THE NOVEL SINGLE-SECTOR HUMAN SIMULATOR TO STUDY CLOTHING EFFECTS ON PHYSIOLOGICAL RESPONSE

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INTRODUCTION

Many human activities in outdoor and indoor spaces often require additional protection against adverse effects of the ambient environment (e.g. equipment, clothing, sleeping bag). One of the methods to provide an efficient barrier for excessive heat exchange and/or pollution is wearing protective clothing, which properties should ensure protection of both health and comfort of a wearer.

To meet this demand, the number of international standards and devices to measure clothing properties has been developed (EN13537 2002; ISO15831 2004; ASTMF1291-05 2005; ASTMF2370-05 2005; ISO9920 2007). Others were designed to test properties of textiles alone at steady state (ISO11092 1993; ASTMF1868-02 2002; ASTME96/E96M-05 2005) and, to some extend, dynamic conditions (ASTMF2298-03 2003; ASTMD7024-04 2004). These standards, however, are insufficient to evaluate the dynamic properties of ensembles in wearing conditions and to predict its physiological effects on a wearer. Effectively, human subject tests are performed (ISO9886 2004), however, only when the health safety of an individual is guaranteed.

In this study, a recently developed single-sector thermophysiological human simulator (Psikuta, Richards et al. 2008) was used to determine the physiological response for the actual clothing and environmental conditions as well as the dynamic characteristics of clothing.

METHODS

The single-sector thermophysiological human simulator was validated using experiments in which the clothing worn to demonstrate usefulness of this tool for determination of human-clothing-environment interactions and clothing characteristics (Psikuta, Richards et al. 2008) (ref). In general, it predicted accurately the skin and the core temperatures as showed by the root-mean-square deviations (Barlow 1989) (the average differences between the simulations and the corresponding human experiments) that were lower than 1°C and 0.36°C respectively.

In this study, two clothing samples were chosen and measured using the single-sector human simulator. Both samples consisted of two layers: cotton underwear of tight fit and an outer layer made of either a permeable or an impermeable textile with loose fit. To mimic the air layer between clothing layers, a spacer with thickness of 1cm was used. The thermal insulation of the clothing samples was measured at steady state using the thermal cylinder (at constant surface temperature of 35°C, ambient temperature of 20°C, relative humidity of 50% and air velocity below 0.2m/s). The thermal insulation was calculated from temperature gradient between the cylinder surface and the environment, and the power input to the cylinder. The evaporative resistance of the sample with permeable outer layer was calculated from the thermal insulation according to ISO9920 (p. 7.3). The parameters of the clothing samples are listed in table 1.

Table 1. The thermal and evaporative resistance and clothing area factor measured on the thermal cylinder.

clothing sample	thermal resistance	evaporative resistance	clothing area factor
-	clo	m2Pa/W	-
cotton underwear, 1cm air gap, permeable layer	1.63 ±0.04	37.3	1.07
cotton underwear, 1cm air gap, impermeable layer	1.43 ±0.01	100	1.07

The single- sector thermophysiological simulator was used to simulate a work-and-rest scenario at cool and hot conditions. The environmental conditions in the climatic chamber during this exposure were as follows: ambient temperature and relative humidity of 10°C and 80% or 34°C and 30%, and air velocity below 0.2m/s. The scenario of the simulation consisted of two hours of an active phase at 4.5met followed by a resting phase at 1.2met for 30 minutes. At the beginning of each test, a thermo-neutral state was simulated for a person wearing the tested clothing. This transition lay within the simulation zone of the human simulator described by Psikuta et al. (2008).

RESULTS

Four simulations were run for combinations of two clothing samples (with permeable and impermeable outer layer) and two environmental temperatures (10 and 34°C). Since the Fiala model has been proven to be an accurate prediction tool for situations, when clothing is not worn (Fiala, Lomas et al. 2001; Psikuta 2009), it was used as a reference for the mean skin and rectal temperatures predicted by the human simulator. This model is also capable of simulating clothing worn but only in a simplified way. That means that only thermal and evaporative resistances are used to calculate heat and vapour flow through the clothing for given temperature and partial pressure gradient across the clothing sample. The results obtained from simulations using the Fiala model with its simple clothing model (continuous and dashed lines) and using the human simulator which measured the actual effects of clothing occurring at given scenarios (squares and diamonds) are compared in figure 1.

