supply system and Passive water supply systems. This paper discusses theoretically the active and passive ways of water supply system which make perspiring manikin have distinct perspiring properties and such differences will lead to different measurement methods and potentially different errors in results.

Keywords: perspiring manikin, water supply system, clothing thermal comfort

General Introduction

It is well known that human heat loss always occurs in two ways; dry heat loss and evaporate heat loss. The main parameters for the thermal comfort of clothing are thermal resistance and evaporative resistance. The body heat loss and thermal parameters of clothing can be given as:

\[ H = H_t + H_e \]  \hspace{1cm} (1)

\[ H_e = \lambda \cdot Q \]  \hspace{1cm} (2)

\[ R_t = \frac{A_s (t_s - t_a)}{H_t} \]  \hspace{1cm} (3)
Where, $H$, $H_s$, and $H_e$ are total heat loss and dry heat loss, evaporate heat loss, respectively, (W); $\lambda$ is the heat of evaporation of water, it can be found that $\lambda = 0.67 \text{ W•h•g}^{-1}$ at 34°C; $Q$ is the body perspiring rate (g•h$^{-1}$) and assuming it passes totally through the clothing; $A_s$ is the body surface area (m$^2$); $t_s$ and $t_a$ are the skin temperature and surrounding temperature (°C), respectively; $p_s$ and $p_a$ are the water vapour pressure (Pa) at the skin and the environment, respectively; $P_{s}^{*}$ and $P_{a}^{*}$ are the saturated water vapour pressure (Pa) at skin temperature and surrounding temperature, respectively; $RH_s$ and $RH_a$ are relative humidity (%) at the skin and in the environment, respectively, $R_t$ is the thermal resistance (°C•m$^2$•W$^{-1}$) and $R_e$ is the evaporative resistance (Pa•m$^2$•W$^{-1}$);

The aim of building a perspiring manikin is to measure $R_t$ and $R_e$ of the clothing based on formula (1) - (4). In order to do this, it is necessary to obtain all the variables in the formula. However, the water vapour pressure $p_s$ or relative humidity $RH_s$ at the body surface and the actual body perspiring rate $Q$ are difficult to measure directly, and they then often have to be obtained in an indirect way.

The earliest perspiring manikin was developed in the 1970s which was covered in hydrophilic underwear onto which was sprayed water to simulate body perspiration[1]. This perspiration could, however, not persist for long during a test. Perspiring or sweating manikins built later, were supplied with water to their body skin by using a pipe system, included either simply in an outside manner[2] or in a complex inside manner, such as “Coppelius”[3] and “SAM”[4], so as to continue perspiration. This was the case until “Walter”[5] was developed in a completely different way.

**Active Water Supply System**

Active water supply can be considered as a water supply system that can supply a certain given amount of water to the sweating manikin during a test, e.g. 100g•h$^{-1}$, 200g•h$^{-1}$ independently of how the testing clothing varies. This is the case for the pipe water supply systems in manikins such as “Coppelius” and “SAM”. The active water supply system is generally equipped with a pump and electric controlled microvalve at each water pipe that carries the water to each of the body sweat glands[3,4].

The above system may simulate human body sweating at a certain rate in certain heat balance situations. Nevertheless, the clothing on the manikin acts as a barrier between the body and the environment. If the sweating rate is high and the clothing is thick, only a fraction of the sweat, as vapour, passes through the clothing to the outside while the other fraction condenses in the clothing or drips down as water along body limbs. In this situation, the dripped water should be collected in a container. The $Q$ used to calculate clothing vapour resistance can be obtained by the
amount of water supplied, subtracting the collected water when equilibrium is achieved (then the condensed water in the clothing is a constant and this may require a long time\cite{5}) and RH can be assumed to be 100% since the body surface is all wet. In another situation, if the sweating rate is low and the clothing is thin, all sweat dissipates as vapour through the clothing, the amount of water supplied can be considered as $Q$ to use for calculation. Nevertheless, RH should be exactly measured near the body surface since 100% relative humidity is not achieved, and this has proved to be very difficult.

The question which arises is how to set the sweating rate when a suit is to be measured, since different rates may lead to differences in the water condensing in the test clothing and varying test results.

Another measurement way, is a two-step method suggested and used by Woodcock, McCullough\cite{1} and others, since the amount of water vapour transmitted was difficult to measure directly. The test procedure is as follows:

Step 1 Measure the dry heat loss $H_t$ on a clothed dry thermal manikin (or when the manikin is not sweating);
Step 2 Measure the total heat loss $H$ on a sweating manikin, then subtracting the $H_t$ will give the evaporative heat loss $H_e$. The evaporative resistance $R_e$ can be calculated by:

$$R_e = \frac{A_s (P_s^* \cdot RH_s - P_a^* \cdot RH_a)}{H - H_t} \quad (5)$$

However, this calculation will lead to a relative error since the dry heat loss measured on the dry manikin (no water condensed in clothing) is not equal to that measured on a sweating manikin due to the reduction in insulation when the clothing contains significant amounts of condensed water\cite{5}.

**Passive Water Supply System**

A Passive water supply can be considered as a water system that can supplement water lost when perspiration dissipates. This can be found on the fabric perspiring manikin “Walter”, the amount of supplemented water may change automatically when the suit cover is changed due to differences in the water vapour resistance of the different clothing\cite{6}. Generally, if the clothing is thicker; the amount of supplemented water will be less.

“Walter” is a body shaped breathable fabric container with a water circulation system inside. The inside water perspires through the microporous membranous skin as water vapour and disperses through the clothing to the outside (the amount of recondensed water in the clothing is a constant when equilibrium is achieved) and no excreted condensed water drips down along the limbs. This follows the moisture gradient from the skin inside to the outside of the clothing. In this situation, supplemented water can be measured directly, and 100% relative humidity is certain.
on the inner side of the skin. The calculation, as a one-step method\cite{5,7}, can be given as follows:

\begin{equation}
R_e = \frac{A_s (P^*_{si} - P^*_{a} \cdot RH_a)}{\lambda \cdot Q} - R_{es}
\end{equation}

\begin{equation}
R_l = \frac{A_s (t_s - t_a)}{H - \lambda \cdot Q}
\end{equation}

\begin{equation}
R_{es} = \frac{A_s (P^*_{si} - P^*_{a} \cdot RH_a)}{\lambda \cdot Q_n}
\end{equation}

Where, $P^*_{si}$ is the saturated water vapour pressure at the water contact interface to the inner side of the skin at skin temperature; $Q_n$ is the water supplement for the nude manikin in the wind blowing tests; $R_{es}$ is the evaporative resistance of the breathable skin, and it can be measured by a strong wind blowing onto the nude manikin to eliminate the still air layers.

Many experiments have been carried out by this method and valuable results of both thermal insulation and evaporative resistance have been published since 2002\cite{5,6,8,9}.

**Conclusions**

The active water supply system has been developing over many years since the 1980s, and it was used in many famous perspiring manikins. Nevertheless, it still had some problems in actual measurements, and little data was published on clothing evaporative resistance. The passive water supply systems emerged when the fabric perspiring manikin “Walter” was developed in 2002. The passive water supply system has advantages in that it makes perspiring manikins more suitable for clothing thermal measurement, where the manikin is an instrument with no hypothesis. The passive water supply method will be increasingly recognised in future manikin developments.
References


Section VI
Testing & Standardization
Classical Approach to Heat and Vapour Resistance Calculations Cannot Explain Heat Transfer in Wet Clothing

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Abstract

In this paper, we describe manikin experiments carried out on the effects of different underwear (one layer only) combined with impermeable or more or less permeable coveralls. The underwear was either dry or wet, in order to study the changes in the protective clothing insulative properties as related to the materials under an impermeable coverall and under the influence of the climatic conditions, i.e. ambient temperature.

The manikin was installed hanging in an upright position in the centre of the climatic chamber at CEPA and was always operated statically, i.e. without any body movement. Tests were carried at climate temperatures of 10°, 20° and 34°C and an air velocity of 0.5 m/s. The water partial vapour pressure was maintained at 1 kPa throughout.

The manikin head (4 zones), hands (2) and feet (2) were not included in the calculations. Thus the remaining covered surface still included 28 zones. All manikin surface temperatures were maintained at 34°C and heat fluxes were measured continuously.
In the case of wet clothing, the approach was as follows: the underwear was weighed dry and then immersed into water heated to 34°C, tumbled and weighed again until it contained the required amount of water (from 125 to 500g). The underwear was immediately put into a plastic bag and then put as quickly as possible onto the manikin while equipping it also with the sensors. The manikin was afterwards turned ON.

In addition to the usual results, in terms of heat fluxes and dry insulation for each condition, we obtained both the measured dry heat loss at 10 or 20°C and the measured evaporative heat loss at 34°C over the whole test period. We could therefore compute for the wet condition at 10° and 20°C the theoretical cumulative dry and the evaporative heat loss which we could then compare with the observed data.

Generally, it was found that there was some energy lost from the manikin that could not be explained from the cumulative dry and humid heat losses. It must be admitted that the wet process involved some additional heat exchange. Averaging this extra heat loss from the manikin produces mean values corresponding to an instantaneous heat loss of 35 to 42 Watts.

The thermal imbalance found in our condition of wet underwear under an impermeable coverall implies that some other thermal phenomenon occurred which disturbed the simple calculations usually done. In addition to a likely small experimental bias (some evaporation probably occurring during the setting up of the manikin), mechanisms of evaporation and later condensation inside the clothing layers are suspected which cannot be neglected.

1. Introduction

The main objective of the EU funded research project THERMPROTECT was to provide basic data and models on "Thermal properties of protective clothing and their use" for improving the assessment of heat stress while wearing personal protective clothing (PPC).

The aspect dealt with here considers the effects of water into or onto the protective clothing related to the characteristics of the clothing material. The effects of wetting the underwear were investigated.

In this report, we describe the manikin experiments carried out at the CEPA on these effects on different pieces of underwear (one layer only) that were sometimes combined with impermeable or semi- or permeable coveralls. The clothing parts were either dry or wet, in order to study the changes in the protective clothing insulative aspects related to the material and the permeability of the coverall under the influence of the climatic conditions and/or of the water content.
2. Methodology

2.1. Climatic chamber
The facilities at CEPA make it possible to simulate the thermal environment over a wide range, with high accuracy: air temperature ($t_a$) from 5 to 70°C ($\pm$ 0.2K), dew point temperature ($t_{dp}$) from 3 to 36°C ($\pm$ 0.2°C), air velocity from 0.05 to 1.2 m/s ($\pm$ 0.05 m/s).

The air temperature ($t_a$) is controlled and regulated from dry-bulb temperature readings obtained behind the front wall (6 sensors) averaged with those obtained beyond the rear wall (6 sensors). Ambient water vapour pressure is measured and controlled by a dew point sensor (Acova®). Air velocity ($v_a$) is measured and regulated by a hot-wire anemometer: air velocity was adjusted at the manikin level after verification by measurements obtained regularly from a BK® 1213 device. No radiation was imposed during the tests and wall temperatures were maintained at the level of the air temperature ($t_a=t_g=to$).

2.2. Thermal manikin
The Swedish electrically heated thermal manikin Heatman® was used at CEPA. Its surface area is divided into 36 zones connected to a power supply and a computer-controlled system that regulates each zone’s surface temperature individually to any given level (in this research: 34°C). The computer system also records the surface temperature and supplied power data for each zone and stores them every minute for later data processing.

The manikin was installed hanging in a straight (standing) position in the centre of the climatic chamber and was always operated statically, i.e. without any body movement. Before a series of tests, the surface temperature sensors were calibrated regularly by fixing on 2 occasions the surface temperatures while the power supply was not operating and the environmental conditions were steady and set at either $t_r=t_a=24^\circ$ and 34°C, $v_a=0.5$ m/s, $rh=50\%$. To avoid short circuits due to moisture on the skin surface, the manikin was wrapped all over tightly in polyurethane film (cling film).

2.3. Climatic conditions
Tests for these series were carried at a climate temperature of 10° and 34°C for series 1, and at 20°C for series 2, the air velocity being 0.5 m/s. The water partial vapour pressure was maintained at 1 kPa for all conditions. More details are given in the tables corresponding to the specific tests.
2.4. Clothing and procedures

The manikin head (4 zones), hands (2) and feet (2) were not included in the calculations, the remaining covered surface included 28 zones.

Different types of materials were used as outer layers because of their different permeability: PVC as an impermeable (IMP), O1 as a semi-permeable (SEMI) and O2 as a very permeable material (PERM), respectively. All underwear and coverall were weighed before and after the tests.

In the case of wet clothing, the following procedure was followed; the underwear was weighed dry and then immersed into water at 34°C, tumbled and weighed again until it contained the required amount of water (see the corresponding protocol tables). Then, the underwear was immediately put into a plastic bag and put as fast as possible on the manikin while equipping it also with the sensors. The manikin was afterwards turned ON.

The following two tables provide more details of the two series of tests.

**Series 1: dry - wet underwear under impermeable PVC**

<table>
<thead>
<tr>
<th>Test</th>
<th>Wet-Dry underwear</th>
<th>Underwear</th>
<th>Outer layer</th>
<th>Wind, m/s</th>
<th>Ta = Tg</th>
<th>PaH2O, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dry</td>
<td>N2S</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>wet : 500g</td>
<td>N2S</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>wet : 500g</td>
<td>N2S</td>
<td>IMP</td>
<td>0.5</td>
<td>34°C</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>dry</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>wet : 500g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>wet : 500g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>34°C</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>dry</td>
<td>CAP</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>wet : 500g</td>
<td>CAP</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>wet : 500g</td>
<td>CAP</td>
<td>IMP</td>
<td>0.5</td>
<td>34°C</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>dry</td>
<td>HH</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>11</td>
<td>wet : 500g</td>
<td>HH</td>
<td>IMP</td>
<td>0.5</td>
<td>10°C</td>
<td>1.0</td>
</tr>
<tr>
<td>12</td>
<td>wet : 500g</td>
<td>HH</td>
<td>IMP</td>
<td>0.5</td>
<td>34°C</td>
<td>1.0</td>
</tr>
</tbody>
</table>
### Series 2: dry - wet underwear under various coveralls

<table>
<thead>
<tr>
<th>Test</th>
<th>Wet-Dry underwear</th>
<th>Underwear</th>
<th>Outer layer</th>
<th>Wind, m/s</th>
<th>Ta = Tg</th>
<th>PaH₂O, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dry</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>wet 1 : 125g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>wet 2 : 250g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>wet 3 : 500g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>wet 3 : 500g</td>
<td>CO GN</td>
<td>IMP</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>dry</td>
<td>CO GN</td>
<td>SEMI</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>wet 3 : 500g</td>
<td>CO GN</td>
<td>SEMI</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>dry</td>
<td>CO GN</td>
<td>PERM</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>wet 3 : 500g</td>
<td>CO GN</td>
<td>PERM</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>wet 3 : 500g</td>
<td>CO GN</td>
<td>PERM</td>
<td>0.5</td>
<td>20°C</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Tables 1 and 2: Experimental conditions**

N2S: next to skin, CO GN: cotton, CAP: capilene, HH: Helly Hansen (polypropylene)

The measurements covered:
- local and global manikin heat fluxes and surface temperatures
- 4 local clothing microclimate temperatures and relative humidities (Sensirion® sensors below the outer layer connected to a MSR® portable data logger) located at the level of the left torso, right lower back, left anterior side and left rear calf.
- 4 local skin microclimate temperatures and relative humidities (Sensirion® sensors below the outer layer connected to a MSR® portable data logger) located at the level of the left torso, right lower back, left anterior side and left rear calf.

Due to evaporation in the inner layers, the heat fluxes of the manikin and microclimate variables took a long time to become steady (more than 3 hours in some cases). For this reason, measurements were continued until a steady state of local heat losses and surface temperatures was obtained for at least 20 minutes. Then the values were computed (temperatures and heat fluxes) by averaging 10 minute samples for different phases: after around 40 min, called pseudo-steady state, after 60 min and after 90 min. All the data were recorded in a data file for further treatment.

The results reported here concern only the pseudo steady state values which were observed after the large changes induced by acute humidification of the inner or outer layers.

### 3. Results

The results (except otherwise stated) are given in terms of generated heat flux, which corresponds to the flux generated by the Joule effect in the manikin to keep
the manikin surface temperature as close as possible of those fixed as targets: the greater the flux, the greater the heat required to compensate for the heat dissipation from the manikin surface into the environment, due to both dry heat losses (convection and radiation) and to evaporative heat loss from the wet garments.

3.1. Underwear moisture effect in case the of impermeable outer garment material

Interestingly, at 34 ºC the results show a small heat loss of around 10 W/m², although no dry heat loss was expected (because $t_a = t_g = 34°C$) and theoretically no evaporation could occur, IMP being impermeable (Fig. 1). This can only be accounted by some dry heat exchange (surface temperature of the wetted areas somewhat lower than 34°C due to local cooling) because of some evaporation via the over-garment leakage (neck, wrist, ankles).

Comparing the heat loss for DRY and WET underwear at 10°C shows a mean difference of 33 W/m² for next to the skin, cotton and Capilene while the difference seemed larger (53 W/m²) with Helly Hansen®. These increases in heat fluxes, being significantly larger than 10 W/m², reveal a decrease in the PVC thermal insulation, probably because of the condensation and then accumulation of water on the inner surface of the outer layer.

Since we have measured the amount of heat that was lost only by evaporation (at 34°C), we deducted this amount from the total heat losses at 10°C. And then, we recalculated the thermal insulation of the PVC under the conditions, Fig. 2 giving the results. The decrease in IMP insulation reached an average of 33%.
explanation has still to be found why the Helly Hansen® underwear reduced the coverall insulation more than the other underwear. This could be related to its capability to release more water than the other types (see Table 3).

![Thermal insulation of PVC, °C.m²/W](image)

**Figure 2** Manikin thermal insulation as measured for the whole covered body area (head, hands and feet excluded). The percentages reported correspond to the decrease in insulation due to wetting the underwear.

Figure 2 shows that the next to skin underwear induced a smaller decrease in insulation while the larger drop was found under the Helly Hansen® condition, while Capilene and cotton led to the same reduction in insulation.

Globally speaking, however, the reduction in the thermal insulation due to the wet underclothing is not negligible since it varies from 25 to 50%.

In addition to these results, we made the following calculations. Since we had both the measured dry heat loss at 10°C and the measured evaporative heat loss at 34°C over the whole test period, we could compute for the wet condition at 10°C, both the theoretical cumulative dry and the evaporative heat loss using the previous values adjusted for exposure time.

The procedures used were as follows:
Column 1: Duration of recordings.
Column 2: Actual mass loss of the pre-wetted underwear, the accumulation of water in the coverall being deducted from the mass changes between after and before exposure.
Column 3: Equivalent energy mass calculated from column 2 : (x 0.58 cal/g x 4.18 J/c)
Column 4: Actual total energy losses measured on the manikin, lost by the Joule effect for the duration of column 1.
Column 5: Observed energy lost from the dry manikin during the duration of column 1.
Column 6: Theoretical dry heat loss of the manikin, if dry at 10°C, calculated as flux found in column 5 x duration of column 1 x covered manikin surface area (1.36 m²) and then converted into KJ.

Column 7: Theoretical latent heat loss at 10°C in absence of dry heat loss, deducted from values observed at 34°C under the same condition (column 4 and corrected according to duration ratios of column 1).

At the end, (column 8), we subtracted from the actual energy loss (column 4) the theoretical dry (column 6) and the theoretical evaporative heat losses (column 7). As a result, the last column reports the amount of heat not found in the energy balance.

<table>
<thead>
<tr>
<th>UW</th>
<th>UW OW</th>
<th>Tg°C</th>
<th>Duration h</th>
<th>UW mass loss, g</th>
<th>Energy from mass loss, KJ</th>
<th>Manikin energy loss measured KJ</th>
<th>Theoretical total dry Heat loss at 10°C, KJ</th>
<th>Theoretical Heat Evap. at 10°C KJ</th>
<th>Heat not found KJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2S dry IMP 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2S wet IMP 10</td>
<td>2.6</td>
<td>126</td>
<td>305</td>
<td>1455</td>
<td>952</td>
<td>188</td>
<td>315</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2S wet IMP 34</td>
<td>2.75</td>
<td>87</td>
<td>211</td>
<td>199</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO GN dry IMP 10</td>
<td>1.5</td>
<td>46</td>
<td>949</td>
<td>581</td>
<td>68</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO GN wet IMP 34</td>
<td>2.5</td>
<td>158</td>
<td>83</td>
<td>113</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAP dry IMP 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>76</td>
</tr>
<tr>
<td>CAP wet IMP 10</td>
<td>1.5</td>
<td>76</td>
<td>184</td>
<td>861</td>
<td>558</td>
<td>70</td>
<td>233</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAP wet IMP 34</td>
<td>2.4</td>
<td>178</td>
<td>432</td>
<td>112</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH dry IMP 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>84.4</td>
</tr>
<tr>
<td>HH wet IMP 10</td>
<td>1.5</td>
<td>200</td>
<td>485</td>
<td>1052</td>
<td>620</td>
<td>64</td>
<td>368</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH wet IMP 34</td>
<td>2.35</td>
<td>208</td>
<td>504</td>
<td>101</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Calculations of heat balance using manikin heat fluxes and water losses from underwear (outerwear accumulation deducted). Thermal balance is done over the exposure duration.

Generally, there is some energy lost from the manikin that cannot be explained from the cumulative dry and humid heat losses. It must be admitted that the wet process has involved some additional heat exchange, as also found in the results of our other European colleagues involved in this research. Averaging the extra heat loss from the manikin gives a mean value of 304 KJ which, for a global exposure of 2h, would correspond to an instantaneous heat loss of 42 Watts.

3.2. Underwear moisture effect in the case of outer garment materials of different permeability

In these experiments performed at $t_a = t_g = 20°C$ (0.5 m/s air velocity), the coverall was either impermeable (IMP), semi-permeable (SEMI) or very permeable (PERM). As shown in Table 2, the tests concerned various amounts of water for pre-wetting the cotton underwear.
Results of heat fluxes show that increasing the amount of water in the cotton underwear increased the total heat flux. While in the dry conditions, there was no difference in the various coveralls, the heat flux then being larger as a function of the coverall permeability. For a clear representation of this point, the average values for the replicated 500g conditions are only reported with those of the dry conditions.

Figure 3 Mean microclimate water vapour pressure inside the clothing layers and associated manikin heat losses as measured for the whole covered body area (head, hands, feet excluded; $v_a=0.5\ m/s,\ Pa=1kPa$). For each of the studied coveralls (X-axis), 0g refers to DRY while 500g refers to WET COTTON underwear.

Figure 3 shows that the difference in the local microclimate (between next to the skin and the clothing layers) was small in the case of the impermeable ensemble while it increased with the permeation capacity (from semi-permeable to permeable). Nevertheless the gradient was not as large as could be expected from a permeability point of view.

For these conditions, we also subtracted from the total heat loss the amount of energy that could take place in the absence of any dry heat loss, by an analogy with the previous section. The calculations were exactly the same as previously described taking into account the evaporative heat loss observed in the absence of dry heat loss from files registered in Series 1.

Then, we recalculated the thermal insulation for each condition. The values are reported in Fig. 4. The drop in the PVC with the cotton underwear is of the same magnitude as that observed before at 10°C, although the initial insulation was a little lower here. Interestingly, the drop in insulation due to wetting increased as a function of the permeability index, reaching values higher than 50% for the permeable coverall.
Thermal Manikins and Modelling

Figure 4  Manikin thermal insulation as measured for the whole covered body area (head, hands and feet excluded). The percentages reported correspond to the insulation decrease due to wetting the underwear.

Here we had the measured dry heat loss at 20°C and not the measured evaporative heat loss at 34°C. However, we could compute for the wet condition at 20°C the theoretical dry heat loss. The theoretical evaporative heat losses were calculated by using the numbers found in Series 1, adjusted for the corresponding exposure times. Then, we subtracted from the energy loss calculated from the mass change, the theoretical dry and evaporative heat losses. Again, the last column represents the amount of heat not found in the energy balance. We could make these calculations only for the IMP coverall because the assumptions on evaporated heat losses could not be applied to SEMI or PERM.

<table>
<thead>
<tr>
<th>UW</th>
<th>UW</th>
<th>Duration</th>
<th>UW mass loss, g</th>
<th>Energy from mass loss, KJ</th>
<th>Manikin energy loss at 20°C, dry, Watts</th>
<th>Theoretical dry Heat loss at 20°C KJ</th>
<th>Theoretical Heat Evap. at 20°C KJ</th>
<th>Heat not found KJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Cotton IMP</td>
<td>41.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wet_1 = 125g</td>
<td>Cotton IMP</td>
<td>3.42</td>
<td>88</td>
<td>213</td>
<td>1160</td>
<td>697</td>
<td>155</td>
<td>309</td>
</tr>
<tr>
<td>wet_2 = 250g</td>
<td>Cotton IMP</td>
<td>3.42</td>
<td>100</td>
<td>242</td>
<td>1246</td>
<td>697</td>
<td>155</td>
<td>395</td>
</tr>
<tr>
<td>wet_3 = 500g</td>
<td>Cotton IMP</td>
<td>3.0</td>
<td>130</td>
<td>315</td>
<td>1049</td>
<td>611</td>
<td>136</td>
<td>302</td>
</tr>
<tr>
<td>wet_3 = 500g</td>
<td>Cotton IMP</td>
<td>3.0</td>
<td>148</td>
<td>359</td>
<td>1121</td>
<td>611</td>
<td>136</td>
<td>374</td>
</tr>
</tbody>
</table>

Table 4: Calculations of heat balance using manikin heat fluxes and water losses from underwear (outerwear accumulation deducted). Thermal balance is done over the exposure duration.

The deficit in the thermal balance was again present and it was found not to be very different for the various conditions.

Interestingly, under these conditions, it did not seem to differ as a function of the amount of water nor of the permeability of the coverall. The difference appears to be
somehow systematic and the mean value was 345 KJ for a 3 hour exposure. This surplus in the thermal balance of the manikin corresponds therefore to 35 Watts, a value not far from that previously found under the Series I conditions.

### 4. Conclusions

**Wetting the underwear** has two major consequences:

- It decreases considerably the thermal insulation of any ensemble, permeable or not. In the case of an impermeable coverall, the nature of the underwear implies different decreases in the thermal insulation: for instance the Helly Hansen® underwear had an effect twice as large as the Next to Skin underwear. This probably depends on the capacity of the underwear to release its water content thereby increasing the amount of water absorbed by the outer layer, which in turn may lead to a more pronounced decrease in thermal insulation (Chen et al 2003). This observation should be considered for people working hard and therefore sweating in ambient conditions requiring impermeable coveralls. This decrease in the thermal insulation of impermeable clothing does not seem to be a function of the ambient conditions since exactly the same value was found for cotton underwear + IMP at 10 and 20°C. The thermal insulation drop is also found to be a function of the coverall permeability, it decreases more in the case of larger permeability.

- It resulted in an increase in manikin heat production (which reflects the drop in thermal insulation) but in addition, it leads to a thermal imbalance between dry and evaporative heat losses when an overall heat balance is calculated from the observed results. This verifies a point found previously in our laboratory and by others from the same group (Havenith et al 2006 and Richards et al 2006) which implies that some other thermal phenomenon occurred which disturbs the simple calculations usually made. Mechanisms of condensation and later evaporation on, or inside, the clothing layers are thought to be responsible (Lotens et al 1995) and their values appear not to be negligible.

It seems that the water after condensation onto the inner surface of the coverall does evaporate again, requiring additional heat for this probably coming from the manikin heating system. In terms of the cooling effect, the conclusion would be that the apparent efficiency of the evaporation could be larger than 1 for impermeable garments, since the energy required for the thermal balance is much larger than expected from the theoretical calculations.
5. Acknowledgements

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6. References


Establishing Fit Specifications for Thermal Manikins

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Abstract

Thermal manikins have been used to measure the thermal insulation of clothing systems for many years. Researchers around the world have studied and collected data with regard to clothing ventilation, fabric air permeability, and manikin movements. Each of these variables has been found to contribute to the thermal insulation of garments. In order to obtain consistent and reliable data, studies have been conducted to determine the reproducibility of the values across laboratories with different types of manikins. However, as these studies have found, the fit of the garments on the manikin is one of the many important factors that affect the garment thermal insulation values, while information regarding the garment fit is generally missing or overlooked in the testing procedures or data reported in the publication. Therefore, this paper proposes establishing size and fit guidelines for garment thermal insulation testing using thermal manikins. These guidelines would enable researchers to compare and repeat tests successfully.

