

THE IMPACT OF CLOTHING ON SWEATING IN THE COLD

R. Nielsen

Technical University of Denmark, Institute of Energy Engineering,
Building 402, DK-2800 Lyngby, Denmark

INTRODUCTION

When man enters into a positive heat balance, production and evaporation of sweat plays a major role in the attempt of his thermoregulatory system to restore heat balance. When clothing is worn, sweat will not always be able to evaporate, but accumulates in the clothing. The immediate evaporative cooling of the skin may be reduced and the ability to restore heat balance may be impaired.

During the last four decades researchers have simulated actual working situations using hot plates, thermal manikins and human studies in climatic chambers in order to demonstrate the effect of clothing on heat exchange of man in the cold (e.g. Olesen and Nielsen 1983). However, knowledge about the impact of clothing on sweating in the cold is still insufficient.

The purpose of the research reported in this paper was further to explore, quantify and describe the impact of clothing on sweating and heat loss from man in the cold. The importance of garment characteristics as textile material and clothing layers in combination with the location of sweat accumulation, of body movements, and of air movements have been studied.

MATERIALS and METHODS

Human studies:

A: The influence of the underwear fabric material on sweat production, evaporation, and sweat accumulation in a two-layer clothing system ($I_{\text{tot}} = 0.25 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) was studied ($n=8$). Five different fiber type materials (cotton (C), wool (W), polypropylene (P), and two polyesters with different finish (PO1, PO2)) were tested in the underwear. The 2-hour test comprised a twice repeated bout of 40-min bicycle exercise ($M = 313 \text{ W m}^2$) followed by 20 min of rest. Environmental conditions: $T_a = 5^\circ\text{C}$, r.h. = 54%, $V_a = 0.3 \text{ m} \cdot \text{s}^{-1}$.

B: The influence of the underwear and middle layer fabric material on sweat production, evaporation and sweat accumulation in a three-layer clothing system ($I_{\text{tot}} = 0.29 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) was studied ($n=8$). Two different underwear fabrics were used: a 100% wool (W) or a 100% polypropylene (P). The sweater was manufactured from

either 100% cotton (C), 100% polyester (S), or 100% wool (W). The shell clothing layer was made from 35% cotton/65% polyester (M). Six different combinations of garments were tested: PCM, PSM, PWM, WCM, WSM and WWM. The 2-hour test was the same as in the first study, except $M = 273 \text{ W m}^2$. Environmental conditions: $T_a = 10^\circ\text{C}$, r.h. = 80%, $V_a < 0.1 \text{ m}\cdot\text{s}^{-1}$.

Accumulation of sweat in each garment was measured, as well as esophageal and skin temperature, evaporation of sweat, and total sweat production. Significant differences ($p < 0.05$) were determined using repeated-measures analysis of variance. Tukey's critical difference was used to locate significant differences between means.

Manikin study:

With a thermal manikin (Madsen 1976) the influence of underwear, middle and outer layer fabric material on evaporation and heat loss during drying was determined in various two- and three-layer clothing systems.

Two 3-layered clothing ensembles PSM and WWC ($I_{\text{tot}} = 0.31 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$) and two 2-layer clothing ensembles PM and WM ($I_{\text{tot}} = 0.20 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$) were studied. The underwear was made from either polypropylene (P) or wool (W). The middle clothing layer was manufactured from either wool (W) or polyester (S). The outer layer was made from either 35% cotton/65% polyester (M) or 100% cotton (C).

Heat loss from the dressed thermal manikin was measured throughout the drying of clothing ensembles initially humidified with 175 g water. The manikin was placed on a balance for recording of weight loss. Experiments were done with the manikin in a standing position with or without being exposed to an air velocity of $1 \text{ m}\cdot\text{s}^{-1}$, or the manikin was brought to simulate walking movements with 60 steps per minute. Environmental conditions: $T_a = 10^\circ\text{C}$, r.h. = 70%, $V_a \leq 0.1 \text{ m}\cdot\text{s}^{-1}$.

RESULTS

Human studies: There was a large inter-individual variation in the production, the evaporation and the accumulation of sweat. With all clothing ensembles more sweat accumulated on the upper part of the body compared to the lower part.