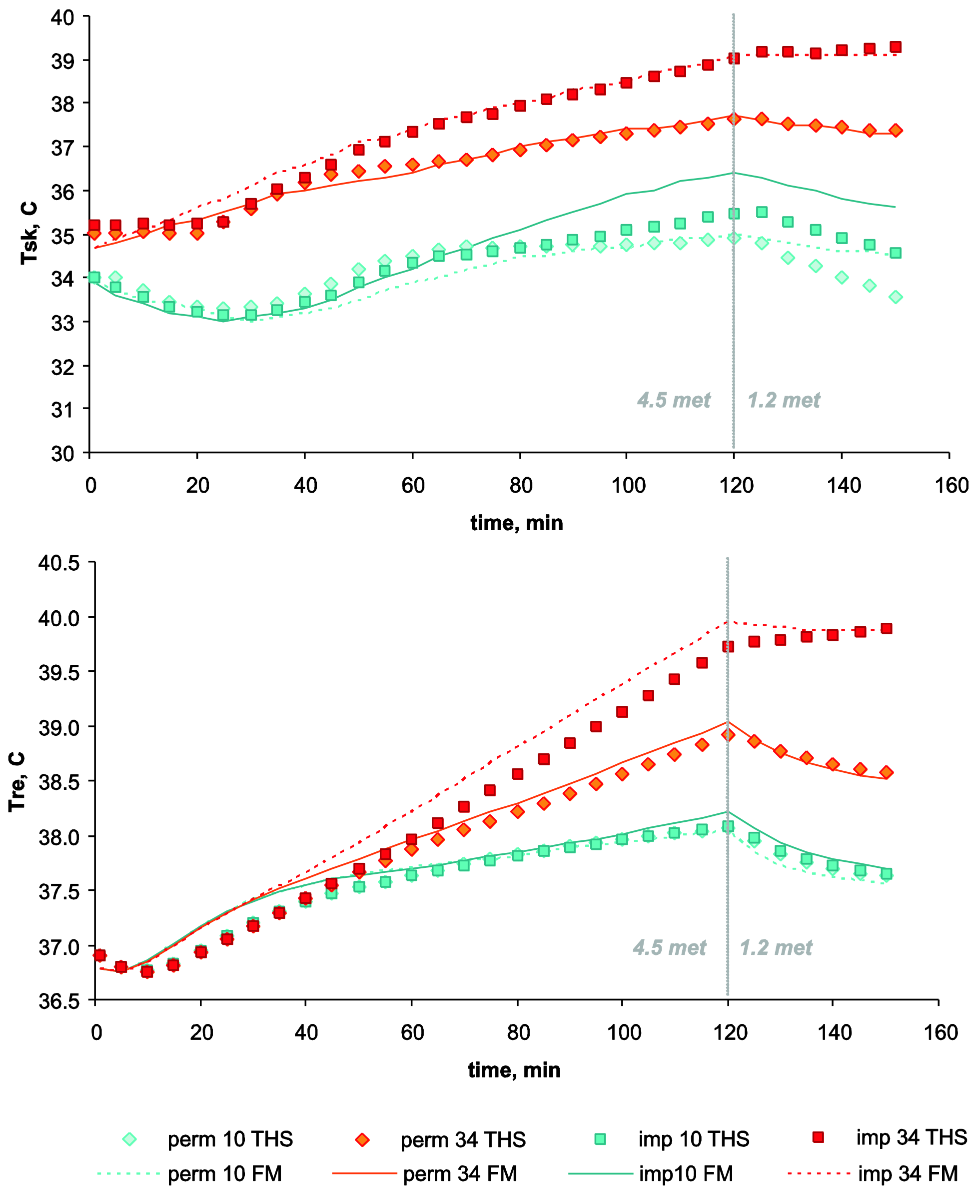

Figure 1. Mean skin and rectal temperatures simulated using the single-sector thermophysiological simulator (THS) and the Fiala model (FM) for the clothing samples with either permeable (perm) or impermeable (imp) outer layer, and the environmental temperature of either 10 or 34°C.

The tests performed using the thermophysiological human simulator provided information on the thermophysiological state of a person, such as body core temperature, skin temperature, skin blood flow, sweat rate, for the given scenario and the actual clothing. These data can provide a useful insight into the thermophysiological response of the simulated average person and can be interpreted in terms of thermal sensation and health safety.

The body core temperatures obtained from the human simulator were predicted as accurately as these simulated using the Fiala model for all conditions tested (rmsd < 0.21°C). The mean skin temperatures predicted using human simulator and the Fiala model for ambient temperature of 10°C differed noticeably, whereas predictions for the environment at 34°C matched very well (rmsd < 0.20°C). The differences in mean skin temperatures can be explained by the distinct approaches to the simulation of the clothing that were used in this experiment.