Fit is defined as the ability to be the right shape and size. Results from research have shown that when the garment is loosely fitted, the air layer which is trapped between the body and the clothing will affect the total thermal insulation. Garment fit is classified as having either wearing ease or design ease. Wearing ease is the added measurement to the garment’s measurement to allow for body movement and breathing. In most cases this could be an additional measurement of 2 to 3 cm to a basic body measurement. For example, if the measurement around the chest of a manikin is 100 cm, then the chest circumference of the garment should be 105 cm in order to provide for wearing ease. When the fit of the garment is standardized and reported, the amount of air space could be calculated in order to obtain consistent and reliable data across laboratories and from different manikins. When using the manikin for garment thermal insulation testing, the size and design of the garment on the manikin are critical in obtaining valid data. Using techniques
and specifications developed for the apparel industry, guidelines and fit specifications can be easily established and communicated. Therefore, as guidelines and standards are being developed for the environmental conditions and testing procedures for thermal insulation testing using manikins, it is important that the fit and garment specifications be standardized and reported as well. By establishing sizing specifications, the thermal insulation value of a garment can be compared and reproduced reliably.

1. Introduction

Garment fit is like garment comfort. Both terms, fit and comfort, are defined in many different ways and often require a subjective measure. In clothing research, fit and comfort are broken down into components which can be measured objectively. We can measure the thermal insulation value of clothing and relate that value to a level of comfort. Garment fit can be defined as the ability to be the right shape and size. Good fit requires the balance between the dimensions of the body and the garment. The size and shape of the body and the garment can be measured and therefore a good fit can be achieved.

In order to obtain consistent and reliable data, studies have been conducted to determine the reproducibility of thermal insulation values across laboratories with different types of manikins. However, as these studies have found, the fit of the garments on the manikin is one of the many important factors that affect the garment thermal insulation values. Information regarding the garment fit is generally missing or overlooked in the testing procedures or data reported in the publication. Anttonen et al. (2004) did report that when garments were four times larger than required for the manikin there was a 10% higher insulation value. Zhihua and Yuhang (1999) also stated that ‘the fitness of clothing will directly affect testing results’.

This paper illustrates size and fit guidelines for garment thermal insulation testing using thermal manikins. These guidelines would enable researchers to compare and repeat tests successfully. The objective of this paper is to present how garment fit, which can be measured and controlled as clothing systems, is evaluated. For studies using thermal manikins, the subjective or psychological aspects of the garment do not need to be considered. The subjective nature of style and fit for the wearer is not a concern nor is the subject’s change in size or shape. Therefore, fit specifications for a thermal manikin and the garment worn can be controlled and reported.

2. Methodology

Using methods developed for the apparel industry, the fit and size of the garment and manikin can be easily reported and considered with the results. The advantage of reporting this information is that results between labs can be more easily compared and replicated. Reporting the fit of the garment will also enable the garment designs to be made in corresponding larger and smaller sizes for testing on human subjects.
2.1. Size

Two variables need to be considered when developing a properly fitted garment. One is the size of the body or manikin and the second is the size of the garment. The body size is different from the garment size. Most tests performed on the manikin are done with a garment that is not close or tight to the body, so body size and garment size should be reported in a test procedure.

An advantage of testing on the manikin is that clothing fit can be controlled. A thermal manikin does not gain or lose weight and does not change shape with age. Manikin size specifications are constant and measurable. Reporting manikin size should be part of any study. Just as the testing conditions are reported, the manikin size can be reported. Since each manikin has been developed to some anthropometric data, it would be a simple inclusion in any report to reference the source of the manikin’s anthropometric data.

Garment size is not the same as the body size. Stretch fabrics which may fit close to body should consider the stretch factor of the fabric in the garment measurements. Garment size should never be reported as a size given by a manufacturer. In the United States, vanity sizing or target consumer sizing is prevalent. Vanity sizing is usually done to make the consumer or wearer feel better about the garment size they are purchasing or buying. Each manufacturer determines the size they use. Garment size can be given as specifications or measurements of garment features. Sizing guides or standards have been developed and can be used.

2.2 Garment Fit

A more difficult and subjective area of garment testing is garment fit. In the apparel industry, fit is defined as having either wearing ease or design ease. Wearing ease is the basic amount of extra room in a garment for breathing and moving. This is often standardized in companies or given as a tolerance level. In most cases, this could be an additional measurement of 2 to 3 cm to a basic body measurement. For example, if the measurement around the chest of a manikin is 100 cm, then the chest circumference of the garment should be 105 cm in order to provide for wearing ease. If more than 4 cm is added to the garment then it is larger than it should be for the manikin’s measurements, and does not fit. Simple measurement of the garments can provide more accurate results when testing.

Design ease is the fullness added to a garment to provide a desired look or shape to the garment. This ease is part of the design of the garment. Having a shirt that fits close at the chest and then falls loosely down to the hips, has design ease incorporated in the waist area. This is not standardized nor easily controlled, but can be reported.
3. Sizing and Fit Guidelines

3.1 Sizing

Understanding and reporting manikin and garment specifications would enable researchers to repeat tests across laboratories more easily. Size specifications include detailed dimensions of the garment, tolerances allowed within a size range, and the description of the procedures followed in measuring a garment. In most companies and anthropometric research, the procedures used to measure and the description of the location are followed from a manual such as given in the Spec Manual (2001) or Human Engineering Guide to Equipment Design (1972). The use of such a manual allows the garment specifications and body specifications to be listed easily without much explanation. Table 1. is an example of body and garment specifications for a knit shirt with set-in sleeve and ribbed cuff. The column labeled as POM (point of measure) is reference locations used in the Spec Manual (2001). The body measurements used the same POM locations. Tolerances describe the acceptable range of variation from a specification and based on the variation reported in anthropometric data. If dimensions are too far above or below the specification the garment will no longer fit, thus providing inaccurate results. Measuring a garment before testing on a manikin is less costly than testing with poorly sized garments.

<table>
<thead>
<tr>
<th>POM</th>
<th>Description</th>
<th>Tolerance (+/-) cm</th>
<th>Body cm</th>
<th>Garment cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Chest width</td>
<td>2.5</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>Across waist</td>
<td>2.5</td>
<td>41</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>Shoulder</td>
<td>1</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>Side</td>
<td>1</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>21a</td>
<td>Arm length</td>
<td>2</td>
<td>64</td>
<td>65</td>
</tr>
<tr>
<td>26</td>
<td>Wrist</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1: Body and garment specifications

If a research lab is obtaining ready made garments for testing, the garment specifications should be easily obtained from a manufacturer. Garment specifications are used to develop any garment product and should be available for the entire size range for the manufacturer. Different sizes are easily calculated through a manufacturer’s grading system. The grading system indicated the differences between sizes and how the differences are distributed across the body. An example is when a cross-chest measurement increases 3 cm from one size to the next, the 3 cm is distributed such that 0.5 cm is included in the neck measure and 1 cm is added to the shoulder and the remaining 1.5 cm is included in the armhole width or underarm.

3.2. Fit

When the fit of the garment is standardized and reported, the amount of air space can be calculated in order to obtain consistent and reliable data across laboratories and from different manikins.
Current studies have evaluated the effects of air trapped between the body and the garment. Kim et al. (2002) studied air gaps entrapped in protective clothing systems. The researchers discovered that the size and distribution of air gaps depend on the drape of the protective garment fabrics as they rest on the underlying geometry of the human body. They also conclude that the air gaps were consistent because the shape of the male human body is alike even though the sizes are different. Reporting the fit of the garment would provide more reliable results across laboratory and garment designs. Yu (2000) indicated that an advantage of using a static manikin for fitting garments that the fit is highly repeatable.

Fit on the thermal manikin can be evaluated as fit of fashion garments are evaluated on dress forms. Numerous evaluation tools and protocols are available to researchers to evaluate fit. In general, the evaluation should address how the garment hangs on the body. Fit standards include how much ease is needed. Ease depends on the type of product, the materials used and the body portion the garment covers. In fit standards simple evaluation of the balance ease, and positioning of the garment can be critiqued. Developing a fit protocol can be part of any project, such as ASTM F1154-99a Standard Practices for Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles. If a more objective measure is needed, using a liker scale instrument can be developed which can give a score to the garment fit, such as the checklist developed by Ashdown and O’Connell (2006).

4. Discussion

Evaluating and reporting the size and fit of garments being tested on thermal manikins is not difficult. Though many studies have concluded that fit and design of the garment were important, none seemed to evaluate or report how these variables were measured or controlled. As in the apparel industry, these variables do not need to be standardized, just reported.

When using the manikin for garment thermal insulation testing, the size and design of the garment on the manikin are critical in getting valid data. Using techniques and specifications developed for the apparel industry, guidelines and fit specifications can be easily established and communicated. Therefore, as guidelines and standards are being developed for the environmental conditions and testing procedures for thermal insulation testing using manikins, it is important that the fit and garment specifications be standardized and reported as well. By establishing sizing specifications, the thermal insulation value of a garment can be compared and reproduced reliably. Knowing the fit and size of test garments will allow researchers to accurately reproduce garments for human subjects that do not have the manikin’s size.
5. References


Initial, Transient and Steady State Evaporative Resistance of Impermeable Protective Clothing

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Abstract

The measured water vapour resistances of clothing ensembles differ among laboratories, particularly for impermeable clothing. Due to the moisture transfer in the clothing ensemble, evaporative heat losses in initial, transient and steady state phases are different. The purpose of this study was to investigate moisture absorption inside underwear and outer layer as a function of time, to quantify the difference in water vapour resistance of protective clothing (impermeable outer layer and cotton underwear) in initial, transient and steady states. Manikin Tore was used, wearing a wet ‘skin’ to simulate sweating. The evaporative resistance is found to be more than two times higher in the initial phase than that in the saturation phase. The moisture content increases exponentially in the clothing ensemble. On the contrary, mass loss directly from the wet skin decreases exponentially. These may partly explain the poor reproducibility while measuring the evaporative resistance of impermeable clothing for a short period.

1. Introduction

Water vapour resistance is one of the most important properties of clothing, but it is not as commonly determined as dry insulation. The measurement techniques are more complicated and the measured values differ among laboratories (McCullough et al 2002 and Richards and McCullough, 2005). There are currently three types of whole body manikin methods being used to measure the evaporative heat loss of clothing ensembles: pre-wetted underwear or skin covered on dry manikins, the manikin with pump regulated constant water supply to the skin surface, and the sweating fabric manikin based on a water filled body covered with waterproof but vapour permeable fabrics (Meinander, 1997; Fan and Chen, 2002, Richards and
McCullough, 2005 and Havenith et al 2006). Some of these methods employ 40 minutes to 3 hours measurement periods. The sweating manikin Walter in Hong Kong requires hours to reach the steady state for cotton underwear and impermeable coverall ensembles (Gao et al 2006). ASTM standard (2005) requires the manikin to ‘reach steady state (that is, the mean surface temperature of the manikin and the power input remain constant ±3%, and test ensemble reaches equilibrium condition and water is available on the surface for evaporation)’. Obviously, according to this standard, different ensembles require different measuring times. Unlike dry heat transfer, due to the more complicated nature of liquid and vapour transfer, capillary action, evaporation, condensation, conduction, etc. the coupled heat transfer between a sweating skin and different clothing layers and the adjacent air layer is more complicated and takes a much longer time to reach the steady state depending on the different types of clothing materials (e.g. impermeable), thickness of clothing, and ambient conditions. The initial state and transient state evaporative resistances can be practically as important as the steady state one, for instance, protective clothing may only be used for a short period.

The purpose of this study was to measure the mass loss from skin as well as from the total manikin system, to investigate moisture absorption inside underwear and outer layer as a function of time, to determine water vapour resistance of protective clothing (impermeable outer layer and cotton underwear) in initial, transient and steady states, and to help to improve the measurement methods.

2. Methods

2.1. Manikin

The thermal manikin Tore was used for measuring dry insulation and was also used to simulate sweating by wearing a wet ‘skin’. Tore is divided into 17 individually controlled zones. The surface temperatures of all the zones were kept at 34 °C, heat losses, manikin surface temperature, wet skin surface temperature and ambient temperature were recorded at 10-second intervals. When used to measure evaporative heat loss, it was covered with a pre-wetted wool stretch ‘skin’ (Ullfrotte 200g/m², 60% wool, 25% polyester, 15% polyamide). In order to fully wet the skin and prevent dripping water, a washing machine was used to rinse the skin for 4 minutes and then centrifuge it for 4 seconds. It contained about 640 g of water (moisture content: 162% of the initial mass). The advantage of this method is that moisture is evenly distributed over the whole skin area. Thermal couples were taped at eight sites on the wet skin in order to record “skin” surface temperature at 10 second intervals. The eight sites were left upper arm, left chest, left scapula, left front thigh, belly, lower back, right lower arm and right calf. Head, hands and feet were uncovered during the tests and thus excluded in the calculations.

2.2. Clothing

Clothing ensemble with COtton underwear (shirt and pants) and Impermeable coverall (polyamide with outer PVC coating) from EU Thermprotect were used (Havenith et al, 2006). A dry and a wet test were carried out separately for the same
Test conditions in the climatic chamber were as follows (Table 1). The clothing saturation phase was achieved by totally wetting the cotton underwear using the same method to wet the skin (it contained about 990 g water, moisture content: 166% of the initial mass).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Dry ’skin’, Ta=20 °C, Va=0.2 m/s, RH=46%</th>
<th>Wet ’skin’, Ta=20 °C, Va=0.2 m/s, RH=46%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase (p)</td>
<td>1st phase</td>
<td>2nd phase</td>
</tr>
<tr>
<td>Duration</td>
<td>1h</td>
<td>1h</td>
</tr>
<tr>
<td></td>
<td>1.5h</td>
<td>2h</td>
</tr>
<tr>
<td></td>
<td>3h</td>
<td>3h</td>
</tr>
<tr>
<td></td>
<td>2h</td>
<td>2h</td>
</tr>
</tbody>
</table>

Table 1: Test conditions, phases, duration for ‘Imperm+CO’ ensemble

Experimental procedure for the sweating test

One sweating test run consisted of 5 test phases (Table 1), which was determined based on pre-tests to ensure a linear overall mass loss rate of the manikin system on the balance, and thus assuming moisture saturation maintained in the wet skin (McCollough et al 2002 and Havenith et al 2006).

- The climatic chamber was set to the desired condition; the manikin was placed on the balance and heated continuously prior to the test. The weight of the nude manikin was set to zero on the balance.
- The test clothing was placed inside the climatic chamber overnight for conditioning.
- Before each test, in order to fully wet the skin and to prevent water from dripping, a washing machine was used to rinse the skin for 4 min. and then centrifuge for 4 seconds.
- The wet skin was weighed before and after each test.
- The underwear and outer layer were weighed before and after each phase.
- Dress the wet skin, tape thermal couples at 8 sites on the wet skin in order to record skin surface temperature at 10 second intervals using Testo 177-T4 temperature data logger.
- Dress underwear and outer layer as quickly as possible. Tighten the outer coverall, the string around the waist, sleeve and feet openings with the self-sealed band provided. No additional tightening measures around the neck.
- Start recording skin temperature, start manikin program, ambient temperature (at 0.1, 1.1, and 1.7 m height from feet), weight (BalanceLink); all recordings were set at 10 second intervals.
• After each test phase during one test run, the outer garment and underwear were undressed, and weighed as quickly as possible. Plastic bags were used where necessary to prevent the loss of moisture.
• Spray water (at 33°C) as evenly as possible onto the skin. The amount of water sprayed was equal to the amount of mass lost from the wet skin during the previous phase.
• Dress again the under and outer garments.
• Repeat the above last three procedures until the end of the entire test run, stop all recordings, undress manikin and weigh all garments and the skin.

2.5. Calculation and analysis

The dry heat loss is calculated based on the last 10 minute stable state values, excluding head, hands and feet. For the dynamic wet test, the total heat loss registered for the manikin was averaged for each 10 minutes, excluding the 1st 10 minutes during each phase. The evaporative heat loss, based on the overall mass loss recorded in each phase, was also calculated each 10 minutes. Since before and after each phase, the inner and outer garments were weighed, therefore, the mass loss from the wet skin of each phase can be calculated as:

\[
\text{Skin mass loss rate (g/h)} = \frac{(\text{underwear mass gain} + \text{outer garment mass gain} + \text{total mass loss})}{\text{time}}. \tag{1}
\]

Skin mass loss can also be directly measured before and after each phase as the manikin was placed on the balance. Skin mass loss in the saturation phase is determined this way since the saturated underwear might also act as a moisture source.

Wet skin surface temperature is area-weighted, summed, and averaged for each 10 min in each phase:

\[
\bar{t}_{\text{wsk}} = \sum f_i * T_{si}, \tag{2}
\]

where \(f_i\) is the fraction of the covered manikin surface area represented by the surface area of segment i.

Enthalpy of evaporation at wet skin surface (J/g)=0.001*(2.792*10^6 – 160*T – 3.43*T^2) \tag{3}

During each phase, evaporative heat loss (W/m^2) is calculated for each 10 min, excluding the 1st 10 min:

\[
\text{Overall Evaporative heat loss (W/m}^2) = \frac{\text{manikin evaporative rate (g/h)} * \text{enthalpy of evaporation (J/g)}}{3600 * \text{wet skin covered manikin surface area (m}^2)}. \tag{4}
\]

Extra Heat Loss (or conduction-condensation heat loss) is calculated as:
Extra Heat Loss = Total Manikin Heat Loss (measured during wet test) – dry heat loss (measured during dry test) – overall evaporative heat loss. [5]

Assuming that the wet skin was saturated, the total evaporative resistance in each phase is calculated as:

\[ R_e = \frac{\text{skin vapour pressure} - \text{ambient vapour pressure}}{\text{evaporative heat loss}} \] [6]

3. Results and discussion

3.1. Mass losses and moisture absorption

The overall manikin weight recorded in different phases shows linear reductions over time (Fig. 1), from which the overall manikin mass loss rate is calculated and shown in Fig. 2 (lower curve). Mass loss rates from the wet skin are shown in Fig. 2 (upper curve). The mass loss rate from the skin is much faster in the initial phase than in the transient and steady state phases, 96% of the skin mass loss is absorbed by the cotton underwear (Fig. 3). Only a very small fraction (4%) is evaporated from the clothing system into the environment. The moisture content gain ((mass gain/initial mass) x 100%) shows exponential relations for both the underwear and outer layers (Fig. 3).

3.2. Three types of heat losses and evaporative resistance

The total evaporative heat loss calculated from the overall mass loss rate shows that it increases with time (Fig. 4) due to the moisture gain in the garments, especially in the cotton underwear (Fig. 3). The total evaporative heat loss is more than twice as high in the saturation condition (9.8 W/m²) than that in the initial phase (4.7 W/m²), and 29% higher than in the 2nd phase (7.6 W/m²) and 62% higher in the 2nd phase than that in the initial phase. The calculated evaporative resistance decreases with time (Fig. 5). The last phase is the saturation condition, which is theoretically the equilibrium condition since the outer layer is impermeable. This is the condition that the ASTM standard requires and the manikin Walter system is intended to reach. For clothing ensembles with impermeable outer layer, the steady state is reached after both the skin and the ensembles are saturated. This requires a longer time than that reported in the literature (McCullough et al 2002, Richards and McCullough 2005 and Havenith et al 2006). This might be one of the main reasons for the large inter-laboratory variations when measuring the evaporative resistance of impermeable clothing for a period of 2-3 hours. The evaporative resistance in this study is higher than that measured on Walter using the same clothing, which is due to the fact that Walter’s uncovered head was included in the calculation (Gao et al 2006). Another explanation is that the outer garment is more tightly fitted on Tore than on Walter (the size of Walter is smaller).
In addition to the dry and the evaporative heat losses, there exists extra heat loss (about 20 W/m²) (Fig. 4), which is attributed to moisture condensation and conduction within the clothing layers. This has been discussed in detail by Havenith et al (2006) and Richard et al (2006). The extra heat loss together with the evaporative heat loss calculated from mass loss, is termed “apparent evaporative heat loss”. This extra heat loss is, however, included in the dry heat loss in the manikin Walter system (Gao et al 2006).
The total heat loss from the manikin is stable throughout all phases and seems unaffected by the increase of the evaporative heat loss. This cannot be explained by the increase in evaporation and by condensation and conduction, which otherwise should have resulted in greater total heat losses. There may be several reasons. One possible explanation is that in the saturation phase, the evaporation partly takes place from the underwear, which does not immediately and directly influence the manikin heat loss. Another reason is that the tested clothing ensemble covered a slightly greater area than the area used to calculate the total manikin heat loss. The evaporation might have increased partly from around the neck, wrist and ankle regions; these areas were not included in the calculation of the covered area of the manikin. Furthermore, the dripped water would also have evaporated, which did not take heat away from the manikin. Finally, due to the saturation in the middle layer, the partial vapour pressure gradient between the wet skin and the middle layer became smaller, which resisted the evaporation from the skin.
4. Conclusions

The moisture content in the ensembles increases exponentially with time. Mass loss directly from the wet skin decreases exponentially. Measuring the evaporative resistance of the clothing ensembles with a hygroscopic inner garment and an impermeable outer garment takes hours for both layers to reach saturation state. Measured values in initial, transient and steady states (moisture saturation in the clothing ensembles) are therefore different if calculated from the total manikin mass loss into the environment. Evaporative resistance is found to be more than two times higher in the initial state (1st hour) than that in the saturation state. This might be one of the main reasons of poor reproducibility when the measurement time is too short.

In a cool environment, with the above clothing ensemble, there exists three types of heat losses, i.e.; 1) dry heat loss (obtained from dry measurement) due to radiation and convection, dry heat loss is about 57% of the total heat loss during wet measurement; 2) heat loss due to condensation and conduction (28% of the total heat loss) and 3) evaporative heat loss (15% of the total).

![Figure 5 Initial, transient and steady state evaporative resistance](image-url)
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The Effects of Walking on Dry Heat Exchange of a Newly Developed Fire-fighter’s Clothing

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Abstract

The aim of this study is to estimate the dry heat exchange of a newly developed fire fighter’s clothing using a thermal manikin. As it is important to simulate the walking of fire-fighters to study the pumping effect of air layers inside the clothing, we measured heat exchange under ‘walking’ (0.75 steps/s, 0.45 m/s) as well as to standing posture conditions. In this study, we used a climate chamber to keep the room temperature at 20°C and humidity at 50% around the thermal manikin. The total clothing heat resistance (Rt) was measured at a skin temperature of 34°C. We tested three kinds of fire-fighter’s clothing, made from the same materials but in the different sizes (M, L and LL). Testing was also done on a T shirt, trousers, work gloves and boots under the fire-fighter’s clothing (MT, LT and LLT). The results showed that during ‘standing’ Rt was 0.225, 0.227, 0.229, 0.295, 0.300, 0.308°C·m²/W for M, L, LL, MT, LT and LLT, respectively, the Rt of LLT being significantly larger than that of MT and LT. The heat resistance calculated for each part of body showed that the hip region was the largest, followed by the back and stomach in every size. A large air gap would lead to an increase in Rt of LLT. During ‘walking’, Rt decreased to 0.164, 0.166, 0.157, 0.226, 0.231, 0.228°C·m²/W for M, L, LL, MT, LT and LLT, respectively. The Rt of LL was significantly lower than that of M and L and the large difference between the Rt of LLT and that of MT or LT (observed for standing) disappeared. The heat resistance decreased in the hip, back and stomach regions. These results showed that Rt was reduced by ‘walking’ and that of the Rt of large fire-fighter clothing decreased due to the associated air gap. The heated air near the manikin skin presumably had a greater chance escape from the larger gap between the clothing and the manikin skin, through the larger space.
1. Introduction

Fire fighters are exposed not only to external heat from fire but also to internal heat produced by their physically demanding tasks. They are at high risk in terms of heat disorders during their intensive work, such as fire extinction, personal assistance and rescuing people from disasters. In the practice, when fire-fighters exercise in heat (Rossi, 2003), radiation is the largest component, reaching more than 10kWm\(^{-2}\). The environment temperature was more than 100°C. Fire-fighter clothing worn when fighting fire are made to protect against external heat, therefore their heat resistance is very high. In the experiment (Rossi, 2003), the heat production during exercises in a heated room was estimated to be at least 500W. In another study of fire-fighters (Holmer, 2006), metabolic rate reached about 600W/m\(^{2}\) in the most physically demanding task, even under normal temperatures. Rescuing persons from places of risk is the hardest work (Heimberg, 2006). Other physiological tests (Ftaiti, 2001) of fire-fighters, with fire protective clothing during treadmill exercises, showed that there was a significant increase in heart rate and body core temperature compared to that measured without fire protective gear. This indicated that considerable heat is accumulated within the fire-fighter’s clothing and that core temperature increases sharply. This hyperthermia caused by physical stress and wearing fire protective clothing could reduce physical activity (Tucker, 2004) and increase the probability of injury. It therefore is important to reduce the heat resistance of fire-fighter clothing.

As the air gap and microenvironment ventilation are important factors in determining the heat resistance of clothing, three sizes of fire-fighter clothing were measured under ‘standing’ and ‘walking’ conditions. Moreover, T shirt, trousers, work gloves and boots, under the fire-fighter clothing were incorporated in the test, in order to bring the experimental clothing close to the actual outfit.

2. Method

We measured dry heat resistance of fire-fighter clothing using a thermal manikin (Measurement Technology NW, Seattle WA) in a climate chamber at a temperature of 25°C.

2.1. Garments

We tested the following clothing: M (medium size fire-fighter clothing: 83cm waist, 70cm inside leg), L (large size fire-fighter clothing: 90 cm waist, 70cm inside leg), LL (extra large size fire-fighter clothing: 98 cm waist, 70cm inside leg), AB (T shirt + trousers), MT (M + AB + boots + work gloves), LT (L + AB + boots + work gloves), LLT (LL + AB + boots + work gloves). The fire-fighter clothing and trousers were made of Meta Aramid.
2.2. Manikin

The thermal manikin was of an Asian size (169 cm height, 75 cm waist) and had 5 pairs of joints in the shoulders, elbows, hips, knees and ankles) and could simulate a walking motion. ‘Standing’ and ‘walking’ at 0.45 m/s (0.75 steps/s) were investigated. The skin temperature was set 34°C for the 26 body shell zones. Electric heat power supplied from a Power Enclosure was automatically controlled to keep the shell temperature at 34°C. These measurements were made for each garment in both ‘standing’ and ‘walking’ modes.

2.3. Calculations

Total clothing heat resistance (Rt) was calculated by the “parallel method”. Each body part’s heat resistance was also calculated to estimate the partial resistance by using equation (1):

\[ Rti = fi \times (Tsi - Ta) \times ai / Hdi \]

Where, Rti: heat resistance of i parts; fi: body surface area ratio of i th body region; Tsi: surface temperature of i th body region; Ta: air temperature; ai: body surface area of the i th body region.

3. Results

Figure 1 shows the results for Rt, its standard deviations being less than 2.5%. During ‘standing’, LLT was significantly greater than LT and MT. In contrast, LL was significantly smaller than L and M during ‘walking’. By ‘walking’ at 0.45 m/s, Rt was reduced by between 20.2 and 31.6%. The smallest reduction was for the nude manikin and the largest was LL. The heat resistance of each body part during ‘standing’ is shown in Fig. 2A and ‘walking’ in Fig. 2B. In the shoulder, stomach and back regions, the heat resistance of the clothing was largely decreased, except for the nude manikins. For the nude manikins, the heat resistance was reduced in the hand and foot regions.

![Figure 1](image-url)  
*Effect of ‘walking’ at 0.45 m/s on total heat resistance of fire-fighter clothing of different sizes.*
Section VI: Testing & Standardization

Each symbol indicates the following: M: medium size, L: large size, LL: extra large size, AB: T shirt + trousers, MT: M+AB+boots+work gloves, LT: L+AB+boots+work gloves, LLT: LL+AB+boots+work gloves.* p < 0.05

4. Discussion

Rt during ‘walking’ at 0.45m/s was lower than during ‘standing’. When the fire-fighter clothing increased in size, the Rt of LLT was larger than that of MT or LT during ‘standing’. In contrast to this, the Rt of LL was lower than that of M or L during ‘walking’. The ratio of heat resistance during ‘walking’ to that during ‘standing’ was most reduced in the shoulder, stomach and back regions.

To investigate the heat resistance effect of the air layer inside the fire-fighter clothing, different sizes of fire-fighter clothing were tested. During ‘standing’, though there was no difference in the Rt of the M, L and LL, clothing, there were significant differences between those of the MT, LT and LLT clothing. It could be concluded that the T shirts or trousers between the skin and the fire-fighter clothing had the effect of increasing the air layer inside the fire-fighter clothing. It is felt that during ‘walking’ the air between the skin and fire-fighter clothing moved more easily through the larger gap, because the Rt of LL decreased more than that of L or M.
Figure 3 shows the ratio of heat resistance during ‘walking’ to that during ‘standing’ for each of the 26 body parts, Rt being calculated by the parallel method. For the nude manikin, the extremities of the body parts (forearm, hand, calf and foot), which swung during ‘walking’, the ratio was reduced most due to the disturbance of the outside air layer while that of the body trunk was not reduced as much due to the small disturbance of the air layer. For M, L and LL, the ratio for the body trunk was low. In particular that of LL was lower than that of M and L for the trunk, body, hip and thigh. In the calf regions, the reduced Rt was relatively high, indicating that the air layer around the calf did not move to the outside or come inside as expected. The Rt for the hand and foot was the same as that for the nude, since the hand and foot were also nude. For MT, LT and LLT, the Rt for the body, trunk and calf was reduced for M, L and LL while the heat resistance for the calf, foot and hand regions was not reduced as much as they were covered with boots or work gloves.