With different 2-layered clothing ensembles there was no detectable difference in heat loss as illustrated by T_{es} , t_{sk} , wettedness and onset of sweating. However, underwear fiber type material significantly influenced total sweat production, evaporation of sweat, and accumulation of sweat within the clothing. Sweat production was lower with polyester underwear compared to other textile materials ($PO1 \leq C, W, P$; $PO2 < W$). Total evaporation of sweat was highest with underwear of polypropylene ($P > PO1, PO2$) and wool ($W > PO2$).

Sweat accumulation in the clothing at the end of the test amounted 20-32% of the total sweat production. Less sweat accumulated in a clothing ensemble with polypropylene compared to wool underwear. Most sweat accumulated in the outer garment. A larger percentage of the accumulated sweat was localized in the outer clothing layer when the underwear was constructed from synthetic (82% - 92%) compared to natural fibers (**64%**). Significantly more sweat accumulated in the underwear itself when made from wool or cotton fibers compared to synthetic fibers.

With 3-layered clothing ensembles there was **no** detectable influence from textile material on sweat production and evaporation. However, sweat accumulation in the clothing was influenced from the textile material in both inner and middle layers.

Accumulation of sweat in the clothing at the end of the test period amounted 19-31% of sweat production. Accumulation of sweat in the underwear was considerably higher with wool underwear compared to underwear with polypropylene fibers ($p < 0.05$). Sweat accumulation in the underwear was not affected by the fiber type material of the sweater. Sweat accumulation in the middle layer was significantly affected by both fiber type of the underwear ($W < P$) and of the fiber type of the sweater itself ($S < C$; $S < W$). Sweat accumulation in the outer layer was higher when the sweater was constructed from synthetic fibers compared to natural fibers ($p < 0.05$), whereas no effect of underwear fiber type was observed. With a 3-layer clothing ensembles sweat accumulation was not mainly in the outer layer, but distributed over all layers dependent on fiber type material.

Thermal manikin: Dressing a thermal **manikin** with humidified clothing immediately increased its heat loss. Then heat loss decreased over several hours to the steady-state level for the actual combination of clothing insulation worn. Evaporation of water from the humidified clothing took place **in** two phases: **an** initial fast phase with **an** almost linear evaporation rate followed by a slower curved drying out phase.

Fiber type material had **a** significant influence on evaporation from humidified clothing and **on** the percentage of drying energy consumed from the thermal manikin. Evaporation took place at **a much** faster rate from ensembles manufactured from synthetic materials compared to ensembles manufactured from natural hygroscopic fibers. As a consequence drying time was much longer with WWC than with PSM. Totally, drying of PSM on the standing thermal **manikin** in still air consumed significantly more energy from the manikin than drying of WWC.

The number of layers in the clothing ensemble had a major impact on both drying time and heat loss. Drying of a 3-layer clothing ensemble lasted 2-3 times longer than drying of a 2-layer clothing ensemble; regardless of the location of water. Initially, evaporation rate was higher with a 2-layer compared to a 3-layer clothing

ensemble. The percentage of energy consumed from the thermal manikin with 2- and 3-layer clothing systems was in the same range when the underwear was wet, whereas drying of the outer layer consumed more energy from the manikin with 2 layers compared to 3 layers.

The location of the water in the clothing did not have a major influence on the initial evaporation rate. With water placed in cotton outer layer of WWC, drying time was extended considerably. Energy consumption from the thermal manikin during drying of the wetted clothing was significantly higher the closer to the manikin surface, the water was localized - independent of textile material.

Walking movements increased evaporation rate from the wetted clothing slightly regardless of where the water was placed. Energy contribution from the thermal manikin to drying of the outer clothing layer was increased by more than 10%. With woolen clothing an increase in energy contribution from the manikin was also seen when water evaporated from the inner and middle layers.

In the wind evaporation was much faster from clothing manufactured from synthetic materials, and more the further out in the clothing the water was placed. With the ensemble manufactured from natural fibers evaporation was only higher when water was placed in the outer layer. The manikin contributed most energy during drying of the inner layer. For drying of middle and outer clothing layers, wind only increased the energy consumed from the thermal manikin with wool/cotton clothing.

CONCLUSIONS

In the research reported it was shown that textile material has a significant impact on both the amount of sweat accumulating in a clothing ensemble and on the site of the sweat accumulation. Drying rate and drying time of clothing wet from sweat were primarily determined by textile material and clothing composition, and secondary affected by the location of the sweat, by external air velocity and body movements. The energy delivered from the skin to evaporation during drying of the clothing was primarily determined by the location of the sweat in the clothing, but textile material, external air velocity and body movements did also have an effect.

REFERENCES

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