When the clothing with permeable outer layer was used at 10°C with the long period at high activity level followed by resting phase, the skin temperature predicted by the human simulator (perm 10 THS in figure 1) decreased faster than this predicted by the Fiala model (perm 10 FM in figure 1). The most plausible explanation of this effect could be moisture retention within the clothing layers during the first active phase and its evaporation with a certain delay in the second rest phase. The Fiala model does not account for the moisture retention within the clothing as it uses only the basic clothing parameters as inputs. Thus, the phenomena of moisture retention and delayed evaporation could not be simulated properly. On the other hand, the human simulator measured directly the post-exercising cooling effect present in the rest phase under these conditions.

When the clothing with impermeable outer layer was used at 10°C during exercise promoting sweating, the mean skin temperature predicted by the human simulator (imp 10 THS in figure 1) was lower than this predicted using the Fiala model (imp 10 FM in figure 1). This decrease, which was measured in the actual clothing, resulted the most probably from the occurring “heat pipe” effect described by Havenith et al. (Havenith, Richards et al. 2008). They reported that the apparent evaporative heat loss of manikin (that is an increase in heat loss from the wet manikin as compared to the heat loss from the dry manikin at the same temperature) can be higher than the evaporative heat loss deducted from the mass loss. That means that the sweat evaporated from the skin condensates on the inside of the outer clothing layer and this heat of condensation is released at the clothing surface without the moisture leaving the clothing. They also reported that for impermeable outer clothing layer at 10°C the cooling effect can be by up to four times greater than this resulting from mass loss of the manikin at steady-state. In practice, however, sweating develops dynamically, i.e. increases in the active phase and reduces in the resting phase rather than remains at steady-state for a prolonged period of time. This fact makes the physiological effect of such additional cooling difficult to estimate using only steady-state clothing characteristic. Yet the human simulator was capable of determining these effects as it measured actual heat flow through the clothing in real-time. Specifically, the human simulator predicted a decrease of mean skin temperature by 1°C after two hours of active phase at 4.5met (with sweating beginning in 25th minute) at 10°C and for the similar impermeable clothing as in the experiment of Havenith et al.

CONCLUSIONS

The single-sector physiological simulator has been shown to provide complementary data on the physiological response of an average person to the given environmental conditions, activity level, clothing worn and initial condition prior to the actual exposure. Analysis of these data provided a much more complete picture of the actual clothing performance than a single steady-state thermal and evaporative resistance values as demonstrated on the examples of the moisture retention within the clothing and the extra cooling due to the “heat pipe” effect in the impermeable clothing.

Time saving testing, repeatability of the physiological response measurement and the ability of testing in unsafe for human conditions are major advantages of this human simulator. The intended application of this device is to measure thermophysical properties and physiological effects of a broad range of clothing and sleeping systems, including multi-layer ensembles, sleeping bags, mattresses and blankets over a wide range of climatic conditions.

REFERENCES

ASTMD7024-04 (2004). Standard Test Method for Steady State and Dynamic Thermal Performance of Textile Materials.

ASTME96/E96M-05 (2005). Standard Test Methods for Water Vapor Transmission of Materials.

ASTMF1291-05 (2005). Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin.

ASTMF1868-02 (2002). Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate.

ASTMF2298-03 (2003). Standard Test Methods for Water Vapor Diffusion Resistance and Air Flow Resistance of Clothing Materials Using the Dynamic Moisture Permeation Cell.

ASTMF2370-05 (2005). Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin.

Barlow, R. J. (1989). Different definitions of the standard deviation. Statistics. A Guide to the Use of Statistical Methods in the Physical Sciences. D. J. Sandiford, F. Mandl and A. C. Phillips. Chichester, John Wiley & Sons Ltd.**:** 10-12.

EN13537 (2002). Requirements for sleeping bags.

Fiala, D., K. J. Lomas, et al. (2001). "Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions." International Journal of Biometeorology **45**(3): 143-159.

Havenith, G., M. G. Richards, et al. (2008). "Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects." Journal of Applied Physiology **104**(1): 142-149.

ISO9886 (2004). Ergonomics — Evaluation of thermal strain by physiological measurements. Geneva, Switzerland, ISO.

ISO9920 (2007). Ergonomics of the thermal environment -- Estimation of thermal insulation and water vapour resistance of a clothing ensemble.

ISO11092 (1993). Textiles - Physiological effects - Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test).

ISO15831 (2004). Clothing - Physiological effects - Measurement of thermal insulation by means of a thermal manikin. ISO.

Psikuta, A. (2009). Development of an 'artificaial human' for clothing research. Institute of Energy and Sustainable Development. Leicester, De Montfort University. **PhD thesis**.

Psikuta, A., M. Richards, et al. (2008). "Single-sector thermophysiological human simulator." Physiological Measurement **29**(2): 181-192.