Compared to the results of other researchers (Havenith, 1990) in terms of the ‘walking’ effect on Rt, the present Rt results during ‘walking’ were about 0.02-0.04°C m²/W lower than that obtained by them, suggesting that the air could move more easily during ‘walking’ in the fire-fighter clothing used here.

![Figure 3](image_url)

**Figure 3** Ratio of heat resistance during ‘walking’ to that during ‘standing’ for each of the 26 body parts, and as well as for total heat resistance.

Each symbol indicates the following: M: medium size, L: large size, LL: extra large size, AB: T shirt + trousers, MT: M+AB+boots+work gloves, LT: L+AB+boots+work gloves, LLT: LL+AB+boots+work gloves.
5. References


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Application of Human-Clothing-Environment Simulator to Determine Comfort Properties at the Extreme and/or Transient Conditions

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Abstract

In order to predict comfort properties of the garments at the end use condition, Human-Clothing-Environment simulator is developed. Microclimate temperature and humidity change, surface temperature of the fabric and sometimes the fabric weight change are recorded at various sweat pulse/level and environment conditions when layers of fabrics are incorporated. The coupled heat moisture transport properties at static, dynamic and/or extreme end use conditions are observed. Three applications are shown as examples. 1) Buffering capacity and moisture management properties were calculated based on the temperature and the relative humidity data collected. The depth and width of the well of the graph formed by the initial state of the transient period was analyzed: clothing system with hydrophilic layer showed better buffering capacity than hydrophobic layer and hydrophobic layer showed better moisture management properties than hydrophilic layer. 2) Effect of PCM and air inflation on the temperature adaptability was compared: PCM showed heat release and higher buffering capacity than inflated air and control at the very initial period time, but after 30 minutes or so, the microclimate temperature was lower than air inflation and even the control. 3) Effects of layer design on the heat and moisture transport and condensation within cold weather ensembles at subzero condition: layer layout of a multiplayer clothing system can alter the condensation profile within each garment layer even if the total condensation mass flux is almost the same. When insulating layer is separated from the waterproof breathable fabric, condensed moisture is kept away from the body efficiently and the
results can provide a useful insight on the layer design of cold weather protective gears. These examples of application show how to use this instrument to establish criterion for establishing thermal and comfort parameters for a garment or garment system.

1. Introduction

In order to assess the comfort properties of fabrics or garments, the 5 level tests (level 1: Physical Analysis, Level 2: Biophysical Analysis, Level 3: Human Validation, Level 4: Controlled Field Test, Level 5: Field Trial) (Goldman, 1978) are being used depending on the requirements for the information, reproducibility and cost. Scientific information with reproducibility can be obtained at lower level and as the level goes up physical and biophysical evaluations are introduced to make prediction model, and validation of prediction is performed by human subject tests. Often times, the final step, the human subject test or user trial provides questionable results unless the lower level tests are preceded. Likewise, each level provides key elements to predict comfort properties of the test garments. In other words, to predict comfort properties of the fabrics or garments, lower level tests should be adequately provided.

Recently, functional clothing including smart or intelligent textile systems of temperature/humidity adaptation is competitively produced. We need proper test method to predict and verify the end use specific performance properties of these functional clothing. There are limits to measure these functional clothing by the traditional skin models (ISO 11092) or thermal manikins. In our lab, new instrument is developed to measure comfort related properties at transient conditions where consumers are frequently encountered through their daily life, and at extreme conditions where the clothing is required but have difficulty to test at the given environmental conditions. The basic concept of the instrument is a skin model but layers of fabrics can be mounted as we wear layers of garments and two separated chambers make it possible to provide a wider control range than the conventional type so that the performance of functional textiles can be studied in the range of extreme outdoor conditions and transient conditions. As the instrument is composed of skin part, clothing part and environment part, it is called the Human-Clothing-Environment (HCE) simulator (Korea patent, 2004, USA patent pending, 2005).

The construction and the features of the HCE simulator are described and the reproducibility/accuracy and the advantageous characteristics over existing apparatuses are explained in the previous studies (Kim et. al., 2003). In this paper advantages over a traditional static type experiment were demonstrated based on the some of the applications we have practiced.
2. HCE Simulator

The HCE is composed of a vertical guarded hot plate with sweating device for skin and clothing system, and two chambers to simulate various environmental conditions. The control range of hot plate is 22 to 42°C and mostly set at 34±0.5°C to simulate average human skin temperature at comfortable condition. The required input power to maintain the temperature constant is recorded. Temperature and humidity sensors (CHS-APS, TDK) are located in each fabric layer to monitor the microclimate of the clothing system. The sweat-distributing layer is attached onto the hot plate and the sweat pulse/level can be controlled with consideration of activity level and/or environmental conditions using micro water supply pump (IPC ISM 932, Ismatec) with 6 channels. Two detachable environmental chambers are individually controlled from -30°C to 18°C for the cold conditions and from 18°C to 50°C for warm conditions. The control accuracy of the temperature and humidity is ±0.5°C and ±2%, respectively.

![Figure 1 Human-Clothing-Environment Simulator](image)


3.1. Purpose

Often times the comfort properties measured under the steady state conditions cannot predict the performance of clothing under actual wear situations as the heat and moisture transport mechanisms through a clothing system are very complicated at the transient and dynamic condition. In this study, two fleece shirts, which have very similar thermal insulation property and same thickness but the hydrophilicity is different, were compared how the microclimate changes when the environmental condition changes from warm to cold as if we go in and out of rooms wearing the garments.

3.2 Experimental

3.2.1 Specimens

Two sets of 3 layer fabric combinations were constructed. The characteristics of the specimens and the layer layout are shown in Table I.
3.2.2 Test Procedure
The simulated clothing system was exposed to a warm chamber (28°C, 50% RH) for 30 minutes and quickly connected to the cold chamber set at 0, -10, or -20°C for 30 minutes respectively. Temperature and the relative humidity profile inside each fabric layer systems layer were collected and recorded every 30 seconds by the data logging system. Two levels of sweat (65g/m²·h for light sweat, 160g/m²·h for heavy sweat) were applied to the hot plate.

Table I: Characteristics of Test Fabrics and Layer Layout

<table>
<thead>
<tr>
<th>Fabric layer</th>
<th>Fiber content</th>
<th>Weave type</th>
<th>Air Permeability (cm³/cm²/s) **</th>
<th>Thermal Insulation (%)*</th>
<th>Thickness (mm)</th>
<th>Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st undershirt layer</td>
<td>100% PET</td>
<td>Knit</td>
<td>124.40</td>
<td>11.20</td>
<td>0.16</td>
<td>143.5</td>
</tr>
<tr>
<td>2nd shirts layer</td>
<td>100% PET</td>
<td>Fleece</td>
<td>103.33</td>
<td>65.80</td>
<td>1.63</td>
<td>249.5</td>
</tr>
<tr>
<td></td>
<td>100% Wool</td>
<td>Fleece</td>
<td>41.80</td>
<td>63.71</td>
<td>1.63</td>
<td>359.5</td>
</tr>
<tr>
<td>3rd outer layer</td>
<td>2layer ePTFE Laminated</td>
<td>-</td>
<td>55.40</td>
<td>55.40</td>
<td>0.24</td>
<td>113.0</td>
</tr>
</tbody>
</table>

3.2.3 Buffering Capacity and Moisture Management Properties at Transient Condition (Mₘₜ)
Indices of temperature buffering capacity were calculated based on the following equation (1).

\[ B_t = \frac{C}{\tan \alpha \cdot \Delta T_{\text{init-final}}} \]  

Where, \( B_t \): temperature buffering index  
\( \tan \alpha \): Initial decrease rate of microclimate temperature  
\( \Delta T_{\text{init-final}} \): temperature difference between initial and final state  
\( C \): constant (100)

Indices of moisture management properties at transient condition \( (M_{\text{mt}}) \) were calculated using the equation (2).

\[ M_{\text{mt}} = \tan \beta \cdot \Delta P_{\text{init-final}} \cdot K \]  

Where, \( M_{\text{mt}} \): moisture management index at transient condition  
\( \tan \beta \): initial decrease rate of microclimate vapor pressure  
\( \Delta P_{\text{init-final}} \): vapor pressure difference between initial and final state  
\( K \): constant (100)

3.3. Results and Discussions
Buffering capacity index and moisture management index were calculated for wool and polyester clothing systems at two sweat levels when the environmental condition was changed from room temperature to 0, -10 and -20°C. As is shown in Fig. 2, temperature buffering capacity for wool was higher than PET especially at
the high sweating condition. The low sweat level did not show much difference by 
the hydrophilicity of the fabric. Moisture management property (Fig. 3) showed that 
the hydrophobic fabric was better than the hydrophilic fabric.

![Figure 2 Temperature buffering capacities (B_t)
of wool and PET clothing systems](image1)

![Figure 3 Moisture management capacities (M_m)
of wool and PET fabric layer](image2)

The temperature buffering capacity decreases as the environmental temperature 
decreases. The difference was bigger at the higher sweat level.

3.4. Summary

The ambient temperature changes and the sweat rates as well as the fabric 
hydrophilicity affected the temperature buffering capacities of the clothing under 
transient conditions. Considering that the thermal insulation was similar for the two 
fabrics, it was easy to observe the microclimate temperature difference when the 
system was exposed to lower ambient temperature. In other words, the hydrophilic 
fabric is expected to give buffering effect when the garment system is exposed 
sudden changes to cold environment. Moisture management property was better 
with the hydrophobic fabric than hydrophilic fabric.

4. Application 2: Comparison of PCM and air inflation for 
temperature adaptability (Yeo, et al., 2005)

4.1. Purpose

PCMs are advantageous in terms of storing and releasing heat minimizing the 
microclimate change, by which keep the wearer comfortable. Recently, by using 
trapped air, which is the most effective insulator, inflation and deflation is applied to 
the clothing system depending on how much warmer or cooler the wearer would like 
to feel especially at the cold environment. In this study, the efficiency of the two 
systems was compared in terms of temperature range that can be regulated and the 
response time to reach to the comfortable macroclimate in a transient condition of 
warm to cold.
4.2. Experimental

4.2.1 Specimen

PVC pouch was made to contain and test PCM and air inflation and incorporated to make clothing system with PET knit and PTFE laminated fabric. Their characteristics are shown in Table 2 and the layout for each test is shown in Table 3.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Fiber content</th>
<th>Weave type</th>
<th>Thermal Insulation (%)</th>
<th>Thickness (mm)</th>
<th>Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st undershirts</td>
<td>100% polyester</td>
<td>Knit</td>
<td>11.22</td>
<td>0.71</td>
<td>143.5</td>
</tr>
<tr>
<td>2nd pouch</td>
<td>PVC</td>
<td>-</td>
<td>63.71</td>
<td>1.23</td>
<td>535.0</td>
</tr>
<tr>
<td>3rd outer layer</td>
<td>2layer ePTFE Laminated windstopper</td>
<td>plain</td>
<td>55.40</td>
<td>0.18</td>
<td>113.0</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of the specimens to test temperature adaptibility

<table>
<thead>
<tr>
<th>Clothing system</th>
<th>Layer layouts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Inflation</td>
<td>PET knit+PVC pouch(empt y)+PTFE film laminated fabric</td>
</tr>
<tr>
<td>PCMs system</td>
<td>PET knit+PVC pouch(PCMs 1g or 5g)+PTFE film laminated fabric</td>
</tr>
</tbody>
</table>

Table 3: Layer layout to test PCM and air inflation

4.2.2. Test Procedure

One chamber was maintained 30°C to simulate warm condition and another chamber maintained -5, -10, and -15°C to simulate cold condition. Clothing system was composed as Table 3. Between fleece and windbreaker, inserted was PCM containing or empty PVC pouch, which can be inflated or deflated by air pump. In the pouch, 1g or 5g octadecane (T_m 28.2°C, T_c 25.4°C, Heat Storage Capacity 244J/g) was evenly spread. The clothing system was exposed to warm environment for 30 minutes and then quickly moved to the cold environment. Air thickness was controlled to make 2cm by pumping air into the pouch with a gauge. Temperature buffering capacity was calculated based on the ratio of temperature drop after the cold exposure.

4.3. Results and Discussion

When the clothing system was exposed to warm environment, the two specimens, empty or PCM contained, showed the same temperature at each air layer(Fig. 4). When the system was moved to cold environment, the microclimate temperature dropped instantaneously. PCM slowed down the temperature drop and heat release was observed. Temperature changes between the PET knit and the P.V.C pouch layers showed clearly that 1g of PCM was not sufficient to provide temperature adaptable properties within clothing systems. The 5g of PCM containing system seemed to slow down the temperature drop due to heat release. However, the effects disappeared after about 20min and at the end of the test temperature went down to lower than that of the trapped air system. On the other hand, the trapped air provided steady insulation throughout the test period and the microclimate temperature was the highest and the efficiency was better at lower condition.
As the temperature differences between the warm and the cold conditions increased, buffering properties (Bt) decreased (Fig. 5). Comparing trapped air and PCM systems, 5g of PCM did work for temperature buffering properties at sudden ambient temperature changes and this might be mainly due to the slower decrease microclimate temperature. However, 1g of PCM showed even worse buffering capacity than control.

![Figure 4 Temperature changes of air and PCM after cold exposure to -15°C](image1)

![Figure 5 Buffering capacity of PCM and air](image2)

4.4. Summary

PCM is recognized as a smart material but needs certain level of quantity and environmental condition to meet Tc where as the air, which is pumped into the system showed the thermal insulation for the prolonged period of time. It was suggested to use the smart material to utilize this air.

5. Application 3: Effects of Layer Design on the Condensation within cold weather Ensembles. (Yoo and Kim, 2005)

5.1 Purpose

Since the accumulated moisture may freeze and be trapped within the clothing system and cause a reduction in heat resistance as well as wearer’s discomfort, the condensation in the clothing system has to be prevented, especially under the cold weather situation and with high activity levels such as winter sports or sweat causing physical activities. We tried to figure out the water vapor distribution in clothing system with various layer design.

5.2. Experimental

5.2.1. Specimen

In order to assess the layer design effects only, three layouts were constructed with identical sets of fabrics. The characteristics of the selected specimens are shown in Table 5. Five layers of fabrics were mounted to the sweating hot plate in three different layouts as shown in Figure 6.
<table>
<thead>
<tr>
<th>Fabric layer</th>
<th>Fiber type</th>
<th>Description</th>
<th>Weight (g/m²)</th>
<th>Thickness (mm)</th>
<th>Thermal resistance (Rct, m²°C/W)</th>
<th>Evaporative resistance (Ret, m²Pa/W)</th>
<th>Air permeability (cm³/cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>Polyester</td>
<td>Knit</td>
<td>143</td>
<td>0.16</td>
<td>-</td>
<td>-</td>
<td>124.4</td>
</tr>
<tr>
<td>2nd to 4th layers</td>
<td>Polyester</td>
<td>Fleece</td>
<td>246</td>
<td>1.63</td>
<td>0.083</td>
<td>11.68</td>
<td>103.3</td>
</tr>
<tr>
<td>outer layer</td>
<td>Polyester</td>
<td>ePTFE laminated waterproof</td>
<td>120</td>
<td>0.24</td>
<td>0.019</td>
<td>7.29</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5: The characteristics of the specimens to test condensation

![Table 5](image)

**Figure 6** Five-layer cold weather clothing layouts (Layout A: All separated; Layout B: separated with an extra air layer; Layout C: 4th and outer shell combined)

### 5.2.2. Test Procedure

The hot plate temperature was set at 34°C. Two sweat pulse (2 and 5 ml) were spread over the surface of the sweating hot plate to simulate light and heavy sweating. These are approximately equivalent to 65 and 160 g/m²/hr of sweat rate. The cold chamber was set at -15±0.5°C, 20±5% to simulate cold condition. The five-layer test ensemble was placed outside of the sweating skin and the plate unit was completed, it was connected to the cold chamber and kept in it for 1 hour. The data of the temperature and the relative humidity inside each layer were collected and recorded every 30 seconds through the data logging system. The vapour pressure profile was calculated from the data and the amount of condensation on each layer was measured by weighing the each fabric layer before and after the test.

### 5.3. Results and discussion

The total amount of condensation is very similar in the three layouts.(Table 6) However, it is clear that quite different behaviours are produced in individual layers as a function of the layer layout. The amount of condensation in individual layers for three layouts at different sweat levels is presented in Figure 7.
<table>
<thead>
<tr>
<th>Layout</th>
<th>Sweat Rate</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>65 g/m² hr</td>
<td>160 g/m² hr</td>
<td></td>
</tr>
<tr>
<td>(light sweat)</td>
<td>(heavy sweat)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>14.26</td>
<td>61.08</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>13.31</td>
<td>56.65</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>12.36</td>
<td>52.20</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Total amount of condensation of different layer layouts of cold weather ensembles at two different sweat rates

Representative profiles of the moisture distribution in the clothing system are shown in Fig 8.

5.4. Summary

It was shown that the layer layout of a multiplayer clothing system could alter the condensation profile within each garment layer even if the total condensation mass flux is almost the same. When insulating layer is separated from the waterproof breathable fabric, condensed moisture is kept away from the body efficiently and the results can provide a useful insight on the layer design of cold weather protective gears.
6. Conclusions

As is shown on the above applications, the Human-Clothing-Environment Simulator provides useful information to predict comfort properties from micro scale to macro scale. Ultimate goal of thermal comfort evaluation and prediction is to provide ‘meaning’ and guidelines for acceptable range to the ‘numbers’ we get from either models or apparatuses. For that purpose, we may create a large data base of thermo physical characteristics and human thermal responses for diverse textile materials using the proper methods, and also find reasonable relations between the two results.

Acknowledgments

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References


A Comparative Investigation of Clothing Moisture Vapour Resistance Measured under Isothermal and Non-isothermal Conditions

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Abstract

It is sometimes recommended (ASTM F2360, 2004) to conduct tests under isothermal conditions, i.e. the mean skin temperature equals the environmental temperature. Tests under isothermal conditions will give the real resistance of clothing to moisture transmission under such conditions. Nevertheless, since absorption and condensation in clothing in actual use can greatly affect the clothing thermal insulation and moisture vapour resistance, tests under non-isothermal conditions are closer to the actual conditions in use of clothing. From the present investigation, it can be observed that the total static clothing moisture vapour resistance, measured under a typical non-isothermal condition (i.e. 20°C and 50% RH), is less than that measured under isothermal conditions, and the difference varies from 17 to 32%. The actual difference is related to the clothing moisture vapour resistance. Generally, a greater reduction takes place in clothing systems having higher clothing moisture vapour resistance. The difference between the clothing moisture vapour resistance tested under isothermal and non-isothermal conditions decreases when the wind velocity increases from 0 to about 1.8 m/s, thereafter the difference remains almost unchanged with a further increase in wind velocity.

Keywords: clothing moisture vapour resistance, isothermal, wind
1. Introduction

The actual process of the heat and moisture vapour transfer through clothing system is generally very complicated as it is a complex function of evaporation, condensation and absorption and desorption of moisture (Spencer-Smith 1977). Generally, temperature and moisture concentration gradients are the driving force for the heat and mass transfer, respectively. When they are present at the same time, they can affect each other (Cengel, Y.A., 2003). These two interact, however, since with reducing temperature along this temperature gradient, the dewpoint of the local air is also reduced. This dewpoint limits the water vapour concentration at that location, and if that is exceeded, condensation of moisture, with a release of heat, will occur at that point, raising the local temperature, and resulting in an increase in the temperature gradient and heat conductive transfer through clothing. The reduction in total static thermal insulation during sweating compared with no sweating varies from 2–8% (Chen, et al, 2003). On the other hand, the condensation also increases the moisture vapour concentration in the clothing and the moisture vapour pressures difference between the clothing and environment increases, resulting in the moisture vapour transfer through the clothing being increased (Ren and Ruckman, 2003).

In the past, due to limitations in the measurement technology, the thermal insulation and the moisture vapour resistance of the clothing are measured separately. Simulation and determination of the moisture vapour transfer on a dry thermal manikin (McCullough et al, 1989) require a two-step method. In this case, the evaporative heat loss was calculated from the total heat loss minus the dry heat loss. The difference between clothing thermal insulation in sweating and non-sweating conditions may cause errors when calculating dry heat loss during sweating, and consequently errors in evaporative heat loss and in the determined moisture vapour resistance. Using the trace gas dilution method (Havenith et al, 1990) can determine the gas transport through clothing. It reveals the real resistance of gas through clothing, but does not take into account the effect of water vapour absorption and condensation in clothing. ASTM standard (ASTM F2360, 2004) suggested conducting the measurement of clothing moisture vapour resistance on a sweating manikin under isothermal conditions. This method eliminates the effect of condensation on the measurement. Of course, ASTM F2360 allows the clothing moisture vapour resistance to be measured under environmental conditions that simulate actual conditions of use (non-isothermal conditions). The moisture vapour resistance determined under non-isothermal conditions is referred to as the apparent evaporative resistance. Usually, tests under isothermal conditions will give the real resistance of moisture transmission through clothing, where-as tests under non-isothermal conditions are closer to condition of the clothing during use. Up-to-now, few experiments have investigated the difference in the moisture vapour resistance under these two environmental conditions and little experimental data can show what differences there are, especially for a clothed body walking in windy conditions.

The aim of this paper is therefore to investigate and compare the clothing moisture vapour resistance measured under typical non-isothermal conditions (i.e. 20°C and 50% RH) and those measured under isothermal conditions.
2. Experiment

The experiment was conducted on the walk-able sweating manikin-Walter (Fan and Qian 2004) which was located in a climate chamber, it being possible to change the environmental conditions in the thermal chamber. Twelve sets of clothing ensembles were tested in the present study, which included one-layer, two-layer and three-layer fitted garments with permeable and impermeable fabrics. The nude and total clothing thermal insulation and moisture vapour resistance were measured under both normal (35°C of skin temperature, 20°C and 50% relative humidity) and isothermal (35°C of skin temperature, 35°C and 40% relative humidity conditions for the sweating manikin standing in still air. Only six sets of clothing ensembles were tested under normal and isothermal conditions for the sweating manikin standing in windy conditions.

3. Results and discussion

The clothing total static moisture vapour resistance measured under isothermal conditions for the sweating manikin standing in still air are illustrated in Figure 1, which is also compared with the results tested under 20°C and 50% RH (a typical non-isothermal condition).

It can be seen that the total static clothing moisture vapour resistance measured under the typical non-isothermal condition (i.e. 20°C and 50% RH) is less than that measured under the isothermal condition, the difference varying from 17 to 32%. The reduction is related to the clothing moisture vapour resistance. Generally, a greater reduction takes place in clothing systems having higher clothing moisture vapour resistance (See Figure 2).
There are two possible reasons for the lower moisture vapour resistance under the non-isothermal condition in comparison with that under the isothermal condition. Firstly, the presence of the nature convection induced by the temperature gradients in the non-isothermal condition increases the transmission of moisture vapour not only within the clothing layers, but also at the outer surface. The second reason for the reduction in the measured moisture vapour resistance is the moisture absorption and condensation within clothing. This means some of the “perspiration” from the manikin or human body is not transmitted through the clothing system, but accumulated within the clothing, resulting in an apparently lower moisture vapour resistance than the actual value. Furthermore, the higher moisture content and condensation within the inner layers of clothing creates higher rate of moisture transmission through the outer layers of the clothing system (Ren and Ruckman, 2003).

The reduction due to the first cause will decrease with an increase in wind velocity, and diminish under very windy conditions (Qian and Fan 2005). Figure 3 plots an example of the change of surface and clothing moisture vapour resistance tested under isothermal and non-isothermal conditions against wind velocity. As can be seen, the difference between the clothing moisture vapour resistance tested under isothermal and no-isothermal conditions decreases as the wind velocity increases from 0 to about 2.5 m/s, thereafter the difference remains almost unchanged with an increase in wind velocity. The remaining difference is believed to be due to the second cause, i.e. the moisture absorption and condensation within clothing.
The effect of wind speed on the surface (nude) and clothing moisture vapour resistance (CL_30 clothing ensemble)

![Graph showing the effect of wind velocity on clothing moisture vapour resistance](image)

**Figure 3** Effect of wind velocity on the clothing moisture vapour resistance as tested under isothermal and non-isothermal conditions, respectively.

Tests under isothermal conditions will give the real resistance of clothing to moisture transmission under such conditions, but tests under the non-isothermal condition are closer to the actual conditions under which clothing are used. From the present investigation, it can be observed that the clothing moisture vapour resistance measured under isothermal conditions are linearly related to that measured under non-isothermal conditions. This relationship is shown in Figure 4.

![Graph showing the relationship between Rt measured under normal conditions and that measured under isothermal conditions](image)

**Figure 4** The relationship between $R_t$ under isothermal conditions and $R_t$ under non-isothermal conditions

For the prediction of moisture vapour resistance, ISO 9920 employs $i_m$ directly to estimate the dynamic moisture vapour resistance of clothing from the dynamic clothing thermal insulation.

$$\frac{I_{tdyn}}{R_{tdyn}} = L_R i_m = \frac{I_{st}}{R_{st}}$$

(1)
Where $I_{tdyn}$ and $R_{tdyn}$ are, respectively, the total thermal insulation and total moisture vapour resistance of the clothing system in the case of walking in windy conditions. $I_{st}$ and $R_{st}$ are the total thermal insulation and total moisture vapour resistance of garments in the case of standing in still air, and $i_m$ is the moisture vapour permeability index. $L_R$ is Lewis constant $L_R=0.0165 ^\circ C/ Pa$.

Figure 5 shows the clothing dynamic moisture vapour resistance using values predicted by means of the ISO9920 model plotted against the measured values for both non-isothermal and isothermal conditions. As can be seen, the ISO 9920 prediction model holds under normal conditions, while it somewhat over-estimates the values measured under isothermal conditions.

Due to the condensation of moisture vapour in the clothing system, the evaporative water at the surface of the skin does not transfer through the whole clothing system totally; some water will condense and accumulate in the clothing system, especially that from the inner part of the clothing system. That is why the moisture vapour resistance of clothing with a lower thermal insulation and vapour impermeable (CL_ID of 32) under the normal condition is lower than that of clothing with a higher thermal insulation but vapour permeable (CL_ID of 28). Therefore, although the moisture vapour resistance measured under isothermal conditions in theory represents the real resistance of clothing to moisture vapour, the moisture vapour resistance measured under normal conditions is closer to the moisture vapour resistance from the skin to the environment in reality.
4. Conclusion

Moisture condensation in clothing may greatly affect the heat and water vapour transfer through clothing. The static and dynamic clothing moisture vapour resistance have been investigated on the recently developed walk-able sweating manikin under normal and isothermal conditions. It has been shown that the static clothing moisture vapour resistance, measured under non-isothermal conditions is about 17–32% lower than that measured under isothermal conditions. The difference is due to moisture condensation within the clothing and the increased natural convection as a result of the increase in temperature gradient under the non-isothermal conditions. The moisture vapour resistance measured both under normal and isothermal conditions, decreased as wind velocity increased. From the present investigation, it can be observed that the clothing moisture vapour resistance measured under isothermal and non-isothermal conditions are linearly related. The dynamic moisture vapour resistance measured under normal conditions can be predicted by means of the ISO 9920 prediction model with a very high precision.

References
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Evaluation of Tactile Properties of Wet Fabrics

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Abstract

A new instrument, which can be used to measure the cling force of wet fabrics, has been developed. The experiments to measure cling force have been carried out on weft knitted and woven fabrics using the new tester, and the relationship between cling force and the moisture regain established. Using sensory evaluations, it is concluded that there is a high correlation between the tactile properties and the cling force. This study is helpful for choosing suitable fabrics for clothes worn under wet environmental conditions, such as swimwear, sportswear, etc.

1. Introduction

The importance of the comfort properties of garments has been well recognised throughout the world in the textile industry hence, a considerable amount of research on this topic has been carried out. Clothing comfort has two aspects; thermo-physiological comfort [1] and sensorial comfort [2].

This paper focuses attention on the topic of sensorial comfort, which relates to the interaction of the clothing with the tactile response of the skin, for wet fabrics. During heavy sweating, caused by strenuous activity or climatic conditions, such as rain, people feel uncomfortable as the wet clothes cling to the body. The reason can be that the mechanical properties of fabrics and the nature of the fabric and skin interface are changed with moisture. Some studies have been carried out on people’s sensory perception, such as moisture and wet sensory perceptions, etc., but there are comparatively few studies on tactile sensory perception considering the mechanical properties of fabrics. In order to improve the cling properties of sportswear, Takatera et al [3] made a simple device and measured cling force for wet fabrics when it
clings to an object. Researchers have developed many kinds of testers, but there still is no universal tester to measure cling force.

In this paper, a new instrument for measuring the cling force of wet fabrics is reported, with experiments being carried out on both knitted and woven fabrics. Sensory evaluations are also performed and compared to the measured cling force. It is concluded that there is a high correlation between the sensory evaluation and the cling force. The results will be helpful for people to choose fabrics suitable for special conditions, such as sportswear, swimwear, etc.

2. Experiments

2.1 Wet cling properties
When a wet fabric clings to an object, the cling force that affects the sensory perceptions of people can be defined as of two kinds, the force when a wet fabric is lifted from an object and the force when a wet fabric slides along the tangential direction of an object. The first is very difficult to measure because large changes in sample size and the contact state, whereas the second is also difficult to measure when a sample is laid on a horizontal surface because of the same reasons. In order to solve this problem, a new instrument, based on Takatera’s device [3], has been developed, as schematically illustrated in Fig. 1.

2.1.1 Description of the apparatus
In order for a sample cling to a surface, a roller is adopted. The sample is set as shown in Fig. 1. One side of the sample is connected to a load cell in order to record the cling force and the other side is attached to a weight which provides the initial load in order to decrease the experimental error. When the roller is driven by an electric motor, a wet frictional force is generated at the interface between the sample and the roller and a stabile connected state will be maintained.

![Figure 1 Schematic diagram of the instrument.](image)

In this study, the wet frictional force is defined as the wet cling force and the comparison of each tested sample are made based on the measured wet cling force. The measured cling force is the input into a personal computer for processing.
2.1.2 Test method

The motor is rotated in the opposite direction to the load cell and the force in the tangential direction is measured. In order to eliminate the effect of speed, the lowest rotation speed is selected. Theoretically, the largest friction force should occur when the rotation begins. However, considering the rotation stability of the motor and a sample clinging to the roller surface, the data recording begins 10 seconds after the motor starts to rotate. The largest force per unit area recorded is defined as the cling force of the wet fabrics.

2.1.3 Measurement of cling force

The cling force is measured at 65% relative humidity and 25°C. In order to study the relationship between moisture regain, cling force and time, the motor is rotated at 10 second intervals for 5 minutes.

2.1.4 Measurement of drying speed

According to the preliminary experiments, the wet frictional force changes with the moisture regain. Here, the momentary frictional force is measured by rotating a roller intermittently. In order to investigate the relationship between the measured cling force and the moisture regain, the measurement of the drying speed is carried out. Wet fabric samples are suspended from the load cell and their mass recorded at regular intervals, and the test results are fed to a computer for processing. The moisture regain can be calculated from the following formula:

\[
\text{moisture regain(\%)} = \frac{\text{mass(wet conditions)} - \text{mass(dry conditions)}}{\text{mass(standard conditions)}} \times 100 \quad \cdots \cdots (1)
\]

2.1.5 Measurement of gap area fraction

From the preliminary experimental results, it appears that the contact area of the sample clinging to the roller surface affects the cling force. However, it is very difficult to measure the contact area because of the reflection of water, etc. Here, a Micro CCD Scope is used to take images of every dry sample by 100 times and the images are transferred into a computer. The saved images are binarised using image-processing software (Pop Imaging). The area ratio of the yarn area and the gap area is defined as gap area fraction.

2.1.6 Samples

The test fabrics are described in Table 1. Three kinds of knitted fabrics and two kinds of plain-woven fabrics were selected for this research. Sample W2 is a 100% cotton woven fabric selected as a reference specimen; whereas all the others are special fabrics used as a lining for swimwear and all of them have good tactile properties and rapid drying properties.

The rotation axis direction and the rotation direction of the roller are regarded as the lengthwise direction and the widthwise direction, respectively. A sample is cut at a width of 10cm, and length of 22cm along the warp (course) direction. In the long transverse direction, one side is sewn as a loop in order to insert a light bar to connect the sample to the load cell and only a horizontal force is imposed on the sample. The other side is attached to a suitable weight to provide an initial load to the sample.
2.2 Sensory properties

In order to investigate the relationship between the measured cling force results and human sensory perceptions, sensory evaluations were carried out by the SD (semantic differential) method.

2.2.1 Decision of evaluation items

Three evaluation items, shown in Table 2, were selected in advance and considered to be suitable for the tactile evaluation of wet fabrics. Evaluators were asked to wear blindfolds in order to prevent visual influences and to make an oral response to each evaluation item.

<table>
<thead>
<tr>
<th>Clinging</th>
<th>↔</th>
<th>No clinging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad tactility</td>
<td>↔</td>
<td>Good tactility</td>
</tr>
<tr>
<td>Discomfort</td>
<td>↔</td>
<td>Comfort</td>
</tr>
</tbody>
</table>

Table 2: Evaluation items

2.2.2 Evaluators

Seven male and nine female students in their twenties were selected as evaluators. The meaning of every evaluation item was explained to all the evaluators and the sensory evaluations were carried out until each evaluator had an acceptable understanding of the experiment. Six samples were provided in a random order so as to prevent evaluators from comparing reactions, thereby ensuring that completely independent ratings were obtained from each evaluator.

2.2.3 Sensory evaluation

The instrument for measuring cling force was used for the sensory evaluations. As shown in Fig. 2, evaluators placed their fore arm on a table, with the arm as high as the roller. First, a sample, one side of which is fixed to the roller, is placed on the arm. Then, the roller is made to rotate at the same speed as in the cling force measurement. Each evaluator makes his sensory evaluations until the sample slips past his arm. All sensory evaluations are carried out at 65% relative humidity and 25°C as in the case of the cling force measurements.
For each sample, the moisture regain was set at two levels; a low level (20-50%) and a high level (120-150%, sample W2 is 100%) and the evaluation was performed along the warp and weft directions, respectively. Each test session is made up of seven individual evaluation periods as follows:

- Clinging
  - Very
  - Rather
  - A little
  - Neither
  - A little
  - Rather
  - Very

- No clinging
- Good tactility
- Comfort

### 3. Results and Discussion

#### 3.1 Results of drying speed

![Figure 3 Relationship between area density and time](image)

The relationship between area density and time is shown in Figure 3 and the relationship between moisture regain and time is shown in Fig. 4.

From Figs 3 and 4, for sample W1, it can be seen that the area density changes very little, whereas the moisture regain changes greatly. Sample W1 is made of non-absorbable materials and is full of big gaps. Water enters these gaps easily and causes an increase in moisture regain. For samples K2, K3 and W2, area density exhibits almost the same tendency while the moisture regain differs greatly from each other.
3.2 Results of cling force

The relationship between cling force and time, cling load and moisture regain are shown in Figs 5 and 6 respectively.

From Figs 5 and 6, it can be concluded that the largest cling force does not correspond to the largest moisture regain. It should be noted that when a sample absorbs water fully, the surface of the sample will be coated with water so that the lubricating layer effect will arise. Although this phenomenon differs from one sample to the other, it can be concluded that the lubricating layer effect will be produced when the absorbed water is heavier than the mass of the sample, and the cling force will reach the largest value when the moisture regain varies from 80 to 100%.

Sample W2 exhibits extremely large cling force values. Since sample W2 is made of cotton, the contact area will increase when the fabric absorbs water and expands, and further, the sample has a higher area density. The increased contact area and the high area density will lead to the very large cling force observed. Moreover, sample W2 is a woven fabric, the difficulty of tensile deformation along the warp and weft directions may have some influence on the clinging force.

![Figure 5](image1.png)  **Figure 5**  Relationship between cling force and time.

![Figure 6](image2.png)  **Figure 6**  Relationship between cling force and moisture regain.

3.3 Results of sensory evaluations

The results of the sensory evaluation are shown in Fig. 7.

The sensory evaluations at low moisture regain show higher average values than those at high moisture regain. It turns out that the moisture regain influences the tactile properties greatly. Samples K2 and K3 show higher average evaluation values than the other samples. The two samples are made from materials that do not cling to people’s skin even if they are wet. Hence it is difficult to feel uncomfortable.
3.4 Relationship between cling force and tactile properties
Based on the measured cling force results and the sensory evaluation results, the relationship between the two factors is shown in Fig. 8.
From Fig. 8 it can be seen that the average evaluation results are quite different for the low moisture regain and the high moisture regain conditions. A quite good correlation between the cling force and the average evaluation values is also shown for all items. The larger the cling force, the smaller the average evaluation values. That is to say, the tactile sensory evaluation deteriorates as the cling force increases. However, there is no correlation for sample W2 because of its extremely large cling force values.

4. Conclusions

A new tester has been developed and used to measure the cling force of wet fabrics, which is defined as the largest force per unit area on the contact surface between a wet fabric and a rotating roller. The results obtained show that the cling force is highest when the moisture regain varies from 80 to 100%. For the same samples, sensory evaluations were also carried out and the relationship between cling force and tactile properties of wet fabrics was clarified. The tactile sensory perceptions deteriorate with increasing cling force. The study provides a theoretical basis for selecting a suitable fabric according to specific wear conditions.

5. References
Air Permeability Evaluation of Clothing in Extreme Windy Conditions

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Abstract

Nowadays it is possible to notice a growing popularity of clothing for sport and leisure. In this process consumer places an emphasis not only on design but also on maximal wear comfort, especially in clothing for specific use under extreme climatic conditions. Development of such clothing fabrics introduces new types of high functional fabrics and clothing made from it became one of the most important commercial products of the textile industry. Such functional clothing finds application not only in closely specified areas but also for avocational sport and very often also for wearing under urban conditions. It is necessary to determine how functional fabrics work under given conditions of wearing, especially under extreme climatic conditions where its functional performance is truly exploited. These factors require a new approach in evaluating qualitative clothing properties.

Air permeability is one of the most important physiological properties of clothing. There are methods for evaluating clothing fabric air permeability by estimating the quantity of air, which passes through areas of fabric under a set pressure gradient. With these methods it is easy to compare different fabrics but they do not give the correct information about true wear characteristics of clothing because the test conditions are completely different from those during wearing. Standard methods use flat samples oriented perpendicularly to the airflow (where the bending of the fabric due to airflow is neglected) in the whole sample area, whereas during wearing the surface of the fabric have a cylindrical (limb) or elliptical (trunk) shape. Fabric of the cylindrical shape under different angles is affected by pressure generated by airflow; in addition fabric deformations are generated by turbulence (dynamic
deformations created by whirling of air), the weight of the clothing materials as well as their deformational properties.

This paper deals with air permeability of clothing under perpendicular turbulent airflow and describes experiments, which examined the velocity of air around the human limb underneath a clothing layer. The measure of air permeability and particularly air velocity under the clothing would approximate the conditions when the clothing is worn from the point of view of air velocity and turbulence. Finally, experimental and computational results are compared.

1. Introduction

The human body represents to a certain extent a self-regulating system, with physiological mechanisms aimed at securing a balance between the heat produced and that given out to the surroundings and so maintain a constant temperature. This is one of the basic conditions of existence for endothermic organisms, including the human body.

The thermoregulatory ability of the human body is limited and when it cannot be maintained a constant body temperature becomes necessary to be insulated and protected from the surroundings. This is one of the main clothing functions. When the human body is exposed to the morning air, against which it is not sufficiently protected, it leads to a disruption or removal of the thermal air layers in the space between body and the clothing layer (microclimate) and its displacement by cold air. It is a fact that with increasing air velocity the body loses heat faster and the skin and body temperatures decrease. The human body reacts to heat losses by producing more energy to warm the air layer under the skin. The heat necessary to do this is taken from the skin and this phenomenon is experienced as cooling. This is more severe under windy conditions, also when the skin is moist due to sweat or covered by wet clothing.

Nowadays, when the demand for clothing with maximal wear comfort is increasing, it is necessary to know how these materials behave under specific wear conditions, particularly those where the clothing material functions are essential. This is the reason why many contemporary testing methods are not adequate and seems to be necessary to modify them, or develop new ones especially for extreme climatic conditions.

2. Description

Standard methods of air permeability testing do not correspond to the actual conditions during wear. At best they are good for testing one layer of woven fabric. Problems can also arise in case of measuring knitted or nonwoven fabrics.

The arrangement of the test sample as well as the test conditions in classical air permeability testing are different to those pertaining to the wearing of clothing. During the classical test, the sample is oriented perpendicularly (ignoring sample
bending caused by the moving air) to the airflow over the whole area of the sample (Fig. 1).

In case of clothing, the fabric shape is cylindrical (sleeve) or elliptical (trunk). The air stream and the pressure impact are completely different in case of a cylindrical sample. Pressure impact on the fabric at different angles and deformations of the fabric due to the flowing air (dynamic deformation caused by air vorticity), are affected by the area density of the clothing material and their deformation properties.

Measurement of air permeability under the conditions of rapidly flowing air should be closer to the conditions of actual wear in terms of velocity and turbulence of the air stream as well as the geometry of the test sample. Arrangement of the air velocity under a clothing layer under windy conditions comes from the concept of a human limb (represented by a solid cylinder), which is protected by clothing, namely a sleeve. The sleeve is composed of different layers of clothing material, according to their function in a clothing system for sport (underwear, thermal insulation layer and layer protecting against wind). The air layer is situated between the solid cylinder and the clothing. In order to simplify testing, it is necessary to make certain assumptions; such as that there is a constant air gap between the solid cylinder and the clothing layer. This gap is necessary on the whole perimeter for measuring of the air velocity, which passes through the clothing sandwich. This is illustrated in Fig. 2.

Fan and Keighley (Fan, 1989) and Sobera et al. (Sobera, 2003) deal with the study of air permeability and thermal insulation properties under conditions of flowing air. The first mentioned work focuses first of all on the analysis of the thermal insulation properties of a clothing material ensemble composed of an outer fabric and an inner porous fibrous material with thickness 20 mm. The measurement system was placed in an aerodynamic tunnel with adjustable velocity of the airflow.

The second work by a Sobera et al (Sobera, 2003) deals with the measurement of the air velocity around a cylinder in a central line and under clothing, modelling this phenomenon in area Reynolds Number Re = 9 – 36·103, which corresponds with the area of subcritical flow around a circular cylinder.
3. Theory

3.1 Reynolds number

Flow around a circular cylinder is characterized by the dimensionless so called Reynolds number \([1]\). The Reynolds number \((Re)\) reflects the physical similarity of phenomenon characterised by the ratio of inertial and frictional forces of the affected body, in this case a circular cylinder (Noskievič, 1987, Schlichting, 2000).

\[
Re = \frac{\nu d}{\nu}
\]  

[1]

The value of the Reynolds number, considered in this work, is within the interval \(10^4 – 10^5\), which corresponds to the region of subcritical flow around a circular cylinder as in the work of Sobera at al (Sobera, 2003).

3.2 Continuity equation

The continuity equation represents one of the basic physical laws – the law of mass conservation. Fluid is considered as a continuum in which small control volumes are selected. The total change in fluid weight flowing through a controlled volume has to be zero. The general continuity equation for the non-stationary three-dimensional flow of a compressible liquid has the following form:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} = 0
\]  

[2]

Equation [2] can be simplified in cases of non-compressible liquids because the liquid density does not change making it possible to consider \(\rho\) a constant, hence the first term of the previous equation becomes \(\frac{\partial \rho}{\partial t} = 0\). Then the continuity equation can be written in its simplified form:

\[
\text{div } \mathbf{v} = 0
\]  

[3]

3.3 Equation of motion

The equation of motion of a real fluid represents its state of motion as a result of external pressures and inertial forces, which influence the unit of weight of the flowing liquid with respect to the inner friction as a result of liquid viscosity (Churchil, 1988). Equilibrium of forces impacting on a liquid volume unit is given by their vector summation:

\[
\mathbf{F} = \mathbf{F}_m + \mathbf{F}_p + \mathbf{F}_t
\]  

[4]

Forces can be written in component form and the equation of motion [4] can be rewritten in the following vector form:

\[
\mathbf{a} - \frac{1}{\rho} \text{grad } p + \nu \Delta \mathbf{v} + \frac{\nu}{3} \text{grad} \cdot \text{div } \mathbf{v} = \mathbf{v} \text{grad } \mathbf{v} + \frac{\partial \mathbf{v}}{\partial t}
\]  

[5]

This equation is known as the Navier – Stokes equation. The fourth term of equation [5] represents the influence of the viscosity for a compressible liquid. In the case of
a non-compressible liquid, in this case air, this term is zero and it is possible to simplify the equation and then it has the form:

\[ a - \frac{1}{\rho} \nabla p + \nu \Delta v = \nabla \cdot (\nu \nabla v) + \frac{\partial v}{\partial t} \]  \[ 6 \]

3.4 Flow through porous material

In the case of flow, which complies with small values of the Reynolds number, Darcy’s equation for liquid flowing through a porous material is used (Churchil, 1988):

\[ -\nabla p = \frac{\mu \cdot \nabla}{K} \]  \[ 7 \]

Darcy’s law, as one of the possibilities describing flow in porous models, is valid only in the case of laminar flow. Bliesner (Bliesner, 1963) adequately verified this law for fibrous layers, justifying its frequent use in cases of liquid in inter fibrous spaces of textile materials.

The model describing flow in a porous system, based on Darcy’s law, is used in cases where it is possible to neglect shear stress influences in the vicinity of a stationary wall surface. If it is necessary to take this fact into consideration it is possible to use Brinkman’s equation (Churchil 1988) for describing flow in a porous system. The Brinkman’s equation is an expansion of Darcy’s law:

\[ -\nabla p = \frac{\mu \cdot \nabla}{K} - \frac{\mu}{\varepsilon} \text{div} v \]  \[ 8 \]

4. Experiment

The aim of the experimental part of this work was to study the flow velocity under a layer of clothing material as a function of wind velocity and pressure change at the cylinder perimeter caused by the wind flow and to compare the results with simulated data from the CFD system.

The clothing materials used in the experiments are used for the production of sports clothing where the preferred trend is to use several layers of clothing (most often three). Each layer performs a specific function. These functions relate to each other and together create a functional system of clothing, the function of which is to help the human body maintain an optimal microclimate with respect to performance intensity and outside environment. The textile sandwiches comprising the first two sport clothing layers, were used in the experiments:

1\text{st} layer – underwear – considered being the most important part of the clothing system. Its function is to conduct sweat from the skin and maintain a dry pleasant feeling and balance under intense activity and in extreme climatic conditions too.

2\text{nd} layer – ensure the optimal thermal insulation of the body. Fleece materials made from polyester fibres are best for this layer. The thermal insulation function is
given by the weight of the fleece. This layer reduces heat lost and simultaneously has a good air permeability in order to quickly conduct sweat from the body to the outside environment. It prevents vapour condensation between the layers and maintains body temperature.

The first part of this work involved measurement using an aerodynamical tunnel with rectangular cross section with measuring zone $0.1 \times 0.4 \text{ m}$ and length of $1.2\text{ m}$. The measurement of air permeability of the clothing sandwiches under conditions of rapidly flowing air with high turbulence in the aerodynamic tunnel was made at air velocities of 10, 13, 15 and $20\text{ m·s}^{-1}$. The cylinder represents the human limb and is centred in the measurement zone of the tunnel perpendicular to the airflow direction. The air permeability device was designed and constructed with a constant distance between the solid cylinder representing the human limb and the clothing sandwich represented by the clothing sleeve. The distance is necessary for measuring the air velocity passing through the clothing and flowing around the limb. A thermal anemometric probe at a location halfway between ‘limb’ and ‘sleeve’ at 24-degree angular steps measured the velocity.

The measured data were compared with the data obtained by computations with CFD Fluent 6. The computations were based on the finite volume formulation using second-order upwind spatial discretization and a SIPO pressure – velocity – coupling algorithm. The model is constructed in 2-D and has 3 zones – external airflow, porous and air gap. Parameters of the porous zones were computed from known values of experimental pressure and velocity obtained from measurement on a classical device used for the evaluation of the air permeability of textile materials (SDL M 021S).

Figure 3 presents velocity values measured with the aerodynamical tunnel and data computed by Fluent as a function of angle for various external airflow velocities. Both are measured at a location halfway between the solid and clothing cylinder and scaled by the external airflow velocity and Reynolds number.

![Figure 3: Air velocity as a function of angle for measured (m) and simulated (s) data and external airflow velocities of 5, 10, 13, 15 and 20 m·s$^{-1}$.](image-url)
5. Discussion and conclusions

This work presents a brief introduction to the problem of measuring the permeability of clothing sandwiches under windy conditions. The measured values were compared with values obtained by CFD simulations. The maximum velocity occurs for an angle of about 63 deg and the minimum for an angle of 180 deg. The measured values are a little different from those simulated. This can be due to inaccuracies in the measured air permeability and pressure drop in the determination of inertial and viscous resistance as porous material parameters. The measured velocity in the air gap and neglecting the geometrical deformations in airflow with high intensity of turbulence as measured with the aerodynamical tunnel and in simulations could cause other inaccuracies.

Notation

- \( d \): characteristic dimension (in the case of cylinder – diameter) [m],
- \( F_m \): weight force [N],
- \( F_p \): pressure force [N],
- \( F_i \): inertial force (given by inertial acceleration and weight) [N],
- \( F_f \): frictional force [N],
- \( K \): permeability \([m^2]\),
- \( p \): pressure [Pa],
- \( Re \): Reynolds number [–],
- \( v \): velocity \([m\cdot s^{-1}]\).

Greek symbols

- \( \varepsilon \): porosity [–],
- \( \mu \): dynamic viscosity \([Pa\cdot s]\),
- \( \nu \): kinematic viscosity \([m^2\cdot s^{-1}]\),
- \( \rho \): density \([kg\cdot m^{-3}]\),
- \( \tau \): shear stress [Pa].

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Section VII
Applications of Thermal Manikins
Application of a Sweating Manikin Controlled by a Human Physiological Model and Lessons Learned

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Abstract

The National Renewable Energy Laboratory (NREL) has developed a suite of thermal comfort tools to help develop smaller and more efficient climate control systems in automobiles. The tools consist of a thermal comfort manikin, physiological model, and psychological model that are linked together to assess comfort in a transient non-homogeneous environment. The manikin and models have been validated against physiological data that are available in the literature and test subject data that were used to develop the psychological model. The manikin was used in NREL’s Vehicle Climate Control Laboratory (VCCL) to assess the impact of an automotive ventilated seat on thermal comfort and fuel economy. In a test program with NASA, the manikin was used to evaluate liquid cooling garments (LCGs) worn underneath spacesuits.

1. Introduction

Our goal at NREL is to help the automotive industry reduce the fuel used for air conditioning (A/C). NREL is investigating techniques to reduce the peak soak temperature, which allows the A/C system size to be reduced. We are also looking at improved delivery systems and alternative methods to cool the passenger compartment, which will reduce the power requirements of a climate control system.

Since a key requirement is to maintain or enhance passenger comfort, we need to understand how advanced cooling techniques will affect human thermal comfort. NREL has developed a portfolio of thermal comfort tools, including an ADvanced
2. Thermal Comfort Tools

The integrated human thermal comfort system consists of the thermal manikin controlled by a finite element physiological model of the human body. The thermal manikin is a surface sensor that measures the rate of heat loss at 120 independently controlled zones. The skin heat transfer rates are sent to the physiological model, which computes the skin and internal temperature distribution and surface sweat rates. This information is then sent back to the manikin, which generates the prescribed skin temperatures, surface sweat rates and breathing rates. As the model steps forward in time, this loop provides a transient measurement tool. The psychological comfort model uses temperature data from the physiological model to predict the local and global thermal comfort as a function of local skin and core temperatures and their rates of change. Using this manikin as a sensor simplifies the complex clothing and environmental heat transfer into local heat loss measurements from the skin.

2.1 ADvanced Automotive Manikin

The manikin is approximately 175 cm tall and was sized to comply with the 50th percentile western person. He weighs approximately 61 kg; heavy enough to compress an automotive seat and give a realistic contact area. The manikin’s skeleton is composed of laminated carbon fibre, which supports its structure, houses all internal components and provides mounting locations for surface zones. The manikin’s fundamental components are the 126 individual surface segments, each with a typical surface area of 120 cm². Each segment (Figure 1) is a stand-alone device with integrated heating, temperature sensing, sweat distribution and dispensing, a heat flux gauge, and a local controller to manage the closed-loop operation of the zone. The high-thermal conductivity of the all-metal sweating surface yields increased thermal uniformity and response speed. A high-porosity layer within the surface provides lateral sweat distribution while the lower porosity exterior promotes uniform sweat across the surface. Distributed resistance wire provides uniform heating across the zone surface. Six segments are controlled in pairs, and result in 120 separately controlled zones. A single zone controller, including flow control, is mounted directly on the back of each segment. The skin temperature of each zone is determined by an array of thermistors (typically four) on...
each zone. A heat flux gauge, integrated onto the internal surface of each zone, measures heat transfer between the surface zones and the internal body cavity.

ADAM was built by Measurement Technology Northwest in Seattle, Washington. The characteristics that make ADAM a unique thermal manikin are:

- High spatial resolution (120 zones)
- Self-contained
- Uniform sweating and heating over the entire area of the manikin
- Finite element physiological model control.

### 2.2 Human Thermal Physiological Model

The NREL Human Thermal Physiological Model is a three-dimensional transient finite element model of the human body. The model simulates the human internal thermal physiological systems, such as muscle and blood, and thermoregulatory responses. The model was developed with the commercially available finite element software ANSYS. This software computes heat flow by conduction, convection and mass transport of the blood. The arms and legs consist of bone, muscle, fat and skin. There are additional lung and abdominal tissues in the torso and brain tissues in the head.

Blood flow is modelled with a network of supply and return pipe elements within each body zone. The diameter of the pipes decreases from the centre of each zone outward, toward the skin and extremities. The thermoregulatory system controls physiological responses, such as vasoconstriction/dilation, sweating, shivering, and metabolic changes.

### 2.3 Human Thermal Comfort Empirical Model

The University of California, Berkeley performed 109 human subject tests in its Controlled Environmental Chamber under a range of steady-state and transient thermal conditions to explore the relationship between local thermal conditions and perception of local and overall thermal comfort. Core and local skin temperature data and subjective data were used to develop a predictive model of thermal sensation and perception\(^3\,^4\).

Zhang concluded that overall comfort is not an additive function of all local perceptions, but instead is “complaint” driven. This means that the most uncomfortable body parts drive the overall thermal comfort perception. We encountered difficulties using this approach. Using the data available, we found a straight average to be a better predictor of subjective responses. This topic may warrant further investigation.

### 3. Validation Tests

#### 3.1 Steady-State Conditions

NREL ran a series of tests to compare ADAM’s skin temperatures with steady-state subject data from Werner and Reents\(^5\). We placed ADAM nude and horizontal in our Manikin Environmental Chamber. The chamber was maintained at a uniform...
temperature with negligible airflow. We ran ADAM with physiological model control. Although the actual metabolic rates of the subjects are unknown, the suggested 45 W/m² for a reclining human from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook was applied to the human in the model.

We compared the resulting core and skin temperatures with the Werner and Reents data in Fig. 2 for an air temperature of 23.2°C. The manikin/model tended to predict warmer skin temperatures than those measured, with a maximum deviation of 4.2°C. The overall trends were encouraging: the core temperature agreed within 0.6°C, and skin temperatures decreased in regions further from the torso.

Figure 3 shows the comparison for an air temperature of 30°C. The core temperature was within 0.1°C, and the maximum skin temperature deviation was 2.1°C at the hands. The manikin and model under-predict skin temperatures at higher ambient air temperatures. The core temperature matched exactly, but the maximum under-prediction was 2.5°C at the hands.

Initial results indicate the manikin with physiological model control yields human-like skin temperature distribution. Compared to data from Werner, the skin temperatures were within approximately +4.2/-2.5°C for a wide range of ambient air temperatures. The core temperatures agreed to within 0.6°C. Details on the testing and analysis are available in Rugh and Bharathan7.
3.2 Transient Conditions

During our automotive testing, we noted the predicted core temperature responded quickly when ADAM was moved into a hot passenger compartment environment. Xu and Werner\textsuperscript{8} and Haslan and Parsons\textsuperscript{9} show a 0.004-0.007 °C/min change in core temperature during temperature step-up experiments. Similar transient step change tests were performed at NREL. ADAM and the subject each were dressed in cotton pants, short sleeve shirt, undergarment and socks. The subject core temperature was monitored with a wireless pill that was injected ~4 hours prior to the test. The Manikin Environmental Chamber was conditioned to 38°C and 50% relative humidity. ADAM and the subject were seated and conditioned in a 21°C office environment for ~ 3 hr. Then both were moved to the Manikin Environmental Chamber for 2 hr. Figure 4 shows the core temperature of the two NREL subjects was similar to the Xu and Werner data, while ADAM’s core temperature overshot. We are looking into the reasons, including the model circulation system and the lag between commanded sweat and actual evaporation.

![Figure 4 T\textsubscript{core} during Step-up Temperature Test](image-url)

4. Ventilated Seat Application

Improving the delivery methods for conditioned air in an automobile is an effective way to increase thermal comfort with little energy cost. This reduces A/C needs and thus fuel use. Automotive seats are well suited for effective delivery of conditioned air due to their large contact area with, and close proximity to, the occupants. Normally a seat acts as a thermal insulator, increasing skin temperatures and reducing evaporative cooling of sweat. Ventilating a seat has low energy costs and eliminates this insulating effect while increasing evaporative cooling. W.E.T. Automotive Systems manufactures a ventilated seat that pulls air through the seat cushion and back. We assessed one of these seats using ADAM.

The VCCL at NREL was developed to simulate the soak and cool-down of a vehicle passenger compartment\textsuperscript{10}. The passenger compartment from a compact car, A to C pillar, was heat soaked using a 963 W/m\textsuperscript{2} ± 23% full spectrum solar simulator for 3.5 hours. During this time, the average room environment was controlled at 31.6°C ± 0.4°C and 30% ± 5% RH. ADAM and the subjects were conditioned in an office environment. The subject entered the heat soaked room, stood for 30 seconds, and then did step exercises for one minute to simulate walking to the car. The subject entered the heat soaked car and took a pre-cool-down thermal comfort and sensation vote. The A/C system was started 45 seconds after the subject entered the vehicle, at which time the first cool-down vote was taken. Thermal comfort and sensation votes followed every two minutes for the duration of the test.
Figure 5 shows that an operating ventilated seat increased the heat loss from ADAM’s back and bottom by ~ 60 W/m² (25-35 minutes into the cool-down) compared to no ventilation (baseline). The seat contact temperature was reduced by ~ 4.7°C resulting in an overall thermal sensation improvement of 0.28 (on a +4 to –4 scale) shown in Fig. 6. We determined that if the A/C system capacity was reduced by 7% and the ventilated seat was used, the same thermal sensation and comfort as the baseline seat would result. Using NREL’s A/C fuel use model\textsuperscript{11}, an estimated 522 million gal/year or 7.5% reduction in U.S. A/C fuel use could be achieved.

5. Liquid Cooling Garment Application

NASA currently uses LCGs under spacesuits to remove heat from the human body during a spacewalk. Thermally conditioned liquid is circulated through small tubes distributed around the suit. We used ADAM to assess a Shuttle LCG (Fig. 7) as well as an Orlan LCG, a Russian-designed cooling garment\textsuperscript{12}. NASA uses a comfort curve to determine the inlet flow temperature as a function of

![Figure 5 Heat Loss from ADAM's Back and Bottom](image1)

![Figure 6 ADAM Thermal Sensation](image2)

![Figure 7 Shuttle LCG](image3)
metabolic rate for the Shuttle LCG. We tested three points on the curve and two points off the curve. The test is determined to reach steady state when the core temperature stabilizes.

The room temperature was set at 27ºC, which yielded a spatially averaged air temperature of 26.6ºC around ADAM. The room humidity was maintained at 25%.

A flow rate of 1.81 l/min was used in all tests. It took 3-4 hours to reach steady state for M=275 W and 7 hours for M=350 W. At the higher metabolic rates and inlet temperatures, the core temperature initially overshoots due to a lag in sweat evaporative cooling, which subsequently causes excessive sweating. This sweat (deionised water) flows into the segments, evaporates, and causes a resulting undershoot in core temperature.

Figure 8 shows the core temperature for the Orlan LCG was an average of 0.06ºC lower than the Shuttle LCG for all tests. Since the sweat rate is a function of core temperature in the model, the Orlan LCG also has lower sweat rates. The heat transfer to the LCG fluid in Fig. 9 was on average 15 W greater with the Orlan suit indicating the improved heat transfer compared to the Shuttle LCG.
The skin temperature results are not as consistent. While the Orlan LCG resulted in a lower average skin temperature in two cases, a higher average skin temperature resulted during the lowest fluid inlet temperature cases. This is because the Orlan LCG does not have cooling tubes in the calf region. The Shuttle LCG has tubes and subsequently lower calf temperatures. This also lowers the foot temperatures due to cooler blood flow and results in a lower overall average skin temperature. The dashed lower curves in Figure 10 present the average skin temperature for three inlet temperature cases at M=275 W. At Tinlet=17.5ºC, the Orlan LCG has a higher average skin temperature. Taking the calves and feet out of the average (solid lines), the Orlan LCG has significantly lower skin temperatures for the M=275 W cases, as well as for the M=350 W and M=200 W cases.

6. Conclusions

Results of validation testing of NREL’s thermal comfort tools indicate the manikin with physiological model control yields human-like skin temperature distribution. Comparison with subject data shows the predicted skin temperature distribution of the manikin and model is similar to that of the human subject except for the hand and foot. The manikin and subject data were used in NREL’s VCCL to assess the impact of an automotive ventilated seat on thermal comfort and fuel economy. Results show an improvement in thermal comfort with the ventilated seat. This yields a potential 7% reduction in A/C compressor power and 7.5 % reduction in vehicle fuel use. ADAM was successfully used to assess the thermal performance of Shuttle and Orlan LCGs. Comparing results with the same manikin and room conditions, the Orlan LCG had slightly better heat transfer, which resulted in lower core and skin temperatures.

During these previously discussed test programmes, a number of challenges with the manikin and physiological model were encountered. At high metabolic rates or high temperature/humidity environments, it took a long time for the system to reach steady state due to an oscillation in the predicted core temperature. This may be caused by a lag in evaporative cooling compared to the commanded sweat rate or an artifact of the model responding too quickly to changes in skin heat loss. A few segments failed due to broken heaters and controllers, but the large number of segments allowed testing to continue using data from adjacent segments. We
reviewed the psychological results (sensation and comfort) and determined an average of local comforts was a better method to calculate the overall comfort than the original correlation.

7. Acknowledgements

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8. References


A Comparison of Apparatus Used to Measure Thermal Insulation Properties to Determine Thermal Comfort

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Abstract

Thermal insulation properties of clothing systems can be defined through physical measurements using different methods. This article describes the two basic methods employed to evaluate fabric and cloth thermal comfort. A novel Perspiring Fabric Thermal Manikin is developed to measure the thermal insulation and moisture vapour resistance of clothing ensembles. An ordinary Guarded Hot Plate can be used to measure the thermal conductivity of various textiles. Thermal resistance of a series of shirts and their fabrics are tested on the above two apparatus. The data shows that these two apparatus all have high accuracy and reproducibility. The thermal resistance of fabrics with an air layer obtained from the Guarded Hot Plate Apparatus is less than the thermal resistance of clothes with an air layer tested with the Perspiring Fabric Thermal Manikin.

Keywords: Thermal Comfort; Thermal Resistance; Perspiring Fabric Thermal Manikin; Guarded Hot Plate Apparatus; Fabric; Clothing

1. Introduction

The main purpose of clothing is to maintain normal body temperature and to protect the body against varying external conditions. This is significant for developing new apparel fabrics to evaluate thermal comfort. According to ASTM 1518 Standard [1], a Guarded Hot Plate is used for measurement of thermal transport properties. And in order to obtain a rapid technique to measure the thermal properties of fabrics...
simulating the condition of sweating, different kinds of thermal manikins [2] were developed. According to ASTM F1291 and ISO 7730 [3, 4], thermal insulation measured by thermal manikins can be used to predict thermal comfort of overall clothing systems. Many previous studies have been done to compare the two methods of measurement. The results show that Guarded Hot Plate testing can be used to screen and rank a large number of textiles, but it is not always the same as when the textile is constructed into an ensemble. The vertical hot plate is helpful in understanding the results of the thermal manikin [5, 6, 7]. Recently, a novel Perspiring Fabric Thermal Manikin was developed, which can simulate different rates of perspiration, and requires only one step to measure thermal insulation and moisture-vapour resistance [8].

In this paper, experiments were carried out using the Guarded Hot Plate Apparatus and Perspiring Fabric Thermal Manikin. An investigation was undertaken to compare the thermal resistance of shirts and their fabrics. The evaluation methods of thermal transport properties of garments and fabrics have been discussed.

2. Apparatus

2.1 Perspiring Fabric Thermal Manikin

Figure 1 is a view of the Perspiring Fabric Thermal Manikin. General features are as follows [8]: (1) There are two heaters and a water pump that control the temperature of the manikin body 37°C, similar to a real person’s body temperature: (2) Perspiration simulation using a waterproof, but moisture-permeable fabric skin, which holds the water inside the body, but allows moisture to pass through the skin: (3) The skin of the manikin can be interchanged so as to simulate different rates of perspiration: (4) It takes only one step to measure the thermal insulation and moisture-vapour resistance of textiles.

With this manikin, the total thermal insulation $R_d$ of garment can be measured and calculated by using the following equations:

$$R_d = \frac{A \times (t_s - t_a)}{H_d}$$

$$H = H_d + H_e$$

$$H_e = E \times Q$$

(1)

Where, $R_d$ is the total thermal insulation value (m$^2$·°C/W); $A$ is the total surface area of the manikin ($A = 1.79$ m$^2$); $t_s$ is the mean skin temperature (°C); $t_a$ is the mean temperature of the environment (°C); $H$ is the total heat which the manikin needs to maintain constant core temperature (W); $H_e$ is the
evaporative heat loss from the water evaporation (W); $H_d$ is the dry heat loss (W); $E$ is the heat of evaporation of water at the skin temperature (0.672 W·h/g at 35°C); $Q$ is the “perspiration” rate or water loss per unit time, which can be measured by measuring the amount of water needed to top up the water level in the projecting tube to the original level (g/h).

![Figure 1  View of Perspiring Fabric Thermal Manikin](image)

### 2.2 Guarded Hot Plate Apparatus

The Guarded Hot Plate Apparatus (see Fig. 2) is composed of a test plate, guard section and bottom plate, each electronically maintained at a constant temperature within the range of human skin temperature (33 to 36°C). The guard section shall be designed to prevent lateral loss of heat from the test plate. Thermal resistance is calculated by measuring the temperature difference between the surface of the heated measurement area of the guarded hot plate and the temperature of the ambient air away from the plate. The temperature difference drives heat transfer through the fabric [9]. The plate’s dry heat loss, the temperature difference between the plate’s mean temperature and the chamber’s air temperature, heating time as well as the CLO of samples can be read directly from the apparatus. The CLO can be calculated using the following equation.

$$CLO = \frac{U_{bp} - U_1}{0.155 \times U_{bp} \times U_1}$$

Where: $U_1$ is the thermal conductivity with a sample (W/ m²·°C); $U_{bp}$ is the thermal conductivity without a sample (W/ m²·°C).
Considering the thermal resistance, including the surface air layer resistance, we use the following equation to calculate the total thermal resistance:

\[ R_d' = \frac{A' \times (t_s' - t_a')}{H_d'} \]  

(2)

Where: \( R_d' \) is the total thermal resistance with air layer (m²·°C/W); \( A' \) is the area of test section (0.09m²); \( t_s' \) is the surface temperature of the plate (°C); \( t_a' \) is the air temperature (°C); \( H_d' \) is the heat loss (W).

3. Samples

The specifications of the specimens are summarized in Table 1. The measurement of the warp and weft density followed the ISO 7211/2-1984 standard, that of weight in accordance with the ISO 3801-1977 standard and that of thickness according to the ISO 5084-1977 standard. The tightness of warp, weft and total are calculated. According to the dimensions of the perspiring fabric thermal manikin, the fabrics listed in Table 1 were sewn as shirts with the same measurement and the polyamide check functional cloth was sewn as trousers for testing on the manikin.
Table 1: Characteristics of tested materials

<table>
<thead>
<tr>
<th>No.</th>
<th>Fibre</th>
<th>Fabric count</th>
<th>Porosity (%)</th>
<th>Weight (g/m²)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55/45 Linen/cotton plain cloth</td>
<td>240×160</td>
<td>55.46</td>
<td>71.93</td>
<td>203</td>
</tr>
<tr>
<td>2</td>
<td>55/45 Linen/cotton plain cloth</td>
<td>240×160</td>
<td>61.52</td>
<td>77.30</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>55/45 Linen/cotton plain cloth</td>
<td>196×142</td>
<td>53.29</td>
<td>71.33</td>
<td>175</td>
</tr>
<tr>
<td>4</td>
<td>Cotton yarn-dyed cloth</td>
<td>270×280</td>
<td>37.38</td>
<td>61.65</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>55/45 Hemp/cotton plain cloth</td>
<td>270×220</td>
<td>48.94</td>
<td>69.30</td>
<td>132</td>
</tr>
<tr>
<td>6</td>
<td>Hemp plain cloth</td>
<td>240×240</td>
<td>46.99</td>
<td>71.90</td>
<td>131</td>
</tr>
<tr>
<td>7</td>
<td>70/30 Nylon/cotton plain cloth</td>
<td>420×320</td>
<td>72.89</td>
<td>87.94</td>
<td>141</td>
</tr>
<tr>
<td>8</td>
<td>50/50 Wool/polyester valitin</td>
<td>240×240</td>
<td>50.23</td>
<td>75.23</td>
<td>172</td>
</tr>
<tr>
<td>9</td>
<td>Polyester plain cloth</td>
<td>420×400</td>
<td>58.15</td>
<td>81.33</td>
<td>126</td>
</tr>
<tr>
<td>10</td>
<td>Polyamide check functional cloth</td>
<td>480×300</td>
<td>58.90</td>
<td>74.03</td>
<td>120</td>
</tr>
</tbody>
</table>

4. Results

The average values of three measurements after the stabilization of moisture accumulation within the clothing and fabrics are listed in Tables 2 and 3. All tests were conducted at 21±2°C with a relative humidity of 65.0±4%, and the manikin’s core temperature was controlled at 37°C. By measuring the heat supply to the manikin, the temperature at the skin and in the environment and the “perspiration” rate, the clothing thermal insulation can be calculated; however, in order to compensate for the “perspiration” water loss, pumping water from a water tank to the manikin is necessary, which requires regulating the pumping rate of the pumps inside the manikin in order to maintain the core temperature and skin temperature. As a result, the heat loss increases, and equation (1) should be revised as follows:

\[
R_d = \frac{A \times (t_s - t_a)}{H_d - 0.001161 \times Q \times (T_a - T_e)}
\]
Where, $T_e$ is the manikin’s core temperature ($T_e = 37^\circ C$).

<table>
<thead>
<tr>
<th>No.</th>
<th>$T_s/^\circ C$</th>
<th>$T_a/^\circ C$</th>
<th>$H/W$</th>
<th>$Q/(g/h)$</th>
<th>$H_e/W$</th>
<th>$H_d/W$</th>
<th>Thermal Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$R_d/(^\circ C.m^2/W)$</td>
</tr>
<tr>
<td>1</td>
<td>33.97</td>
<td>17.51</td>
<td>360.75</td>
<td>296.68</td>
<td>199.37</td>
<td>161.38</td>
<td>0.190</td>
</tr>
<tr>
<td>2</td>
<td>33.59</td>
<td>17.76</td>
<td>360.72</td>
<td>297.65</td>
<td>200.02</td>
<td>160.70</td>
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<tr>
<td>3</td>
<td>33.79</td>
<td>17.62</td>
<td>372.91</td>
<td>306.49</td>
<td>205.96</td>
<td>166.95</td>
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</tr>
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<td>4</td>
<td>34.01</td>
<td>17.39</td>
<td>373.05</td>
<td>301.24</td>
<td>202.43</td>
<td>170.62</td>
<td>0.181</td>
</tr>
<tr>
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<td>34.01</td>
<td>17.08</td>
<td>357.05</td>
<td>295.22</td>
<td>198.39</td>
<td>158.66</td>
<td>0.199</td>
</tr>
<tr>
<td>6</td>
<td>33.88</td>
<td>17.22</td>
<td>367.61</td>
<td>304.48</td>
<td>204.61</td>
<td>163.00</td>
<td>0.191</td>
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<tr>
<td>7</td>
<td>34.15</td>
<td>17.70</td>
<td>358.98</td>
<td>288.72</td>
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<td>164.96</td>
<td>0.186</td>
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<td>33.79</td>
<td>17.48</td>
<td>358.54</td>
<td>301.57</td>
<td>202.58</td>
<td>155.96</td>
<td>0.190</td>
</tr>
<tr>
<td>9</td>
<td>33.66</td>
<td>17.79</td>
<td>358.54</td>
<td>301.46</td>
<td>202.66</td>
<td>153.16</td>
<td>0.210</td>
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</table>

Table 2: Data of Perspiring Fabric Thermal Manikin

<table>
<thead>
<tr>
<th>No.</th>
<th>$H/kJ$</th>
<th>$t/s$</th>
<th>$t_s - t_a/^\circ C$</th>
<th>$H_d/(W/m^2)$</th>
<th>Thermal Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$R_d/(^\circ C.m^2/W)$</td>
</tr>
<tr>
<td>1</td>
<td>12.760</td>
<td>1326</td>
<td>14.77</td>
<td>106.93</td>
<td>0.138</td>
</tr>
<tr>
<td>2</td>
<td>12.725</td>
<td>1311</td>
<td>14.59</td>
<td>107.86</td>
<td>0.135</td>
</tr>
<tr>
<td>3</td>
<td>12.995</td>
<td>1308</td>
<td>15.13</td>
<td>110.40</td>
<td>0.137</td>
</tr>
<tr>
<td>4</td>
<td>12.330</td>
<td>1332</td>
<td>15.57</td>
<td>102.86</td>
<td>0.151</td>
</tr>
<tr>
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<td>12.725</td>
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<td>15.47</td>
<td>107.94</td>
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</tr>
<tr>
<td>6</td>
<td>12.260</td>
<td>1313</td>
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<td>103.76</td>
<td>0.146</td>
</tr>
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<td>13.575</td>
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<td>15.25</td>
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<tr>
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<td>12.885</td>
<td>1269</td>
<td>13.78</td>
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<tr>
<td>9</td>
<td>12.940</td>
<td>1301</td>
<td>14.41</td>
<td>110.52</td>
<td>0.130</td>
</tr>
<tr>
<td>10</td>
<td>11.830</td>
<td>1332</td>
<td>14.05</td>
<td>98.69</td>
<td>0.142</td>
</tr>
</tbody>
</table>

Table 3: Data of Guarded hot plate
5. Discussion

5.1 Test method accuracy
As can be seen from Tables 2 and 3, the coefficient of variation (CV) of the thermal insulation obtained using the Perspiring Fabric Thermal Manikin varied from 0.43% to 4.09%, with a mean of 2.85%. The thermal insulation CV% obtained using the Guarded Hot Plate varied from 0.83-9.67%, with a mean of 3.83%. This indicated that the measurement of thermal insulation by the Perspiring Fabric Thermal Manikin is the more reproducible and accurate.

5.2 Test fabric results
There are differences in the thermal resistance, with the surface air layer, tested with the Manikin and Guarded Hot Plate, respectively. The amount of perspiration [10, 11], which is calculated on the basis of the relationship between the amount of perspiration and the total body heat generated by different kinds of exercises, is proportional to the relative metabolic rate. The core temperature of the body is kept constant by the evaporation of sweat from the skin. The water perspiration rate simulated by the Perspiring Fabric Thermal Manikin, reflected a higher exercise intensity, which is similar to basketball sports [10], as between 3871~4407g/m²d. The total heat loss is between 357.05~374.02W, i.e. 199.47 ~208.9 W/m². Table 2 shows that the skin temperature of the Perspiring Fabric Thermal Manikin is between 33.59~34.17°C, the heat of evaporation of water is still assumed as 0.672W.h/g at 35°C. Thus the dry heat loss of the specimens tested on the manikin can be calculated, and range between 153.16 and 170.62W (equally 85.56 and 95.32 W/m²), which represent 40.95~45.95% of the total heat loss. Results of the thermal insulation of the garments obtained from the manikin range from 0.180 to 0.210°C.m²/W.

Table 3 shows that the heat loss with the Guarded Hot Plate Apparatus ranges from 98.68 to 115.94W/m², the temperature differences between the inside and outside of the fabrics ranges from 14.05~15.57°C, which is lower than the temperature differences when testing on the manikin. Finally, the thermal resistance value obtained on the Guarded Hot Plate Apparatus ranges from 0.125 to 0.182°C.m²/W, which is lower than the results obtained on the manikin.
6. Conclusions

Thermal resistance measurements of a series of shirts and their fabrics were carried out on a Perspiring Fabric Thermal Manikin and Guarded Hot Plate Apparatus, respectively. The water perspiration rate simulated by the Perspiring Fabric Thermal Manikin is similar to that of basketball. The results showed that there were differences between the thermal insulation of the apparel and that of the fabric. Further studies are necessary to change the manikin’s skin to the newly available breathable fabrics so as to simulate different rates of perspiration, and to simulate various work rates under different environmental conditions. This will enable the relationships between the garment thermal resistance and that of the fabric to be determined as well as to establish the thermal resistance index, which could contribute to the evaluation of the thermal comfort of textiles.
References

Evaluation of Heat-Resistant Fabrics Used in Firefighting with a Newly Developed Human Skin Simulation Model

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Abstract

Specialized protective clothing, such as that worn by firefighters, is usually tested only according to standards which give requirements for heat-resistant fabrics (ASTM D 4108). However, this testing often neglects the effects of cylindrical geometry on heat transmission in heat-resistant fabrics. This paper deals with methods to develop a cylindrical testing apparatus incorporating a novel skin simulation model to test heat-resistant fabrics used in firefighting. Results show that fabrics which shrink during the test can have a reduced thermal protective performance relative to that measured with a planar geometry tester. Results of tolerance time from the skin simulation sensor are also compared with those from a copper sensor. It is concluded that the thermal protective performance of a heat resistant fabric can now be characterized more precisely than was possible during previous work.

1. Introduction

Because of its large technological relevance in, for instance, firefighting and energy conversion, heat transfer through thin fibrous materials, such as fabric exposed to high heat flux, has been widely studied. Many bench scale tests [1][2][3] have been developed to measure the relative flame resistance and resistance to heat transmission of fabrics. The foundation for the determination of the time to 2nd degree burns, specified in most of these tests is based upon constant heat flux exposure to a bare copper calorimeter and the time \( t_2 \) is determined by overlaying the curve obtained from ASTM D 4108[4] in the same time scale in these tests. However, the thermal properties of the copper calorimeter used in these bench top
scale tests do not actually replicate the characteristics of a human skin. In addition, little attention has been paid to the maintenance of structural integrity and shrinkage, although some tests require an evaluation of these properties through observation after the exposure.

In an attempt to better capture the effects of fabric shrinkage during the measurement of heat transmission, a cylindrical test device and skin simulation sensor have been developed to assess the potential for skin burn injuries by evaluating the thermal performance of Heat-Resistant Fabrics. The heat flux at the surface of the skin simulation sensor, determined from the temperature rise of the skin simulation sensor is applied to the Pennes’ bioheat equation for human skin temperature prediction and burn evaluation. The prediction of time to 2nd degree burn and the skin temperature obtained from the skin simulation sensor (Pennes’ equation) is compared with results obtained with a copper sensor (Stoll criterion method) in this paper.

2. Skin mathematical model

In quantitatively estimating fabric and garment thermal performance under hazardous conditions, the time to burn damage of skin beneath a layer of fabric is utilized, using different skin heat transfer models [5][6]. Nearly all these models have been based on the Pennes’ skin model, which accounts for the ability of tissue to remove heat by both passive conduction (diffusion) and perfusion of tissue by blood. Perfusion is defined as the nonvectorial volumetric blood flow per tissue volume in a region which contains sufficient capillaries so that an average flow description is considered reasonable. Most tissues, including much of the skin and brain, are highly perfused, with a perfusion coefficient denoted by \( \omega \) (traditionally with units of 100 ml/100 g min =1ml g\(^{-1}\) min\(^{-1}\)). The contributions of heat conduction and perfusion are combined in the Pennes bioheat equation [7]

\[
\nabla (k_{\text{skin}} \nabla T) + \omega_b \rho_b C_{p,b} (T_b - T) + q_m + q_r = \rho_{\text{skin}} C_{p,\text{skin}} \frac{\partial T}{\partial t}
\]

(1)

where \( \rho_{\text{skin}} \), \( C_{s,\text{skin}} \) and \( k_{\text{skin}} \) are the density, specific heat, and thermal conductivity of human tissue, \( \rho_b \) and \( C_{p,b} \) are the density and the specific heat of blood and \( \omega_b \) is blood perfusion rate. \( q_m \) and \( q_r \) are the volumetric heat due to metabolism and spatial heating. \( T_b \) is the artery temperature, and \( T \) is the human temperature.

Heat transfer within a man’s arm or leg is one-dimensional in cylindrical coordinates. Therefore, it is very important to investigate bioheat transfer in cylindrical coordinates. In the paper, a numerical computation program based on the finite difference method in one-dimensional cylindrical coordinates is developed to obtain discrete skin temperatures.
On exposure to a surface of high heat flux, the corresponding boundary and initial conditions are as follows:

Boundary conditions at the heating surface, $r = 0$:

\[
k_{\text{skin}} \frac{\partial \theta}{\partial x} + q(t) + \tau \frac{\partial q(t)}{\partial t} = 0, \quad 0 < t < t_s
\]

\[
k_{\text{skin}} \frac{\partial T}{\partial r} = 0, \quad t > t_s
\]

At the blood vessel:

\[T(r = L, t) = T_m, \quad t > 0\]

Initial condition, $t=0$:

\[T = T_i(r)\]

where $t_s$ denotes heating duration and $L$ is skin thickness. It is assumed that the core temperature at the blood vessel was unchanged even if the surface was heated. To numerically calculate the initial steady temperature, the skin surface temperature and body core temperature were specified as $32.5^\circ\text{C}$ and $37^\circ\text{C}$, respectively.

3. Experimental

3.1 Testing apparatus

To investigate the effect of changing the geometry of a bench top scale tester, from planar to cylindrical, on the thermal protective properties of single-layer fabrics, an alternative test apparatus, in which the planar skin simulation sensor is replaced with a cylindrical one, has been proposed by Dale et.al. [8]. On the basis of this technology, a novel test apparatus was developed here, as shown in Figure 1. The tester consists of three parts: thermal exposure, fabric and skin simulation sensor, which form the heating-heated model. The thermal exposure portion could be manipulated by many quartz tubes circularly distributed along an adiabatic sheath. The fabric specimen (400mm in height) is mounted on a steel frame the diameter of which can be adjusted to obtain different air gap thicknesses between the fabric and skin simulation sensor.

An existing skin simulation sensor was used for evaluating thermal injuries. The techniques uses a 18.8mm thickness glass ceramic cylindrical block with a thermal conductivity of $\approx 1.46\text{W/m} \cdot ^\circ\text{C}$ and a thermal diffusivity of approximately $7.3 \times 10^{-7}\text{m}^2/\text{s}$, which responds to heat similarly to a human skin. Its length and diameter are selected to be 200mm and 80mm, respectively, corresponding to the dimensions of a man’s arm. The glass ceramic cylindrical block is attached to a water-cooled column the temperature of which is kept at $37^\circ\text{C}$ by means of a constant temperature bath. It has four thermocouples, which are evenly distributed on the surface of the skin simulator. A hole is drilled along the normal axis of the sensor to allow the thermocouple wire to run up inside the sensor. The thermocouple wires are attached to the surface by means of a heat-resistant epoxy-phenolic adhesive. Each thermocouple is connected to the transmitter. A National Instruments NI 6110 DAQ is produced using the National Instruments Lab Windows DACQ development tool.
A water-cooled shuttering mechanism, activated by a motor, allows control of exposure time to within 0.5 seconds.

**Figure 1 Sketch of the front view of cylindrical tester**

### 3.2 Procedure for determining human skin burn

The present research adopts a new skin model and not the traditional Pennes’ model to determine the thermal damage to skin. Figure 2 is a schematic representation of the Cylindrical Geometry test. Heat flows from left to right in the diagram. Radiant heat flux from the quartz tubes transfers to the surface of the fabric specimen. Then heat transfers through the clothing fabric, through the air gap located between the fabric and the skin simulator surface and finally to the surface of the skin simulator. The skin simulator sensor is used to determine the heat flux at the skin simulator surface from the increase in the temperature of the skin simulator surfaces. The heat flux data is then applied to the newly developed skin model, and the time to 2nd degree burn is determined utilizing the Henriques burn damage integral method [9] which uses an Arrhenius equation to estimate the time required to achieve a second- or third-degree burn from surface heat flux histories. The formal statement of the Henriques integral is as follows:

\[
\Omega = \int_0^t P \exp \left( -\frac{\Delta E}{R(T + 273)} \right) dt
\]

where \( \Omega \) is the measure of burn damage, \( P \) is a human skin system constant, \( T \) is temperature and \( t \) is time, \( R \) is the ideal gas constant and \( \Delta E \) is the activation energy of the human skin. A 2nd degree burn is indicated when \( \Omega \) reaches a value of 1.0.

Here it is assumed that the 12.8mm-thick glass ceramic block exhibits a semi-infinite behaviour, and the Diller’s algorithm is employed to determine the net heat \( q \) at the skin simulator surface which can be measured by the thermocouple bonded to the glass ceramic block surface. At a sample time step \( t_n \), \( q_n \) can be obtained based on the temperature change (\( T_i - T_{i-1} \)) at all previous time steps, including the one at \( t_n \)

\[
q_n(t_n) = \frac{k \rho C_p}{\sqrt{\pi \Delta t}} \sum_{i=1}^{n} \frac{T_i - T_{i-1}}{\sqrt{n + 1 - j}}
\]

(9)

where \( P \) and \( C_p \) are the density and specific heat capacity of the skin simulator.
3.3 Test fabrics and Protocol
The basic technical description of the fabrics used in the study is shown in Table 1. All flame resistant fabrics were selected from ZhuHai SRO Ltd Co and conditioned at 20(±2) °C, 65(±3)%RH for above 24h before testing.

Typically, the quartz tubes were preheated for 60 seconds before they were exposed to the fabric samples. Simultaneously, the data acquisition system was activated. The quartz tubes temperature was kept unchanged during the whole thermal exposure. The thermal exposure time typically lasted between 8 and 25 seconds, depending on the test requirement and the material being evaluated. After each test, the fabric samples were removed from the apparatus and allowed to cool. The skin simulation sensors were allowed to cool for approximately 15 minutes, allowing the skin simulator to return to isothermal conditions throughout.
4. Results and discussion

A heat flux sensor cut from a piece of standard copper pipe, used in the cylindrical geometry tester, was described in detail in Reference [8]. The temperature of the calorimeter is then used to determine the exposure time to cause a second-degree burn in accordance with the Stoll curves. To provide a rather accurate comparison with the Stoll criterion method, we fabricated a thermal sensor according to the cylindrical copper calorimeter technique instead of the skin simulation sensor in the tester system. In all the comparative tests, the radiant heat flux was the same, namely 21kW/m².

Figure 3 indicates that there are distinct differences in burn evaluations between the Stoll criterion method with copper calorimeter and the Henriques burn integral method with the Pennes’ model, although the tolerance time of the two methods showed the same trends.

It was found that the burn time values derived from the Henriques burn integral with the traditional Pennes’ equation are smaller than that from the Stoll criterion due to the difference in response of the sensors, namely that the copper disk will not absorb heat in a similar manner to skin. Skin increases in temperature faster than the copper disk, and this can lead to calculated heat fluxes that may not accurately represent the heat flux into the skin for a similar situation.
A planar geometry tester, integrating the same skin simulation sensor as that in the cylindrical geometry tester proposed in the paper, was developed by the author [10]. In order to examine the cylindrical geometry effect on the thermal protection of heat-resistant fabric, A1 and A8 samples were chosen to determine heat transmission on both planar and cylindrical geometry testers with the same incident heat flux of 21kW/m² and 6mm air gap between the fabric specimen and the skin simulation sensor.

According to Figure 4, there is a slope change in the temperature history of the skin simulation surface underneath the Aramid fabric when conducting the cylindrical geometry test. This is because upon exposure the Aramid fabric is not dimensionally stable and shrinks close to the skin simulator while FR cotton fabric does not and the air layer size is dramatically reduced in the former case. This therefore increases the heat transfer rate to the skin simulator, which results in an instantaneous change in the temperature history of the skin simulator sensor surface. In addition, keeping the fabrics planar during the bench scale testing does not permit such behaviour to occur, thus limiting the usefulness of such a geometry in predicting the fabric behaviour in the cylindrical geometry test.
5. Conclusions

A test device integrating with a skin simulation sensor for measuring thermal protective properties of heat-resistant fabrics, has been developed which simulates the cylindrical geometry and heat transport features of the human body, human limbs in particular. The test results reported here indicate that significant differences may occur in the tolerance times predicted by the skin simulator and copper calorimeter. The differences are attributed to differences in the manner of heat absorption by the two heat flux sensors. Significant shrinkage of the Aramid fabric has been reported during cylindrical geometry tests.

References
Evaluation of Military Ballistic Helmets Using a Thermal Manikin

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Abstract

Thermal insulation properties of three military light weight ballistic helmets were studied using a 26-sensor sweating manikin. The results showed that among the three ballistic helmets, the ones with liner pad systems offer slightly more insulation than the standard suspension system under dry conditions. However, no significant difference was found between the clo values of the vertical and the horizontal pad systems. Under manikin sweating testing conditions, all three helmet systems showed lower insulation properties compared to the data from dry testing conditions. This is due to the fact that the helmets allow for evaporative cooling in the sweating condition. The placement of the liner pads, however, does not affect either the insulation property or the evaporative cooling of the helmet under the sweating and still air testing conditions. Although the studies were not conducted in an environmental chamber, the temperature, humidity and wind velocity were controlled within the acceptable ranges as specified in the ASTM standards.

1. Introduction

The primary function of a military ballistic helmet is to protect the head from impact related injuries. Technological advances have revolutionized the design of high strength, light weight protective helmets. Generally, the helmet shell is constructed with a composite material of polymeric binder-reinforced Kevlar (Jacobs and Van Dingenen, 2001) which has excellent resistance to high speed impact. The interior portion of the shell is fitted with an internal system which holds the helmet on a soldier’s head and ideally should provide additional protection against impact related injuries. A variety of internal systems exist. One type includes a suspended mesh knit structure that rests against the top of the head and a vinyl strap that fits around the circumference of the head (Fig.1a). This system’s ability to provide adequate cushioning to the head during high level impacts has been questioned.
Therefore, a different type of internal system (Oregon Aero website, 2006) (Fig.1b), consisting of liner pads, has been developed to provide better cushioning and protection when the head is exposed to impact. The liner pads are made of one-half inch thick highly impact absorbent visco-elastic foam which is covered with a waterproof but air breathable coating and a moisture wicking polyolefin fabric cover.

Figure 1: Inside view of light weight ballistic helmets with a) mesh/vinyl suspension system (left) and b) padding system (right).

Although the safety of these ballistic helmet systems is of primary concern, the comfort related to the thermal properties of different helmet systems must also be assessed. Research has shown that despite the head’s small surface area compared to the whole body, the human head is very sensitive with regards to thermal comfort and is an integral part of thermoregulation (Desruelle and Candas, 2000; Brühwiler, 2003). However, most of THE RESEARCH ON physiological aspects of helmets have focused on bicycle and industrial protective helmets (Liu and Holmér, 1997; Liu, et al, 1997; Ellis, et al, 2000; Brühwiler, 2003; Brühwiler, et at, 2004). Since Fonseca’s (1974) study of the heat and moisture transfer properties of military helmets, using the head of a copper manikin, most research related to military protective headgear has focused on the materials and the construction of ballistic helmets (Kobi, et al, 2006, Carter, et al, 2000, Carter, 1992, Folgar, et al, 1991). The objective of the present study is to use a sweating thermal manikin to compare the thermal properties of a basic lightweight military ballistic helmet fitted with three different types of internal helmet systems. The resulting data, used in conjunction with information obtained from prior research surrounding impact resistance, may be used to assess the trade-off between safety and thermal comfort offered by each helmet system.

2. Methodology

2.1. Material

Thermal tests were performed on three large size Marine Corp lightweight ballistic (MLW) helmets with the same outer helmet shell; however, each had a different type of interior suspension or padding system. The first is a standard internal suspension system consisting of a suspended mesh knit structure that rests against the top of the head and a vinyl strap that fits around the circumference of the head; plus chin strap. The second and third are MLW helmets retrofitted with Oregon
Aero’s patented BLSS kit which consists of 7 individual pads and a four-point chin strap / harness. Each retrofitted pad is comprised of a multiple density, visco-elastic foam cushion fully enveloped by a proprietary waterproof yet air permeable coating. The pad is then covered with a fabric cover which is, in part, a moisture wicking polyolefin fabric. Although the size, shape, and material of these internal pads for the second and third systems are identical, pad placement differs. The pads in the second system are positioned horizontally (the longer dimension of the pads is in the horizontal direction), whereas the pads in the third system are placed vertically to improve air ventilation.

2.2. Testing conditions

A sweating thermal manikin with 26 sensors (2 in the head) and walking capabilities was used. Skin temperature was set at 35 degrees Celsius. The manikin remained in a stationary standing position during the tests. Data were collected from both dry conditions and sweating conditions with flow rate of 250 ml/hr/m². Tests were not conducted in an environmental chamber. However, we were able to achieve the high level of consistency in the environmental conditions as outlined in the ASTM F2370-05 test method (2006). The ambient temperature ranged from of 20.0 to 21.3 degrees Celsius and the relative humidity ranged from 52.3 % to 60.6 %.

Tests were conducted under the minimum air velocity as specified by ASTM F2370-05 (2006). To achieve the lowest and most consistent wind velocity during each test and across all tests, a cardboard barrier was configured around the manikin. Wind velocity was measured in four locations around the perimeter of the manikin’s head at the beginning and end of each test and all were in the range of 0 to 0.1 metres per second.

2.3. Dry manikin tests

One dry test was performed on each of the three helmet systems. Each test had a duration of one hour. Data collected during the final 20 minutes of each test were used to calculate heat flux, thermal resistance, and Clo figures. The manikin wore the sweat skin during the dry tests; however, the sweating function was disabled.

2.4. Sweating manikin tests

Each of the three helmet systems received two sweating test replications. Prior to the tests, the sweating skin on the manikin was thoroughly saturated with deionized water. Each replication lasted one hour. Data collected during the final twenty minutes of each test were used to calculate heat flux, and together with data from the respective dry tests, were used to calculate the evaporative resistance figures.
3. Results and Discussion

Dry test results are shown in Tables 1 and 2. When compared to the helmet with the standard suspension system, the helmets retrofitted with either liner pad system exhibit slightly greater insulation under dry conditions. However, from Table 2, the clo values of the vertical pad system and the horizontal pad system do not differ significantly under dry testing conditions.

When exposed to sweating conditions, the heat flux data for all three helmet systems significantly increased compared to the heat flux data from the dry conditions (Tables 1 and 3). This data shows that all three systems allow for evaporative cooling. In addition, under sweating conditions, the helmets retrofitted with either liner pad system exhibited slightly greater insulation than the helmet with the standard suspension system (Tables 3 and 4). The lack of a difference between the vertical and horizontal placements is not surprising, as all tests were conducted under minimal wind conditions. It is anticipated that when increased wind velocity is introduced in the next phase of this research project, the vertical liner pads will provide greater ventilation and result in lower thermal insulation because the gaps between the internal pads (4 cm) are greater than those between the horizontal pads (1.5 cm).

<table>
<thead>
<tr>
<th>Helmet Interior System</th>
<th>No helmet</th>
<th>With helmet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>126.0 ± 2.9</td>
<td>73.5 ± 3.1</td>
</tr>
<tr>
<td>Horizontal Pad Placement</td>
<td>126.0 ± 2.9</td>
<td>64.3 ± 0.9</td>
</tr>
<tr>
<td>Vertical Pad Placement</td>
<td>125.8 ± 5.9</td>
<td>65.6 ± 1.7</td>
</tr>
</tbody>
</table>

Table 1: Dry heat flux (W/m²) data of three ballistic helmet systems

<table>
<thead>
<tr>
<th>Helmet Interior System</th>
<th>Thermal resistance (m²C)/W</th>
<th>Clo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No helmet</td>
<td>With helmet</td>
</tr>
<tr>
<td>Suspension</td>
<td>0.119</td>
<td>0.204</td>
</tr>
<tr>
<td>Horizontal Pad Placement</td>
<td>0.119</td>
<td>0.232</td>
</tr>
<tr>
<td>Vertical Pad Placement</td>
<td>0.120</td>
<td>0.227</td>
</tr>
</tbody>
</table>

Table 2: Dry thermal resistance data of three ballistic helmet systems

<table>
<thead>
<tr>
<th>Helmet Interior System</th>
<th>Replication 1</th>
<th>Replication 1</th>
<th>Replication 2</th>
<th>Replication 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No helmet</td>
<td>With helmet</td>
<td>No helmet</td>
<td>With helmet</td>
</tr>
<tr>
<td>Suspension</td>
<td>290.2 ± 3.7</td>
<td>129.4 ± 1.9</td>
<td>291.4 ± 4.4</td>
<td>132.6 ± 1.2</td>
</tr>
<tr>
<td>Horizontal Pad Placement</td>
<td>290.2 ± 3.7</td>
<td>117.9 ± 1.4</td>
<td>291.4 ± 4.4</td>
<td>121.0 ± 1.7</td>
</tr>
<tr>
<td>Vertical Pad Placement</td>
<td>286.4 ± 3.3</td>
<td>118.8 ± 1.0</td>
<td>287.3 ± 1.7</td>
<td>116.6 ± 2.3</td>
</tr>
</tbody>
</table>

Table 3: Manikin sweating heat flux (W/m²) data of three ballistic helmet systems
Table 4: Evaporative resistance (m²Pa/W) data of three ballistic helmet systems

<table>
<thead>
<tr>
<th>Helmet System Interior</th>
<th>Replication 1 No helmet</th>
<th>Replication 1 With helmet</th>
<th>Replication 2 No helmet</th>
<th>Replication 2 With helmet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>24.3 ± 0.5</td>
<td>69.5 ± 2.4</td>
<td>24.9 ± 0.7</td>
<td>68.4 ± 1.5</td>
</tr>
<tr>
<td>Horizontal Pad Placement</td>
<td>24.3 ± 0.5</td>
<td>73.4 ± 1.9</td>
<td>24.9 ± 0.7</td>
<td>72.2 ± 2.6</td>
</tr>
<tr>
<td>Vertical Pad Placement</td>
<td>24.7 ± 0.3</td>
<td>72.9 ± 0.9</td>
<td>24.5 ± 0.1</td>
<td>75.8 ± 2.4</td>
</tr>
</tbody>
</table>

4. Conclusions

Although the studies were not conducted in an environmental chamber, the temperature, humidity, and wind velocity were controlled within the acceptable ranges as specified in the ASTM standards. Furthermore, consistent baseline data, heat flux values of the nude manikin without helmet, were also achieved for each helmet system prior to the test. The results from this study showed, as expected, that the helmets with liner pads provide better insulation than the helmet with the standard suspension system. When tested under manikin sweating but still air conditions, all three ballistic helmet systems, regardless the type of internal system, allow for evaporative cooling. In addition, data from all tests showed differences between the suspension system and the two liner pad systems on both the thermal and evaporative resistance values. However, these differences appear to be minor. It is difficult to determine whether these minor differences would significantly impact the comfort levels in human subjects. Therefore, there is a need for the development of standards to be used as the guideline for thermal resistance data interpretation.

5. Acknowledgements

Financial support and the three helmet systems used in the tests were provided by Oregon Ballistics Laboratories, LLC. The authors would like to thank Tom Ohnstad and Micah Goettl for their assistance.
6. References


Measurement of Microclimate in Diapers during Supine Posture using a Baby Thermal Manikin

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Abstract

A change in the microclimate of a diaper due to urination was measured using a baby thermal manikin aged a half year-old. The main purpose of this study was to investigate the relevance of diaper structure to its microclimate. Four types of diapers in the market were used in the measurements. Their structure was nearly the same except for the waist belt. In two of the tested diapers, highly elastic belts were installed in the waist part. The other diapers were equipped with non-elastic belts. The measurement was performed at 28 °C and 60 %RH with an air velocity of around 0.2 m/s. A common clothing condition was employed in the test; that is, the baby manikin was dressed with the diaper only and was laid on a mattress, without any blankets, in a supine position during the whole period of the measurement. The test was conducted for 100 min in total. Distilled water of 80 ml at 37 °C was supplied as simulated urine to the diaper at 50, 60, and 70 min. Surface temperatures at eight sites (forehead, back head, chest, back, arms, legs) of the baby manikin were measured. Temperature and relative humidity between the manikin surface and the diaper were also recorded at 4 sites, namely abdomen, buttock, interior and exterior right thigh, as representing the microclimate in the diaper. The microclimate inside of the diaper without urination was kept at a temperature of around 32 °C and at a water vapour pressure of less than 18 mmHg in all the tested diapers. After supply of the simulated urine, the inside water vapour pressure increased remarkably in the case of the diapers with the elastic waist belt, reaching nearly 25 mmHg at the end of the measurement. On the other hand, the inside water vapour pressure of the diapers without the elastic belt was maintained at around 18
mmHg. The difference in the microclimate between the diapers with and without the elastic waist belt can be due to the difference in the volume of the microclimate. That is, the absorbent made of high polymer expands depending upon the amount of the soaked up urine. The microclimate volume inside of the diapers with the elastic waist belt decreases considerably due to the internal expansion of the absorbent, because the elastic belt seriously obstructs the expansion of the absorbent towards the outside. On the other hand, for the diapers without the elastic waist belt, the absorbent is able to expand easily toward the outside, and thus its microclimate volume does not decrease appreciably. Accordingly, one can conclude that, in order to keep the microclimate in the diaper dry, a certain amount of microclimate volume should be maintained irrespective of the expansion of the absorbent due to the absorption of the urine.

1. Introduction

Paper diapers for babies are very handy for parents because they can be disposed. Moreover, the paper diaper is so light and soft compared to cloth diapers as babies can move as freely as they wish. Disposable diapers developed recently, according to material test results, are provided with more functions; e.g., extremely high water absorbability and high breathability to keep the baby comfortable and dry. In this study, microclimate changes inside the diapers, due to discharged urine, have been measured using a baby thermal manikin (Fukazawa et al., 2005) in order to investigate the relevance of the construction of a diaper on thermal comfort.

2. Methods

2.1. Construction of diaper and specimen

In this study, four types of diapers for a baby aged six months, were selected, all having a similar construction except for the fastening system as shown in Figures 1 and 2. The diapers have almost the same length of waist (57 cm including tapes) and leg cuffs (50 cm) so that the baby manikin is always covered in a similar way. A fastening system was employed at the waist in all the tested specimens so as to keep the diaper in the desired position. Two of the diapers, UO and UN, contained a highly elastic belt in the fastening system. The other two diapers, CA and CB, contained non-elastic belts in the fastening system.
2.2. Experimental conditions and procedures

Only one way of donning the diaper was employed in the study, since it covered a large part of the baby’s body surface. All experiments were performed in a climate chamber maintained at the thermoneutral temperature of 28 °C, relative humidity of 60 %, and air velocity of less than 0.2 m/s. Heat energy of 50 W/m² was constantly supplied to the baby manikin, in accordance with the basal metabolism of the baby (Koga et al., 1992).

The experiment was conducted for 100 min in total. During the whole period of the experiment, the baby manikin was laid on a mattress in the supine position as shown in Figure 3. The manikin was clothed without anything for the initial 20 min and then with the diaper. An amount of 80 ml distilled water at 37 °C was charged into the diaper at three intervals, namely at 50 min, 60 min and 70 min, by means of an infusion unit. In the test, the surface temperature of the manikin was measured at 8 sites (of fore and back head, anterior and dorsal torso, arms, and legs including feet) while the temperature and water vapour pressure of the microclimate in the diaper were measured at 4 locations, namely stomach, buttock, medial and lateral thigh on right-side, using thermocouples and hygrometers, at intervals of 1 min. The weight of the diaper was also measured just before clothing and just after the experiment. All measurements started after all the temperatures of the baby manikin surface had reached the steady state.
3. Results and Discussion

3.1. Microclimates of the diapers

No significant differences were found in the local surface temperatures in the 8 sites of the baby manikin. In other words, the mean weighted surface temperatures of the manikin indicated that almost all the corresponding values ranged from 33.9 °C to 34.3 °C in all the tested diapers.

Figure 4 shows the results of the mean weighted temperatures of the microclimate. After donning the diaper, the temperature gradually increased with time. The

![Figure 4](image1)

Figure 4 Change in the microclimate temperatures of the tested diaper are plotted against the elapsed time.

![Figure 5](image2)

Figure 5 Water vapour pressures of the microclimate in all the tested diaper are plotted. The water vapour pressures for UO and UN dramatically reached nearly 25 mmHg just after the 1st infusion, while those for CA and CB showed lower level of 19 mmHg to 20 mmHg.
temperatures of all the diapers rose to around 35.5 °C at the end of the measurement. It was found that the difference in the microclimate temperatures was not so large. Water vapour pressures of the microclimate for the diapers are shown in Figure 5. The water vapour pressures remained at less than 18 mmHg before infusing the simulated urine. The water vapour pressures for UO and UN increased remarkably just after the 1st infusion. The microclimates for UO and UN showed a high water vapour pressure of about 25 mmHg at the end of the experiment. On the other hand, the water vapour pressure of CA and CB did not increase as much as that of UO and UN. The microclimates of both the diapers remained at a lower level of water vapour pressure of 19 mmHg to 20 mmHg, even though 240 ml of water was given in total.

3.2. Evaporated and absorbed water in the diapers

The water vapour evaporated through the diaper is given in Figure 6. The amount of the evaporated water vapour through UO was the largest in the diapers tested. That of the other three diapers was appreciably lower and there were no large differences between the other three diapers.

![Figure 6](image)

Figure 6  Evaporated water vapour through the tested diapers after the whole test period. An amount of 240 ml of distilled water was added at specific intervals during the test period.

3.3. Comfortable microclimate and its volume

Very few studies have been reported on the physiological and psychological thermal comfort of babies due to the ethical and safety considerations. On the other hand, a large number of studies on the thermal comfort of adults have been reported. Humid or stuffy sensations can be perceived when the water vapour pressure on the skin exceeds a particular value which ranges from 15 mmHg to 22 mmHg (e.g. Tamura and Koshiba, 1995; Ushioda et al., 1995). According to numerous papers dealing with clothing thermal comfort (e.g. Harada, 1996), a person remains in a neutral or
comfortable condition thermally when the microclimate is maintained at 32 °C and 50 %RH (= 18 mmHg) under any environmental conditions. If these results can be applied to the thermal comfort of a baby, the results obtained in this study can be discussed by means of a diagram indicating the relationship between thermal comfort and microclimate condition (Harada, 1996).

The temperature and the water vapour pressure (expressed in the relative humidity) in the microclimate are plotted in Figure 7. The numbers in the symbols represent the order in which the water was supplied to the diaper. Thermal comfort was maintained for all the diapers until the 1st simulated urine. That is, the thermal resistance of the diapers did not affect the thermal comfort at the thermoneutral temperature. After the 1st and 2nd supply of the simulated urine, the microclimate reached the slightly uncomfortable zone because of an increase in the water vapour pressure for all the diapers. At the addition of the 3rd simulated urine, the microclimate moved into the uncomfortable zone. Although CA and CB fall into the uncomfortable zone in Figure 7, their water vapour pressures are maintained at a low level (see Figure 5). Accordingly, it can be concluded that the CA and CB diapers are better products than the UO and UN diapers in terms of maintaining the microclimate in a dry condition as long as possible.

The water vapour pressure in the microclimate of UO became the highest after 50 min. Moreover, its evaporated water vapour was the largest in the test. On the other hand, in CA and CB, which did not have elastic bands, the water vapour pressures were lower and the evaporation rate was low. The reasons can be due to differences in the microclimate volumes with and without the elastic belt.
The absorbent polymers inside the diaper expand depending on the amount of liquid soaked up. The microclimate volume in the diaper with the elastic belt (i.e. UO and UN) is reduced considerably due to the expansion of the absorbent towards the body, since the elastic belt seriously obstructs the absorbent expansion towards the outside. On the other hand, the absorbent can easily expand to the outside for the diapers without the elastic belt (i.e. CA and CB). Therefore, the microclimate volume of CA and CB did not decrease as much as that of UO and UN. Hence, the microclimate volume should be maintained irrespective of the expansion of the absorbent due to the absorption of the urine, so as to keep the microclimate inside the diaper dry.

4. Conclusions

Changes in the microclimate of a diaper have been measured by means of a baby thermal manikin. In the study, the effect of the fastening system with/without an elastic belt on the microclimate condition has been discussed. In order to fix the diaper to the body, the fastening system has an important function. Nevertheless, the present results imply that, in case of the diaper with a highly elastic belt in the waist, the microclimate condition rapidly reaches the thermal discomfort zone after urination because of the limited space resulting from the absorbent expanding towards the inside.

Acknowledgements

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Improving Thermal Comfort in an Orthopaedic Aid: Better Boston Brace for Scoliosis Patients

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Abstract

Scoliosis is an S-shaped sideways curvature of the spine leading to the shape change of the torso. Idiopathic scoliosis is one form of this disease with unknown aetiology. 300 children out of 100 000 do need treatment. Treatment duration is till the end of the patient’s growth age (till the ossification of the skeleton) and the brace should be worn 23 hours a day.

Problems with a brace were heat, moisture, weight, stiffness, affects skin, odour, medical appearance, etc. The main objectives of the project were to improve heat and moisture dissipation from the brace. However, it was to be kept in mind that the brace is an orthopaedic aid and its positive effect has been documented and proven over decades.

A new brace was designed but the question was: Is it better? To answer the question the tests on a thermal manikin were carried out using a constant surface temperature mode, stable temperature and humidity in the climatic chamber, recording of power input (heat loss) and having the manikin on a scale for continuous recording of evaporation.

All new prototypes of the Boston brace had better thermal performance than the original one. The new braces were relatively similar in their performance. Heat dissipation from the new prototypes was most probably improved due to higher evaporative heat losses. More open structure of 3D material improved evaporation
more than just openings. Optimizing the openings may improve the ventilation even more.

In addition, the following positive effects were achieved: the brace looks lighter and is more airy and skin friendly because of the openings, the new brace is thinner, therefore better fitting under clothing, the openings and the thinner inner lining reduced the weight of the brace, the changeable inner lining makes frequent machine washing possible, as well as the use of linings in different colours.

**Background and objectives**

Scoliosis is an S-shaped sideways curvature of the spine leading to a change in shape of the torso. Idiopathic scoliosis is one form of this disease with unknown aetiology and about 300 children out of 100 000 need treatment. Historic treatment involves stretching beds, primitive braces and surgery. Nowadays, surgery and braces are used depending on the severity of the disease and the common practice of the country. Special gymnastics is recommended in all cases. Sometimes, especially when the case is not severe, only gymnastics and soft orthoses are recommended. Treatment duration is until the end of the patient’s growth age (ossification of the skeleton) and the brace should be worn 23 hours a day.

The Boston brace (BB, 1972, Figure 1a, 1371 g) consists of a rigid outer layer (4 mm polypropylene) and a soft inner lining (6 mm polyethylene). A cotton shirt is used against the skin under the brace. Problems with the brace are related to heat, moisture, weight, stiffness, that it affects skin, odour development, medical appearance, etc. Some of these properties, e.g. stiffness, are essential for the curing ability of the brace. Thus, it was to be kept in mind that the Boston brace is an orthopaedic aid and its positive effect has been documented and proven over decades. Within this project the main objectives were to improve heat and moisture dissipation from the brace.

![Figure 1: The original Boston brace (a) and the new Boston brace prototypes: b) design product of the same outer shell material as the original brace (polypropylene) with designed holes in the areas where the strength and rigidity of the brace are not compromised; c) brace in structural plastic 3D X-lite; d) brace in structural plastic 3D X-lite with designed holes for original brace. All new braces use a liner of permeable 3D Spacer.](image)
Inputs were received from orthopaedists, orthopaedic engineers, patients, manufacturers, designers, ergonomists and thermal specialists. Within the project a new brace (NB, Figure 1b, 1355 g) involving a more open structure in combination with a new lining (3D Spacer) was designed (Heidmets, 2005). Also, different materials were studied and a new material (3D X-lite) was suggested for the outer shell (3D, Figure 1c, 1260 g). The latter prototype was made after the end of the project. Also, during the work we combined two solutions of more openings and new material and produced a third prototype (N3D, Figure 1d, 1194 g). Nevertheless, the questions remained: Were the new prototypes thermally superior? How much better were they?

**Methods**

To answer the questions, the tests on a thermal manikin were carried out. The walking thermal manikin Tore (Figure 2) is made of plastic with a metal frame inside to support the body parts and for joints. It has the size of an average Swedish male of the first half of the 1980s. Some manikin parameters are shown in Table 1.

Tore is divided into 17 individually controlled zones (Figure 3): head, chest, back, stomach, buttocks, left and right upper arm, left and right lower arm, left and right hand, left and right thigh, left and right leg, and left and right foot. In addition, 3 air temperature sensors set at the heights of 0.1, 1.1 and 1.7 m from soles are connected to the system. Walking movements are created by pneumatic cylinders fixed to wrists and ankles.
The computer system allows the use of 3 measurement modes: constant temperature, constant heat loss and physiological (comfort) mode. Most commonly used is the constant temperature mode where the surface temperature of all the zones is kept at 34 °C and heat losses (power input) are recorded at 10 second intervals. This allows quick stabilization of power and temperature readings and easy calculation of clothing insulation values. Commonly, data of the last 10 minutes is used in data analysis. Special test report files are used for data analysis where areas, heat losses, temperatures and insulation values are shown for each separate zone and for the whole manikin. Total insulation values can be calculated according to both the serial and parallel methods (ISO 15831, 2004).

<table>
<thead>
<tr>
<th>The thermal manikin Tore</th>
<th>34</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant temperature measured over the nude body surface</td>
<td>34</td>
<td>°C</td>
</tr>
<tr>
<td>Distance of surface temperature sensors from the surface</td>
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<td>mm</td>
</tr>
<tr>
<td>Gender (female/male)</td>
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<td></td>
</tr>
<tr>
<td>Heating power (constant power regulation)</td>
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<td>W/m²</td>
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<tr>
<td>Heating principle (constant temperature / constant power)</td>
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<td></td>
</tr>
<tr>
<td>Minimum heat flux of best isolated segment of the manikin</td>
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<td></td>
</tr>
<tr>
<td>Movement mechanism (mechanic/pneumatic/none)</td>
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<td></td>
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<tr>
<td>Normally used garment size</td>
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</tr>
<tr>
<td>Number of zones (body sections)</td>
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<td></td>
</tr>
<tr>
<td>Surface material (plastic/metal)</td>
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<td></td>
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<tr>
<td>Temporal variation of surface temperature (min/max)</td>
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<td>°C</td>
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</table>

<table>
<thead>
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<th>Measures</th>
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<tr>
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<tr>
<td>Body weight</td>
<td>0.32</td>
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<tr>
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<td>Head girth</td>
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</tr>
<tr>
<td>Neck girth</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 1  Manikin parameters

A recommended shirt (Boston Silver T, 165 g) containing, for example, Coolmax fibres, was used under the brace. The tests were carried out in the constant surface temperature mode (34 °C), stable chamber temperature and humidity: 34.0±0.3 °C and 20±2 %, and 21.7±0.3 °C and 60±2 %. Air velocity was kept low (< 0.4 m/s).

At 34 °C, tests with a wet shirt only were carried out for evaporative heat loss calculation. At a room temperature of 22 °C both dry and wet tests were carried out. Power input (heat loss) and temperature recordings were taken each 10 seconds and the manikin was placed on a scale for continuous recording of moisture losses. The shirt was wetted with about 180-200 g water and generally the wet tests lasted for 130 minutes except for the shirt as it dried out earlier.
In order to avoid moisture reaching the manikin inside, it was wrapped with a thin plastic layer. No other clothing was used during the tests. As the brace covered fully or partly only the zones of the torso area, the results from the torso are shown below. Insulation values shown here are based on the parallel calculation model.

Evaporative resistance was calculated by 3 methods for the 50th minute of each test:

- from evaporative heat losses at 34 °C (for torso and stomach)
- from evaporative heat losses at 22 °C according to F 2370 – 05 (2005, for torso and stomach)
- from mass loss according to F 2370 – 05 (2005, for torso at 22 and 34 °C)

Results and discussion

The effective insulation ($I_{\text{cle}}$, ISO 15831, 2004) of the braces for the manikin torso area are given in Figure 4. Air layer insulation ($I_a$) of the manikin torso wrapped in the plastic film was 0.110 m²°C/W and the clothing area factor was not considered as it would be approximately the same for all braces, i.e. differences would have been the same.

![Figure 4](image)

Figure 4  Effective insulation of the shirt only and the braces with the shirt

It can be seen that the insulation of the shirt only (ST) and 3D brace without holes (3D, Figure 4) differ significantly from the others. The reason for the 3D higher insulation is entrapment of air in the structure. However, it would, as do the stitched products, lose the insulation quickly when motion and high air velocity are involved, but such tests were not carried out within this study. It can be seen that the holes do reduce the insulation in both the old shell and the 3D shell, thereby improving heat dissipation.
From the tests at 34 °C the evaporative heat losses from the torso were obtained. The dry heat losses were not present as the manikin surface temperature was equal to the ambient temperature. Figure 5 shows the weight change during the tests at 34 °C and it corresponds to the drying of the shirt. The shirt became practically dry at about the 80th minute. The curve shows that some areas of the shirt did dry out already earlier and the evaporation area became smaller. This influenced the evaporation rate (inclination). Even with braces, the change in slope is noticeable. Considering that all conditions were stable between the 15th and 50th minutes, it is possible to acquire a linear evaporation relationship over time with $R^2>0.99$ for all braces. The slopes indicate that each 10 minutes 25 g are evaporated from the shirt (ST), 16 g from the new 3D brace (N3D), 14 g from 3D brace (3D), 13 g from modified brace (NB) and 9 g from the original brace (BB). By the end of the test ST was practically dry. After 130 minutes there was still 14 g water left in N3D, 16 g in 3D, 36 g in NB and 78 g in BB.

From Figure 6, it can be seen that about 1/2 of the shirt is not covered by the brace. In practice it means that of the about 200 g of water, 100 g did evaporate from uncovered areas and as much from the covered areas. It means that with moisture transport to uncovered areas via the shirt, only about 10 g/h evaporated from under BB. With the same reasoning NB lost about 3 times more, i.e. 30 g/h, and N3D and 3D were close to each other with about 40 g/h.
Figure 6 Brace on manikin: a) NB, view from the back; b) 3D, view from the front.

Figure 7 Total evaporative resistance of the shirt and the braces for the whole torso area at 22 and 34 °C based on heat and mass losses for the 50th test minute (stable state, see Figure 5).

Figure 7 indicates that the calculation of the total evaporative resistance by mass loss is not sensitive enough and most probably not accurate. It confirms the conclusions from an inter-laboratory study on sweating manikins where mass based evaporative resistance differed more from the other results (McCullough, 2002; F 2370 – 05, 2005). It gives relatively similar resistance values for all braces at both temperatures, while we see big differences in original brace and other braces and the shirt. Especially clear differences were obtained for the measurements at 34 °C where evaporative resistance of BB from mass loss lays in the same range as that of other braces based on heat loss. The possible reasons for lower evaporative
resistance from mass loss are shirt covering or touching other zones (see Figure 6), and evaporation heat taken from the environment (larger difference at higher ambient temperature). Larger differences between the calculation methods for impermeable material could be related to higher ratio of moisture transport through shirt to more far areas before the evaporation took place. In more open structures most of the evaporation took place near (warm) manikin surface and eventual moisture transport could have been the opposite than in BB, i.e. towards the drying manikin surfaces.

Confirming the discussion above on area covered by brace, the stomach area of BB has almost an 8 times higher evaporative resistance than the shirt and 4 times higher resistance than any other, modified brace at 22 °C (Figure 8). At 34 °C where other types of heat transfer is eliminated and evaporative heat losses dominate (Havenith et al., 2006a; Havenith et al., 2006b) the differences are even larger. In terms of total heat losses it means that new braces have twice as high heat dissipation from the torso than the original one.

![Figure 8 Total evaporative resistance of the shirt and the braces for the stomach only, at 22 and 34 °C based on heat losses for the 50th test minute (stable state, see Figure 5).](image)

**Conclusions**

All new prototypes of the Boston brace had better thermal performance than the original one. The new braces were relatively similar in their performance. Heat dissipation from the new prototypes was most probably improved due to higher evaporative heat losses. The more open structure of the 3D material improved evaporation more than just openings. Optimizing the openings may improve ventilation.

- The prototypes had twice the higher total heat losses than the original Boston brace at room temperature (22 °C)
• The prototypes had four times lower evaporative resistance than the original Boston brace at room temperature (22 °C)
• Evaporative resistance of the shirt was 2 times lower than that of the new braces.
• Evaporation rate related to the whole torso (covered and not covered areas) was 1.4-1.8 times higher for the new prototypes than in the original Boston brace

In addition, the following positive effects were achieved: the brace looks lighter and is more airy and skin friendly because of the openings, the new brace (NB) is thinner, therefore better fitting under clothing, the openings and the thinner inner lining reduced the weight of the brace, the changeable inner lining makes frequent machine washing possible, and also the use of linings of different colours.

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Section VIII
Functional Clothing
The Physiological Properties of Smart Textiles and Moisture Transport through Clothing Fabrics

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Abstract

This paper deals with the transport phenomena in cloth made from barrier fabrics (for example Goretex, Sympatex Torey) used for sports apparels. The theory for transporting of water vapour through fabric is described and applied for the calculation of the water vapour transport for a windcheater made from barrier fabric. The water diffusion vapour permeability depends mostly on the diffusion coefficient and difference of partial pressure on both (inner and outer) sides of the material, in this case semi-permeable - barrier fabrics. The partial pressure difference determines the direction of the water vapour transport. It means that if partial pressures are balanced, no transport arises. In the case where the partial pressure outside is greater than inside, the moisture comes into the clothing. Therefore, using smart barrier textiles and apparel made from such fabrics has limits and the best applications are between zero degrees and 10°C. This paper describes transport phenomena in smart textiles for sports clothing and the influence on physiological comfort.

1. Introduction

The comfort of clothing material is one of the most important aspects for producers and customers, especially for sports clothing. The modern functional sportswear consists of:

First layer – underwear – the main function of this layer is to transport sweat from the skin to the other layers.
Second layer – works as the thermal insulation layer. In the special structure i.e. fleece uses static air, which causes the thermal insulation function. Some of the latest fleece materials have a membrane, thereby partially resisting wind flow and moisture. In this case the second layer ensures the same time protective function and it is not necessary to use a third layer.

Third layer – works as a barrier between the human organism and the environment. The most important is its air impermeability and water resistance. Simultaneously this layer must be, as much as possible, permeable for water vapour.

The old system of clothing comprised of cotton underwear, cotton shirts and an impermeable protective layer. This system did not work, because it did not have very good physiological properties. Modern systems are composed of functional underwear, a thermal isolation layer and a protective layer as shown in Fig. 1.

Modern apparel materials for sport and leisure must fulfil the demands of good organism protection against cooling and of low water permeability, but on the other hand they have to fulfil contradictory requirements – good air permeability and good permeability of water vapour. Figure 1 shows the evolution of sport clothing, from impermeable clothing on the left side to the functional clothing, which fulfils physiological properties, on the right side.

The semi-permeable textiles represent the modern material, which acts as a resistant barrier to the moisture in the form of liquid water and at the same time permits water vapour transport. The basic principle is that of a laminar membrane. All types of barrier textiles work only in the case of the difference between partial pressures of the water vapour on the two sides of the textile. When the difference in partial pressures on the two sides becomes zero those textiles are not able to function as a barrier textile, and clothing made from such, act as a very expensive raincoat.

Barrier textiles should have good resistance to water, together with good permeability and vapour transport. This principle is presented in Fig. 2.
Physiological comfort is influenced by: the moisture of the air under the clothing, skin moisture, the temperature of the air under the clothing, skin temperature and the content of carbon oxide under the clothing.

The most important properties of clothing materials, from a physiological point of view, are the permeability and transport of water vapour, air permeability and water resistance. The water transport is a combined function of evaporation, capillary drain of sweat, water migration and the diffusion of the moisture. The above mentioned properties act together. Practically it is possible to measure only water vapour permeability through textile material by the difference in the partial pressure of water vapour. Water resistance is typical for barrier textiles. Small, or better no, water permeability is very important for sport clothing, because moisture significantly decreases the thermal insulation properties of textile materials.

Transport of heat and moisture through clothing materials depends on body temperature, human activity, number of clothing layers and environment conditions. The transport is a dynamic process, which can be described as heat conduction and moisture transport in porous bodies. This paper describes a basic theoretical analysis of this problem and the results of measurements of different smart-barrier clothing materials.

2. Theoretical analysis of problem

Transport of heat and moisture through clothing materials is a very complex problem and depends on body temperature, human activity, number of clothing layers and environmental conditions. The transport is a dynamic process, which is possible to describe as heat conduction and moisture transport in porous bodies.

2.1. Water vapour permeability

For a well known type of barrier textile it is possible to determine the value of resistance to water vapour penetration (R_w = 7.96 m²·Pa·W⁻¹) [5, 6]. This value may
be used for a simplified model of moisture transfer, and the water vapour permeability is given by:

\[ W_d = \frac{1}{R_{et} \cdot \Phi T_m} \]  

(1)

where: \( W_d \) ....... water vapour permeability \([\text{g} \cdot \text{m}^{-2} \cdot \text{hod}^{-1} \cdot \text{Pa}^{-1}]\), 
\( \Phi T_m \) ....... latent heat of evaporation \([\text{W} \cdot \text{g}^{-1}]\) at temperature \( T_m = 35 ^\circ \text{C} \) 
(\( \Phi T_m = 0.672 \ \text{W} \cdot \text{hod}^{-1} \cdot \text{g}^{-1} \)).

In our case we get:

\[ W_d = \frac{1}{7.96 \cdot 0.672} = \frac{1}{5.349} = 0.1869 \left[ \text{g} \cdot \text{m}^{-2} \cdot \text{hod}^{-1} \cdot \text{Pa}^{-1} \right] \]  

(2)

Under conditions when the temperature in the microclimate between the human body and the windcheater, with an estimated area about 2.5 \( \text{m}^2 \), is temperature \( T_1 = 35^\circ \text{C} \) and relative humidity \( \phi_1 = 80\% \) the partial water vapour pressure is \( p_{i1} = 4212.3 \ \text{Pa} \). With an outside temperature \( T_2 = 20^\circ \text{C} \) and relative humidity \( \phi_2 = 40 \% \) the relevant partial pressure of water vapour value \( p_{i2} = 893.1 \ \text{Pa} \). When the moisture transport is steady, the total moisture transport is:

\[ W_{d\text{total}} = W_d \cdot \Delta p \cdot A = 0.2 \cdot 3319.2 \cdot 2.5 = 1550.9 \left[ \text{g} \cdot \text{hod}^{-1} \right] \]  

(3)

This is a simplified estimation provided that moisture transport is steady at all the parts of the sports windcheater. In the bibliography [4], it is reported that during hard work or intensive sport performance the human body produce about 1000g of moisture per hour. Thus, in this condition it is possible to say that the membrane material is excellent. In the case where the outside temperature and relative moisture increases, i.e. \( T_2 = 24^\circ \text{C} \) and \( \phi_2 = 55\% \), the moisture transport decreases by about 30%.

2.2. Heat and moisture transport

Heat transportation is possible to describe by the Fourier hypothesis about heat propagation in a body. The flow of thermal energy is given by:

\[ q_{\text{cond}} = -a \cdot \nabla \left( \rho \cdot c_v \cdot \theta \right) \]  

(4)

where: \( q_{\text{cond}} \) ................. heat conduction flow \([\text{W} \cdot \text{m}^{-2}]\), 
\( a \) ............... heat conductance \([\text{m}^2 \cdot \text{s}^{-1}]\), 
\( \nabla \) ................. Laplace’s operator, 
\( \rho \) ................... partial mass density \([\text{kg} \cdot \text{m}^{-3}]\), 
\( c_v \) ................... specific heat \([\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]\), 
\( \theta \) ................... temperature \([\text{K}]\), 

\[ a \cdot \rho \cdot c_v = \lambda \]  

(5)

\[ a = \frac{\lambda}{\rho \cdot c_v} \]  

(6)

where: \( \lambda \) is the coefficient of thermal conductivity \([\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}]\).
Then it is possible to write:

\[ q_{\text{cond}} = -\lambda \cdot \nabla \cdot \vartheta \]  

(7)

From the above mentioned relation it is evident that the heat transfer is given by the coefficient of thermal conductivity \( \lambda \), which is influenced by the type of clothing material, number of clothing layers and particularly by the air enclosed inside the clothing material. This air is a significant thermal insulator. The insulating ability of the enclosed air decreases with increasing moisture of the clothing material. This is the reason why the transport of moisture is very important for all the layers of clothing.

Moisture transport can be described by the relationship for mass transport:

\[ q_{\text{dif},i} = -D_i \cdot \nabla \cdot \rho_i \]  

(8)

where:

- \( D_i \) \………………..coefficient of diffusion transport of mass for \( i \) – component \([m^2 \cdot s^{-1}]\)
- \( \nabla \rho_i \) \………………gradient of partial mass density for \( i \) – component \([kg \cdot m^{-3}]\)

For unit flow of moisture as compound of gaseous environs with partial pressure \( p_i \) (\( p_i' \) – partial pressure inside the porous clothing material, \( p_i'' \) – partial pressure outside the porous clothing material) it is possible to use:

\[ q_{\text{dif},i} = \frac{D_i}{RmT} \frac{M_i}{s} \frac{p_i' - p_i''}{p_i'^{\prime} - p_i''^{\prime}} \]  

(9)

where:

- \( R_m \) \………………universal gas constant \([kJ \cdot kmol \cdot K^{-1}]\),
- \( M_i \) \……………….molar mass \([mol]\),
- \( T \) \………………temperature \([\circ K]\),
- \( s \) \………………layer thickness \([m]\).

From the above relation it is possible to determine the coefficient of the diffusion transport of mass, which determines the diffusion transport of water vapour in fabric. In our modelled case (\( T_1 = 35^\circ C, \ \varphi_1 = 80 \%, \ T_2 = 20^\circ C, \ \varphi_2 = 40\% \)) the diffusion coefficients:

\[ D_{i} = \frac{RmT}{M_i} \frac{s}{p_i'^{\prime} - p_i''^{\prime}} = 620 \cdot 8.32 \cdot 10^3 \cdot 290.5 \cdot 0.005 \cdot \frac{0.0348 \cdot 1.8933 \cdot 0.8620}{18 \cdot (4212.3 - 893.1)} = 0.0348 \text{ m}^2 \cdot \text{s}^{-1} \]  

(10)

This value is about 104 times greater than the moisture permeability of a brick wall with a thickness of 0.5 m.

For example, the diffusion rate of vapour when the temperature under the barrier fabrics is (\( T_1 = 35^\circ C, \ \varphi_2 = 50\% \)) = apx the human skin, and outside temperature is \( T_2 = 0-50^\circ C, \varphi_2 = 30-100\% \). This example is calculated for Gore-Tex 2V, Sympatex2,5V, Torey 3V.

a) \( T_1 = 35^\circ C, \ \varphi_1 = 50 \% \),
360 Thermal Manikins and Modelling

**Gore-tex 2v relative humidity $\varphi=50\%$**

![Gore-tex 2v relative humidity $\varphi=50\%$](image1.png)

**Sympatex 2,5v relative humidity $\varphi=50\%$**

![Sympatex 2,5v relative humidity $\varphi=50\%$](image2.png)

**Toray 3v relative humidity $\varphi=50\%$**

![Toray 3v relative humidity $\varphi=50\%$](image3.png)
It is evident that moisture transport can be bi-directional, depending only on the difference of the partial pressures of water vapour and the diffusion coefficient, which is given by the permeability of the barrier textiles. The barrier textiles are able to transport water vapour inside the microclimate between the human body and the clothing under conditions of high moisture in the environment. During high sporting activity the difference in partial pressures is given by the maximal partial pressure (dew point) inside and the difference $\Delta p$ is limited [1].

B/Influence of washing and dry-cleaning on vapour permeability, see Table below.

![Vapour penetration, washing](image)

It is possible to conclude that the influence of washing on vapour penetration is not significant, but is significant for air penetration and water resistance. But it was found that the influence of dry-cleaning on these properties is very significant.

**Conclusions**

The value of water vapour permeability and the diffusion rate depend most of all on the difference in the partial pressure on both (inner and outer) sides of the material and the material used, in this case barrier fabrics. The partial pressure difference determines the direction of water vapour transport. When the partial pressures are balanced no transport occurs. In the case, where the outside partial pressure is greater than that inside, the moisture comes into the clothing. Therefore, the use of smart barrier textiles and apparel of such fabrics has limitations and the best applications are from zero degrees to 10°C. Nevertheless, smart barrier textiles are very important in improving the physiological properties of sports clothing.
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Measurement of Temperature and Humidity Gradient across Underwear for Optimal Microclimate Regulation of Multi-layered Clothing Systems

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Abstract

Temperature and moisture gradients in the dynamic mode have been investigated using a skin model but not thoroughly with the thermal manikin. Even though thermal manikins have been developed for dry and wet thermal transfer in a steady state, information on the dynamic distribution of the moisture across the clothing layers worn on a sweating manikin would be very helpful to develop more comfortable protective clothing and to advise the wearer how to wear underwear under the protective outer shell. The objectives of this paper are firstly, to obtain temperature and moisture gradients across multiple layers using a sweating thermal manikin by careful experimental procedures and secondly, to find out the most comfortable arrangement of underwear layers under a Gore-Tex outer jacket. Also, to compare the effects of hygroscopic and hydrophobic meshes as innermost underwear compared to ordinary cotton and nylon interlock underwear, on the various aspects of heat and moisture transfer, i.e. total vs. local, as well as steady vs. transient states. Optimized arrangement of clothing layers has been discussed for the multi-layered system based on the results of the dry and wet test using the thermal manikin and the temperature and moisture gradients across fabric layers. Interestingly, the microclimate of the polyester mesh/nylon combination (MpN) is not drier, even when the wet thermal resistance of MpN is smaller. The results indicate that it was not possible to assess the wear comfort of the clothing ensemble based upon the information on dry or wet thermal insulation alone.
1. Introduction

Wearing protective clothing hinders dry and wet heat transfer, thus increasing the heat strain and evoking discomfort under hot conditions and/or high physical exertion. To avoid discomfort while maintaining protection it is necessary to determine the efficient way of wearing underwear. Recently, innovative inter-liners for protective clothing have been developed in Europe (Carosio et al 2006). Materials which are being explored include hydrophobic fibres, for a comfortable contact sensation at the skin, and hydrophilic fibres for providing the suction channels to transport the moisture away from the skin in appropriate combination, possibly incorporating a liquid coolant circulating system within a 3D composite engineered textile structure. Although it appears that the innovative interliner incorporates much of the available ideas on the optimum arrangement of underwear, the need to understand the basic phenomena across the multiple layers of different fabrics still remain.

As for the predominant role of the moisture transmitting capability of the outer shell on dry and wet heat loss, measurements by many research groups (Richards et al 2006 and Gao et al 2006) are in good agreement with each other. However, due to the complex interaction of the fabric/clothing -manikin - environmental conditions, the precise effects of underwear type on the wet heat loss and wear comfort of layered systems are not clear. More rigorous considerations of the experimental conditions are necessary to understand what is happening inside the outer shell of protective clothing.

A thermal manikin is a device resembling the size and shape of a human which is heated so that its surface temperature simulates the skin temperature of a human being. It is also beneficial to simulate dressing in a specific way as in the case of a human. It is known that thermal manikins are designed for steady state measurements so that control systems do not respond like human beings, however, values from manikins or models are only of limited use if they are only used in the measurement of total wet heat loss in a steady state (McCullough, 2005).

It was pointed out that the dynamic thermal responses of clothing within a short period of time would also provide meaningful data in terms of clothing thermal comfort since people rarely wear clothing under constant conditions (Fan & Chen, 2002). In fact, manikins have also been used on a limited basis to quantify and compare the impact of thermal changes in clothing during step changes in relative humidity and temperature (McCullough 1991), where the initial peaks were decreasing within 10-15 min. Manikins have also been used under transient conditions to evaluate and compare the effectiveness of auxiliary heating and cooling of garments (Teal, 1990).

The issue concerning the importance of moisture distribution in the clothing system has been also raised. Richards et al (2006) analyzed their experimental results for impermeable clothing at low temperatures, and found that wet heat loss is markedly higher than expected from evaporation alone. They raised the necessity of examining the location and quantity of moisture within clothing to figure out the conduction and condensation of moisture within the clothing layers. In this context, the temperature and moisture concentration gradient, as a driving force for the heat...
and mass transfer, has long been recognized in thermal comfort research under relatively mild environmental conditions. Hong et al (1988) measured the temperature and moisture gradient across a single layer of cotton and polyester and found that the microclimate of cotton is drier than that of polyester even though moisture flux passing through both systems is almost the same, indicating that even though the total water vapour transmission rate is the same, the amount of moisture is different depending on the location.

Hong et al (1993) later tested multiple layered systems step by step using a skin model and found that up to a double layer, dryness of the microclimate next to the skin could be maintained when cotton was adjacent to the skin. However, the temperature and moisture related comfort properties of a triple layered clothing system cannot be predicted merely from information based upon the single and/or double layer experiments. When a semi-permeable hydrophobic third layer covered the two layers of underwear consisting of cotton and nylon, the innermost layer of microclimate contacting the cotton was no longer drier than the other way around.

Recently, the role of the microstructure of hygroscopic fibres on moisture transfer stimulated new interest in surface diffusion efficiency due to the internal fibre structure. Min et al (2006) compared the surface diffusion properties of cotton and the buffering capacity of wool fibres with those of other fibres, which turns out to be better than the other synthetic fibres. However, the effects of hygroscopic fibres in multiple layered systems, under various environmental conditions and sweating rate, on the heat and mass transfer have not been adequately investigated using thermal manikins.

Other aspects to be considered in terms of the thermal comfort of multiple layered clothing systems include the contact sensation due to clothing surface (Hong and Jung, 1992). Surface characteristics of fabrics influence the path of heat and moisture transfer. At the same time, surface fibres determine the contact area of fabric and skin, which plays an important role in evoking the contact sensation of the skin. Reducing the contact area between skin and fabric is easily achieved if mesh is attached at the inner side of workwear. In the previous work on double layered shirts, hygroscopic mesh was beneficial in avoiding a wet sensation even though it increases the temperature of the microclimate (Jeong and Hong, 2000).

The objectives of this paper are firstly, to obtain temperature and moisture gradients across the multiple layers using a sweating thermal manikin by careful experimental procedure, and secondly, to find out the comfortable arrangement of underwear layers under a Gore-Tex outer jacket. Also, to compare the effect of hygroscopic and hydrophobic mesh as innermost underwear compared with that of ordinary cotton and nylon interlock on the various aspects of heat and moisture transfer, i.e. total vs. local as well as steady vs. transient states.
2. Methodology

2.1. Thermal Manikin

The sweating and walking thermal manikin, ‘Newton’, operated by automatic control software ThermDAC (Measurement Technology Northwest), was used here. The height of the manikin is 170 cm and its surface area is 1.7m², the dimensions of which are closely matched to the average young Korean male. This manikin has 20 independent zones in which heat input or temperature can be controlled to obtain the temperature distribution as in Table 1. It was covered by a stretch skin and has 134 sweat channels for wet heat loss experiments. The manikin was set up in a walk-in type environmental chamber which is maintained at 25°C (±0.3°C), 50% RH (±2.5 % RH) and with a wind speed of 0.1 m/sec. All tests were carried out in the stationary mode, since differences in material properties are usually reduced by motion tests.

<table>
<thead>
<tr>
<th>Segments</th>
<th>Temp(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face</td>
<td>35.0</td>
</tr>
<tr>
<td>Head</td>
<td>35.0</td>
</tr>
<tr>
<td>Upper arms</td>
<td>35.3</td>
</tr>
<tr>
<td>Fore arms</td>
<td>34.7</td>
</tr>
<tr>
<td>Hands</td>
<td>34.9</td>
</tr>
<tr>
<td>Chest</td>
<td>34.5</td>
</tr>
<tr>
<td>Shoulder</td>
<td>34.7</td>
</tr>
<tr>
<td>Stomach</td>
<td>35.3</td>
</tr>
<tr>
<td>Back</td>
<td>34.7</td>
</tr>
<tr>
<td>Hip</td>
<td>33.0</td>
</tr>
<tr>
<td>Thigh</td>
<td>33.7</td>
</tr>
<tr>
<td>Calf</td>
<td>34.4</td>
</tr>
<tr>
<td>Feet</td>
<td>33.9</td>
</tr>
<tr>
<td>Mean skin Temp</td>
<td>34.45</td>
</tr>
</tbody>
</table>

Table 1: Temperature distribution of the manikin surface and mean skin temperature (left) and an example of temperature distribution of twenty segments of the manikin in the ThermDAC (right)

2.2. Test protocol

A pilot study was performed to determine the test protocol for the dynamic test with an appropriate sweating rate. The procedure was shortened by changing the protocol to one of systematically controlled sweating rate during the course of a test, rather than separate tests under each condition, to simulate the realistic situation of prior exercise-rest-exercise.

The sweating rate of the manikin was set at 200 gm⁻²h⁻¹ in the prior and later exercise stages. Water supply from the reservoir was cut off immediately before dressing to achieve the rest phase. Another reason for stopping the water supply through the water channel is so as not to have too much sweat which would ruin the humidity sensor in the microclimate of the multiple layered protective clothing during dynamic measurement. Four humidity sensors and four temperature sensors were attached to the clothing system while dressing up the manikin. It was expected
that water collected in the manikin skin during the stabilized period could have acted as a source of water for dynamic water and/or vapour transfer through the clothing ensemble after the water supply from the reservoir was switched off. In the pilot study it was observed that enough liquid water still remained in the manikin skin for the dynamic water transfer.

Fig. 1 allows one to visualize the entire experimental protocol for the manikin test. A test consisting of 40-50 min initial stabilization, 30-40 min dynamic test and 100 min final stabilization was carried out. To shorten the initial stabilization stage, the skin layer was sprayed with 450 ml of water containing a drop of wetting agent beforehand. Heat flux was observed at every stage to ensure that the system is in a steady state. The next phase was not started if the curve was not considered to be flat enough. Based on the pilot studies, 30 min were considered sufficient for the dynamic measurements in this experiment, which is consistent with previous experiments (McCoulough, 1991; Hong et al 1988). After the dynamic experiment, sweat was supplied again at the rate of 200 gm$^{-2}$h$^{-1}$ until the system reached the steady state as depicted in Fig 1.

![Figure 1](image)

**Figure 1** Representative protocol of the manikin test for dynamic wet test and conventional wet thermal resistance (case: raw data of MpN-Gore-Tex)

### 2.3. Experimental Clothing

The Manikin was dressed with two layers of underwear and a Gore-Tex jacket and pants, as shown in Fig. 2. Underwear is custom-made to fit the given manikin and the physical properties of the underwear are summarised in Table 2. The pants and Gore-Tex outer jacket are described in Table 3.
Table 2: Physical properties of the underwear

<table>
<thead>
<tr>
<th>Garments</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacket</td>
<td>Gore-Tex XCR, 100% stretch fabric, Water resistant zippers, Core vent pockets, Security pocket set inside core vent pocket, Interior zipper pocket, Helmet compatible zippers</td>
</tr>
<tr>
<td>Pants</td>
<td>Soft touch of nylon, Sweat control system (absorbs faster dries quicker), Smooth texture for Sportswear, outdoor &amp; leisure wear</td>
</tr>
</tbody>
</table>

Table 3: Outerwear garment features

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>C</th>
<th>N</th>
<th>Mc</th>
<th>Mp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Content (%)</td>
<td>Cotton: 100</td>
<td>Nylon: 81 Polyurethane: 19</td>
<td>Cotton: 100</td>
<td>Polyester: 100</td>
</tr>
<tr>
<td>Weight (g/m²)</td>
<td>208.4</td>
<td>197.7</td>
<td>186.3</td>
<td>110.8</td>
</tr>
<tr>
<td>Regain (%)</td>
<td>9.18</td>
<td>2.91</td>
<td>6.84</td>
<td>1.28</td>
</tr>
<tr>
<td>Structure</td>
<td>Interlock</td>
<td>Interlock</td>
<td>Mesh</td>
<td>Mesh</td>
</tr>
</tbody>
</table>

Figure 2 Garments used in this study left: underwear worn on the manikin, middle: outerwear, right: manikin dressed with the underwear-Gore-Tex outer jacket- pants

The arrangement of the two layers of underwear and Gore-Tex outerwear is illustrated in Fig. 3. Temperature and humidity sensors (LT 8B, Gram co.) are placed on each layer of the clothing towards the skin side at the chest, avoiding overlapping. It has been difficult to measure the humidity of the surface air layer, especially for a sweating skin. To avoid direct contact of the liquid sweat with the humidity sensors, 5mm spacers are inserted on the skin side and the first layer. Humidity and temperature gradients were measured continuously at 10 second intervals. Since the underwear fitted to the manikin well in this study, it is expected that the distance between the humidity sensor and the surface remained almost the same in each part of the experiment.
A thermogram (Therma CAM P25, FLIR Systems AB) was taken immediately after 3 min, 10 min and 30 min, respectively, after dressing in the dynamic stage. For reference purposes, a thermogram was also taken at the end of the experiment when the sweating manikin is in the steady state.

![Diagram showing the arrangement of the two layers of underwear under the Gore-Tex outerwear and the positioning of sensors for the gradient measurement.]

Figure 3: The arrangement of the two layers of underwear under the Gore-Tex outerwear and the positioning of sensors for the gradient measurement

3. Results

3.1 Dry and wet thermal resistance

The results of dry thermal insulation and evaporative resistance of the four clothing ensembles measured on Newton are shown in Table 4. The thermal insulation of the Gore-Tex outer jacket with four combinations of underwear was almost the same (0.21~0.22 m²°C/W). Consequently, the evaporative resistance of the identical layers of nylon and cotton (NC and CN) was the same. It was noted that the polyester mesh (MpN) demonstrated the highest heat flux in the wet test even though it is the one with the highest dry thermal resistance as shown in Table 4. Thermograms of MpN and McN at the stable stage agreed well with the result of heat flux from the clothing surface as shown in Fig. 4, where the surface temperature of MpN is higher than that of McN.

<table>
<thead>
<tr>
<th>Underwear combination</th>
<th>Dry test</th>
<th>Wet test</th>
<th>Im</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R m²°C/W</td>
<td>Ht Flux(W/m²)</td>
<td>R_wet (m²Pa/W)</td>
</tr>
<tr>
<td>NC</td>
<td>0.210</td>
<td>27.98</td>
<td>64.345</td>
</tr>
<tr>
<td>CN</td>
<td>0.207</td>
<td>31.04</td>
<td>64.436</td>
</tr>
<tr>
<td>McN</td>
<td>0.219</td>
<td>27.14</td>
<td>62.319</td>
</tr>
<tr>
<td>MpN</td>
<td>0.222</td>
<td>25.20</td>
<td>57.729</td>
</tr>
</tbody>
</table>

Table 4: Summary of the dry and wet test using manikin wearing two layers of underwear and a Gore-Tex outer jacket
3.2 Temperature and moisture gradient across the layers

During the dynamic measurement of 30-40min, the humidity at the skin surface sometimes went up to 100 % RH, even though a 5mm spacer had been inserted. When the humidity sensor indicated more than 97 % RH, sensors at the innermost microclimate facing the skin were quickly removed from the clothing by opening the front zipper as little as possible. Water was supplied again at the rate of 200 g m$^{-2}$h$^{-1}$ until the system is stabilized to get the wet thermal resistance for about 100 min. Due to the difficulties associated with this high moisture content in the microclimate, it was not possible to get an equal number of the replications for each underwear combination in this dynamic stage. However, we could tell the effect of the mesh (Figs 5 & 6) and the hygroscopic nature of cotton (Fig. 7) within 10-30 mins, when most of the dynamic results were undertaken as follows.

Figure 5 is the temperature and humidity profiles of the clothing system containing polyester mesh, Mp-N-Gore-Tex. Likewise Figure 6 illustrates the temperature and humidity profiles of the clothing system containing the cotton mesh, Mc-N-Gore-Tex during the 30 min dynamic stage.
It was found that humidity on the skin side with MpN is higher (more than 90% RH) than that with McN (about 80% RH). Recalling that $R_{\text{wet}}$ of MpN is lower, one would expect that the innermost microclimate of MpN would be drier than other combinations. However, this was not the case, which indicates that it is not possible to predict the location of moisture only from the wet thermal resistance.

Figure 6  Temperature and humidity profiles with cotton mesh, Mc (skin side & upper side) –N (upper side of middle layer) -Gore-Tex (outer side)

Figure 7  Vapour pressure gradient at the microclimate skin side and outer side of Gore-Tex in the case of four combinations of underwear, CN, NC, MpN and McN
Vapour pressure of the entire combination of underwear at the innermost microclimate and outermost layers during the transient stage of 10 min is illustrated in Fig. 7. The vapour pressure (kPa) at the skin side of CN-Gore-Tex is lower than that of the other three sets of the experimental group and that at the outer side of CN-Gore-Tex is relatively higher. The vapour pressure curve of Mc-Nylon-Gore-Tex at the skin side was the second driest out of the four different kinds of samples.

4. Discussion and conclusions

In this study, total heat and mass transfer was observed in terms of dry and evaporative heat resistance as well as the distribution of moisture in terms of temperature and moisture gradient during the transient stage. As for the dry and wet thermal transfer, consistent results were obtained. However, with the dynamic test it was difficult to obtain complete replications, even though the rate of water supply was carefully controlled until a stable state was achieved in terms of heat flux and surface temperature of the thermal manikin. In addition, the clothing was dried after each test and conditioned inside the environmental chamber before the experiment. A protocol was developed for this study and the effect of hygroscopic cotton and mesh within 10 - 30 min could be observed for most of the dynamic results as follows.

Depending on fabric structure and fibre type, the moisture accumulation could vary even though the dry thermal resistance was almost the same for identical layers of cotton and nylon (CN and NC). In the case of polyester mesh placed as the innermost layer, the wet thermal transfer of the polyester mesh/nylon underwear combination was larger than that of the cotton mesh underwear, although the dry thermal resistance of the polyester mesh/nylon underwear is higher than that of the cotton mesh/nylon underwear. A dual function of higher thermal insulation and yet, faster wet heat transfer of the polyester mesh was observed. Interestingly enough, when observing the temperature and moisture gradient, it appeared that the microclimate of the polyester mesh/nylon combination (MpN) is not drier, even if $R_{wet}$ of the MpN is smaller. In other words, moisture accumulation in the microclimate is not necessarily less, even when the heat flux due to wet thermal transfer is larger, as in the case of MpN.

The results indicate that it was not possible to tell the wear comfort of the clothing ensemble which is mostly influenced by the microclimate condition at the skin/clothing interface, by merely considering the dry or wet thermal insulation. In addition to thermal insulation and moisture vapour resistance, the percentage moisture accumulation within the clothing is a very useful parameter of clothing comfort as found previously (Hong et al 1988). It would also be helpful, to obtain the area under the heat flux peak during the transient periods in addition to the temperature and moisture gradient measurements. More importantly, if the weight change of the manikin and each layer of clothing was known, it would enable a more intensive analysis of this experiment.

The next question to be answered in terms of comfortable underwear combinations for clothing system is the contact sensation of the innermost layer in a human wear
test. Even though it was found that the moisture concentration in the microclimate is lower in the case of cotton containing underwear, i.e. CN or McN, it is necessary to examine how the human being experiences the surface of the cotton interlock or cotton mesh in terms of contact sensation before the optimized arrangement of underwear under the protective outer shell is selected. Indeed, it is necessary to have various performance values to correctly select the optimized protective clothing system. Total heat and moisture transfer, local distribution of the heat and moisture transfer in a transient state as well as the contact properties of clothing surfaces are necessary to gain a clearer understanding of the direction the product development of protective clothing systems should take from the material engineering point of view.

Acknowledgements

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Thermal Insulation of Three Garment Sleeve Structures

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Abstract

The thermal insulation value (clo) of a garment is determined by many factors, such as material, fit, and garment design. However, no research has been done to determine the contribution of the individual parts of the garment to its total clo value. The objective of this study was to determine whether or not different sleeve designs affect the total garment thermal insulation value by examining the effect of sleeve structure on the thermal insulation in various areas of the torso, arms and shoulders.

Three sleeve structures, set-in, kimono and raglan, were evaluated using a 26 zone Newton sweating thermal manikin. All three garments were constructed using the same sewing construction and single face fleece knit fabric, only the design of the sleeves at the shoulder area were different. To develop the same size and fit for each garment, a basic torso and set-in sleeve patterns were drafted from the manikin’s body measurements. Standard flat pattern techniques were then used to develop two other garments, one with kimono and another with raglan sleeves. To test for reliability, each sleeve type garment was worn by the manikin three different times and data were collected for three hours for each test.

The body temperature for the manikin was set at 34°C. The tests were conducted in a controlled environment of room temperature 20.5°C and 58% relative humidity. During the tests, the manikin was in a standing position with its arms at its side. The thermal resistance data (watts/metre²) were recorded for eight different areas which included left and right forearms, left and right upper arms, chest, stomach, back, and shoulders. The total garment clo value was recorded by the manikin as the total watts expended based on the surface area covered by the garment.

According to the data collected, the overall clo values for the three different sleeve structure garments are different. The areas that have the least variation in clo values
are the forearms and stomach. Since these areas have the same amount of ease and pattern shape regardless of the sleeve structure, their clo values do not vary significantly. However, the shoulders and upper arm areas, where the three garment structures are different, have larger variations in insulation values. The raglan sleeve’s clo values were the highest in all areas of the body, and provide the greatest amount of thermal insulation.

In this study since all factors, such as materials and environment, were controlled, the differences between the clo values should be attributed to differences in the sleeve structure. This study is part of a series of studies to determine the contribution of various garment structures and designs to the thermal insulation of the total garment.

1. Introduction

Thermal manikins have been developed to evaluate clothing systems. The use of the thermal manikin can provide objective results to measure thermal insulation and vapour resistance of garments, which then can be used to predict the thermal comfort of the clothing system. Hot plate test methods, such as ASTM D1518: Standard Method for Thermal Transmittance of Textile Material (2006), are useful in evaluating the thermal properties of fabric, but the results can not be used to predict that of total clothing systems because the thermal resistance of a flat textile does not equate to the total clo value of the garment. Studies have shown that the thermal insulation of the total garment system is determined by the combination of the design of, and the materials used in, the garment (Gavin 2003, Pascoe et al. 1994). However, when evaluating the thermal resistance of a garment, most researchers often evaluated the amount of air trapped or moving through the garment (Bouskill et al. 2002, Kim et al. 2002). The fit and amount of ventilation are directly related to the design of the garment. Only Shivers et al. (1977) have studied the relationship between garment design and their thermal regulation capabilities.

The purpose of this study was to determine the contribution of the garment design to the overall thermal resistance and clo value of a garment. The results of the study will help to develop garments that can enhance the thermal insulation properties of fabrics or materials used in total clothing systems.

2. Methodology

2.1. Sleeve Structures

The major purpose of this study was to determine the effect the sleeve structure or design has on the overall clo value of the garment. Three different sleeve structures were developed and tested for this study. The garment size, construction methods, closures, fabric and testing environment were controlled in all of the tests. A front lapped opening and collar were added to the design to finish edges and to make dressing easy. The different sleeve designs were developed using flat pattern
methods. The basic torso/body and sleeve were drafted from body measurements and draped on the thermal manikin to provide the basic blocks for the set-in sleeve design (Fig.1). The basic blocks were evaluated for garment fit and included fitting ease. The basic ease added to the body measurements were as follows: 5 cm to chest, 5 cm to the bicep, 4 cm to the elbow and 7.5 cm to the wrist in order to develop the set-in sleeve. The patterns were extended to the hip level allowing for the body area of the pattern to be the same shape and dimensions for each sleeve design. The kimono (Fig. 2) and raglan (Fig. 3) sleeve patterns were developed from the basic blocks using flat pattern techniques described by Armstrong (2006). Once patterns were developed, the surface area of each pattern piece was easily calculated from the dimensions of the patterns which had been drafted on a 2.5 cm grid paper. Only half of a pattern is developed, and then cut as two ply to construct the total garments. Since the amount of ease was controlled by the use of the basic block pattern and the same fabric used, any changes in the surface area of the patterns are due to the changes in garment or sleeve structure.

Figure 1 Set-in sleeve garment and patterns

Figure 2 Kimono sleeve garment and patterns
2.2. Thermal Resistance

Three sleeve structures, set-in, kimono and raglan, were evaluated using a 26 zone Newton sweating thermal manikin. All three garments were constructed using the same sewing construction and single face fleece knit fabric, only the design of the sleeves at the shoulder area were different. To test for reliability, each sleeve type garment was worn by the manikin three different times and data were collected for three hours for each test.

The body temperature of the manikin was set at 34°C. The tests were conducted in a controlled environment of room temperature 20.5°C and 58% relative humidity. During the tests, the manikin was in a standing position with its arms at its side. The thermal resistance data (watts/metre²) were recorded for eight different areas, which included left and right forearms, left and right upper arms, chest, stomach, back, and shoulders. The total garment clo value was recorded by the manikin as the total watts expended based on the surface area covered by the garment.

3. Results

The surface area of the patterns shown in Figures 1, 2 and 3 are reported in Table 1. The surface areas are reported as a whole front and back pattern though the figures show one half of the garment pattern. The sleeve area of the kimono sleeve was added to the torso area since this sleeve pattern is one piece with a seam located across the shoulder and down the centre of the arm. As seen in Figures 1, 2, 3; each pattern piece is a different shape and size. The individual surface areas are difficult to compare because of the differences in shape, but the total surface area can be compared since the sleeves were developed from the same basic patterns and cover the same area of the body.
The thermal resistance or watts/metre$^2$ was recorded for eight different areas of the arms and torso. The manikin reports the watts/metre$^2$ for each zone of the body. The 8 zones used for the garment evaluation were left and right forearm and upper arm; chest, stomach, back, and shoulders. From the data collected, the clo value of each area of the garment was calculated. The clo values are reported in Table 2.

### Table 1: Surface area of three sleeve patterns

<table>
<thead>
<tr>
<th>Sleeve types</th>
<th>Front torso (m$^2$)</th>
<th>Back torso (m$^2$)</th>
<th>Sleeves (m$^2$) (total for right and left sleeves)</th>
<th>Total area of garment (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-In</td>
<td>0.290</td>
<td>0.301</td>
<td>0.389</td>
<td>0.980</td>
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<tr>
<td>Kimono</td>
<td>0.484</td>
<td>0.508</td>
<td>Included in torso</td>
<td>0.992</td>
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<tr>
<td>Raglan</td>
<td>0.257</td>
<td>0.282</td>
<td>0.518</td>
<td>1.057</td>
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</table>

### Table 2: The clo values for manikin body zones and sleeve types

<table>
<thead>
<tr>
<th>Manikin body zone</th>
<th>Set-in sleeve (clo)</th>
<th>Kimono sleeve (clo)</th>
<th>Raglan sleeve (clo)</th>
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<tbody>
<tr>
<td>Chest</td>
<td>1.38</td>
<td>1.36</td>
<td>1.53</td>
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<tr>
<td>Stomach</td>
<td>2.43</td>
<td>2.50</td>
<td>2.58</td>
</tr>
<tr>
<td>Back</td>
<td>1.54</td>
<td>1.64</td>
<td>1.79</td>
</tr>
<tr>
<td>Shoulders</td>
<td>1.20</td>
<td>1.26</td>
<td>1.32</td>
</tr>
<tr>
<td>Right &amp; left upper arm</td>
<td>1.18</td>
<td>1.37</td>
<td>1.48</td>
</tr>
<tr>
<td>Right &amp; Left forearm</td>
<td>1.41</td>
<td>1.51</td>
<td>1.51</td>
</tr>
<tr>
<td>Total garment</td>
<td>1.44</td>
<td>1.53</td>
<td>1.63</td>
</tr>
</tbody>
</table>

### 4. Discussion

According to the data collected, the overall surface area and clo values for the three different sleeve structure garments are different. The surface area of the set-in sleeve garment was the smallest and has the closest fit to the body. The set-in sleeve has the smallest clo value. The differences between the kimono and raglan sleeve patterns are due to the extra ease that is incorporated into a pattern in the armhole area during pattern development.

The differences in thermal resistance follow the same trends as the surface area. The areas that have the least variation in clo values are the forearms and stomach. Since these areas have the same amount of ease and pattern shape regardless of the sleeve structure, their clo values do not vary significantly. However, the shoulders and upper arm areas, where the three garment structures are different, have larger variations in insulation values. The raglan sleeve’s surface area and clo values were the highest in all areas of the body.

In this study, all factors, such as material and environment, were controlled. The variable which was changed was the design of the garment sleeve. In this study, it was shown that the surface area of the garment is related to the clo value. As stated in other studies, the fit of the garment can affect the total insulation value of the garment, but fit should be related to the garment design as well. In this study, the
differences between the clo values are attributed to the differences in the sleeve structure, not just fit.

5. References


Use of a Spacer Vest to Increase Evaporative Cooling Under Military Body Armour

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2Batelle Natick Operations, Natick Soldier Center, Natick, MA USA
3U.S. Army Program Executive Office – Soldier, Fort Belvoir, VA USA

Abstract

U.S. military forces are currently using the Interceptor Body Armour (IBA) system which can increase human thermal stress when worn in arid environments. This study investigated a spacer vest (SV) designed to distance the IBA from the wearer’s skin surface, increasing evaporative cooling around the torso. A series of lightweight SV designed to be worn under the IBA was tested for thermal insulation (clo) and water vapour permeability (im) on a sweating thermal manikin (TM). The TM was dressed in 3 configurations: with the U.S. Army Temperate Battle Dress Uniform (TBDU); with the IBA over the TBDU; and with the IBA over the various SV and the TBDU. TM results were used as input to a computer model predicting core temperature \( T_c, ^\circ \text{C} \), skin temperature \( T_{sk}, ^\circ \text{C} \), heart rate (HR, bpm), sweat rate, (SR, g/min), skin wettedness (SW, %), and total body water loss (WL, l). Output described responses when exposed to desert environments with air temperatures of 30, 40 and 50\(^\circ\)C during repeated, intermittent exercise (10 min rest/ 30 min walk). TM results showed thermal insulation increased and water vapour permeability decreased when IBA was worn over the TBDU. Use of a SV between the IBA and TBDU reduced thermal insulation and increased water vapour permeability. This translated into a theoretical increase in whole body evaporative cooling potential \( (im /clo) \) of approximately 20% when wearing a SV compared to when wearing the IBA without a SV. Predictive model results showed thermo-physiological benefits when using a SV with lower SW at 30\(^\circ\)C, lower \( T_c \), \( T_{sk} \), HR, SR, SW, and WL at 40\(^\circ\)C and lower \( T_c \) at 50\(^\circ\)C.
1. Introduction

U.S. military forces are currently using the Interceptor Body Armour (IBA) system consisting of an outer vest, front and rear ballistic plates, and attachments for throat, groin, and upper arm protection. When fully configured, the IBA weighs 9.9 kg and covers 30-35% of the body surface area, including the entire torso, with multiple layers of impermeable, synthetic materials (Figure 1). Specifically, the IBA utilizes fine-weave Kevlar™ fibres for small arms/fragmentation protection and boron-carbide ceramic plates for stoppage of higher-velocity projectiles. Use of the IBA can contribute to heat stress and limit wearer performance.

![Figure 1 Photographs showing tactical wear configurations of Interceptor Body Armour (IBA) during combat operations in Iraq.](image)

This study investigated the use of a spacer vest (SV) designed to distance the IBA from the wearer’s skin surface, increasing the potential for evaporative cooling around the torso. Wearing body armour in humid environments has been associated with increasing the wet bulb globe temperature around the wearer by about four centigrade degrees (Goldman, 1). It is hypothesized that an increase in evaporative cooling could reduce overall sweat rates and consequent soldier dehydration. The negative impact of heat stress and dehydration on soldier performance is well recognized by the U.S. Military (U.S. Army and Air Force, 2).

2. Methods

A series of seven lightweight (average weight=0.29 kg), 1 cm thick SV designed to be worn under the IBA was tested for thermal insulation (clo) and water vapour permeability ($i_m$) on a sweating thermal manikin (TM). The thermal insulation represents the total resistance to dry heat transfer between the skin’s surface and the ambient environment. Water vapour permeability is the total conductance for latent heat transfer between the skin and environment. Both properties are functions of wind speed with increased air velocity resulting in lower clo and higher $i_m$ measurements.

The TM was dressed in 3 test configurations: with the U.S. Army Temperate Battle Dress Uniform (TBDU); with the IBA over the TBDU; and with the IBA over the various SV and the TBDU (Figure 2).
Figure 2 Photographs showing the thermal manikin (TM) configured with the Temperate Battle Dress Uniform (TBDU), and a spacer vest (SV, both left), and under the Interceptor Body Armour (IBA, right).

The SV test series was designed to evaluate if there was any difference between a separate, stand-alone SV and one intended to be permanently integrated into the inner lining of the IBA. Furthermore, the SV test series included two types of material construction: an open mesh style and a waffle style with indented dimples. Table 1 shows total and regional clo and \( i_m \) values when the thermal manikin (TM) was dressed in the Temperate Battle Dress Uniform (TBDU), Interceptor Body Armour (IBA), and the various spacer vests (SV).

The TM results were used as input to a computer model predicting core temperature \( (T_c, ^{\circ}C) \), skin temperature \( (T_{sk}, ^{\circ}C) \), heart rate \( (HR, bpm) \), sweat rate \( (SR, g/\text{min}) \), skin wettedness \( (SW, \%) \), and total body water loss \( (WL, l) \). The human responses of a standard soldier (70kg, 1.7 m tall) were simulated with the model to quantify the thermo-physiological effects of adding a SV under the IBA. Output described responses when exposed to desert environments with air temperatures of 30, 40 and 50°C during repeated, intermittent exercise (10 min rest/ 30 min walk). The soldiers were engaged in walking on a hard smooth surface and began the activity from a comfortable thermal neutral state. The humidity level for the environments was constant with a dew point of 15°C and wind speed was 1 m/s. Solar radiation was modest such that the mean radiant temperature was 10°C warmer than the air temperature.
3. Results and Discussion

<table>
<thead>
<tr>
<th>SV type</th>
<th>Total manikin</th>
<th>Front torso</th>
<th>Rear torso</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clo</td>
<td>iₘ</td>
<td>iₘ/clo</td>
</tr>
<tr>
<td>Prototype separate mesh</td>
<td>1.28</td>
<td>0.41</td>
<td>0.32</td>
</tr>
<tr>
<td>Integrated waffle-in</td>
<td>1.23</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td>Integrated mesh</td>
<td>1.21</td>
<td>0.43</td>
<td>0.36</td>
</tr>
<tr>
<td>Separate waffle-in</td>
<td>1.16</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td>Separate mesh</td>
<td>1.19</td>
<td>0.37</td>
<td>0.31</td>
</tr>
<tr>
<td>Integrated waffle-out</td>
<td>1.14</td>
<td>0.39</td>
<td>0.34</td>
</tr>
<tr>
<td>Integrated+separate mesh</td>
<td>1.18</td>
<td>0.38</td>
<td>0.32</td>
</tr>
</tbody>
</table>

TBDU only: iₘ /clo=0.44  TBDU+IBA: iₘ /clo=0.27

Table 1: Total and regional thermal and water vapour resistance values when the thermal manikin (TM) was dressed in the Temperate Battle Dress Uniform (TBDU), Interceptor Body Armour (IBA), and the various spacer vests (SV).

TM results showed average clo increased by 16% and iₘ decreased by 26% when only IBA was worn over TBDU. However, average changes were reduced (clo=9%, iₘ=14%) when wearing the various SV under IBA. Table 1 shows that on average, these lowered resistances to heat and water vapour transmission translated into a theoretical increase in whole body evaporative cooling potential (iₘ / clo) of approximately 20% when wearing a SV compared to wearing the IBA without a SV.

Table 1 shows that there were no significant differences in total TM iₘ /clo when comparing SV with material construction in the open mesh style or a waffle style with indented dimples. There were no significant differences between SV designed to be a separate component or those designed to be integrated into the inner lining of the IBA. Table 1 also shows that attempting to increase the distance between the IBA and TBDU by wearing two SV did not provide any increase over that provided by one SV.

Regional front torso TM iₘ values were generally higher with integrated-style SV while rear torso iₘ values were higher with separate-style SV.

The unique profile of torso-protective body armour, requiring very specific surface area coverage, does not allow for numerous design variations that could significantly improve wearer thermal comfort. A study that tested six different configurations (closed, open front, open sides, all with and without additional armour) of a modular body armour system, found no significant differences in final core temperatures, final heart rates, rates of heat storage, sweating rates, and evaporative heat loss when subjects walked on a treadmill for 100 minutes at 40°C, 20% rh (Cadarette, 3).

The prediction model results presented in the following graphs show selected soldier responses to desert outdoor environments with air temperatures of 30, 40 and 50°C. The SV selected for analysis was the prototype separate mesh item described in Table 1.
Figure 3  Predictive model results of skin wettedness (SW, %) for the 3 clothing configurations at 30°C.

Figure 4  Predictive model results of sweat rate (SR, g/min) for the 3 clothing configurations at 40°C.

Figure 5  Predictive model results of core temperature (Tc, °C) for the 3 clothing configurations at 50°C.
Figure 3 shows that use of the SV reduces SW, particularly during rest periods. However, in this modeled scenario, SW remains above approximately 50%, which would probably be perceived as uncomfortable by most wearers.

Figure 4 shows that SR is lower when wearing SV and this could lessen rates of dehydration while improving both physical and cognitive performance and decreasing the risk of heat injury.

Figure 5 shows use of the SV resulted in consistently lower $T_c$ throughout the entire simulated exposure even at the highest ambient temperature of 50°C.

Overall, the model results predicted thermo-physiological benefits when using a SV with lower SW at 30°C, lower $T_c$, Tsk, HR, SR, WL at 40°C and lower $T_c$ at 50°C.

4. Conclusions

The U.S. military is developing numerous products in an attempt to mitigate heat stress for personnel deployed in the Middle East. Wearing body armour around the torso impedes the evaporation of sweat over a large percentage of the body surface area. The SV concept was designed to provide a continuous air channel between the TBDU and the entire inner surface of the IBA. These results show that this “stand-off” distance reduced the inherent thermal and evaporative resistances of the IBA, allowing for increases in predicted human sweat evaporation and overall thermal comfort during exposure to simulated desert environments. Military research and development in this area is ongoing. Future evaluations will be investigating new torso cooling vests that actively deliver cooled air to the open channel created by the spacer materials.

5. References

6. Disclaimer

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