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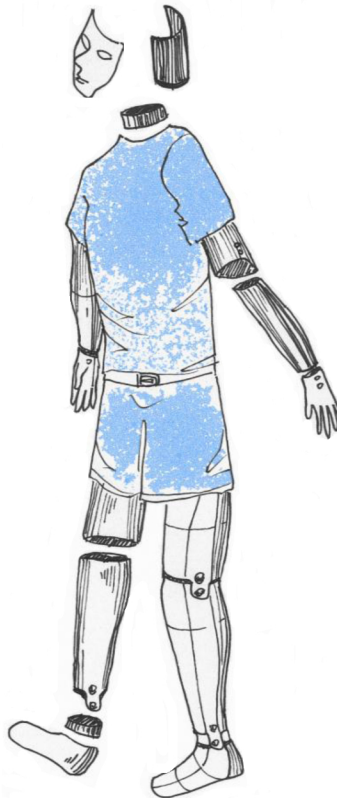
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DOCTORAL THESIS

Clothing Evaporative Resistance: Its Measurements and Application in Prediction of Heat Strain

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Department of Design Sciences
Lund University
Sweden 2011



Clothing Evaporative Resistance: Its Measurements and Application in Prediction of Heat Strain

Faming Wang

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Division of Ergonomics and Aerosol Technology

Department of Design Sciences

Faculty of Engineering, Lund University

Clothing Evaporative Resistance: Its Measurements and Application in Prediction of Heat Strain

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Popular science summary

Clothing plays an important role in our lives. It serves four main functions: adornment, status, modesty and protection. Wearing popular clothing with one's favourite decorations, contributes to a person reaching his or her mental comfort. Clothing is also a symbol of status, and was particularly so in ancient times. Moreover, it protects the human body from injury from abrasions, scratches, fire, radiations, and insect bites and helps the body maintaining core temperature.

From a heat transfer point of view, clothing acts as a thermal and moisture barrier. In cold weather, it is always good to have such a thermal barrier to prevent body heat loss. But in hot environments, clothing can greatly hinder sweat evaporation and heat dissipation. Construction workers and fire-fighters, for example, should wear protective clothing whatever the environment. They usually have a very high metabolic rate. If the heat produced cannot be balanced by sweat evaporation and/or dry heat losses, their body core temperature will rise. As body heat storage and core temperature increase, work performance will be greatly impaired, and the high body core temperature may eventually threaten their lives.

Evaporative resistance is one of the most important factors in quantifying and characterising the role of clothing as a moisture barrier. The research reported in this thesis examined several potential factors that may cause manikin measurement errors in clothing evaporative resistance. The findings can help designers to optimise functional protective clothing. They can also be a help in standardising test protocols and in enhancing measurement accuracy. An example of using clothing evaporative resistance in a heat strain model is given. The results of human trials presented in this thesis provide a picture of how humans physiologically respond to various thermal environments and protective clothing systems. Such studies contribute to the body of knowledge on how human respond to various environments.

Abstract

Clothing evaporative resistance is one of the most important inputs for both the modelling and for standards dealing with thermal comfort and heat stress. It might be determined on guarded hotplates, on sweating manikins or even on human subjects. Previous studies have demonstrated that the thermal manikin is the most ideal instrument for testing clothing evaporative resistance. However, the repeatability and reproducibility of manikin wet experiments are not very high for a number of reasons such as the use of different test protocols, manikins with different configurations, and different methods applied for calculation. The overall goals of the research presented were: (1) to examine experimental parameters that cause errors in evaporative resistance and to set up a well-defined test protocol to obtain repeatable data; and (2) to apply the reliable clothing evaporative resistance data obtained from manikin measurements and physiological data acquired from human trials to validate the Predicted Heat Strain (PHS) model (ISO 7933).

Most of the calculations on clothing evaporative resistance up until now have been based on manikin temperature rather than fabric skin temperature because the fabric skin temperature was unknown. However, the calculated evaporative resistance has been overestimated because the fabric skin temperature is usually lower than the manikin temperature. This is mainly due to that water evaporation cooling down the fabric skin. In **Paper I**, the error of using manikin temperature instead of fabric skin temperature for evaporative resistance calculation was examined. In **Paper II**, a universal empirical equation was developed to predict wet skin temperature based on the total heat loss obtained from the manikin and the controlled manikin temperature. **Paper III** investigated discrepancy between the two options for the calculation of clothing evaporative resistance and how to select one of them for measurements conducted in a so called isothermal condition. **Paper IV** studied localised clothing evaporative resistance through an inter-laboratory study. The localised dynamic evaporative resistance caused by air and body movement was examined as well. In

addition, reduction factor equations for localised evaporative resistance at each local segment were established.

The thermophysiological responses of eight human subjects who wore five different vocational garments in various warm and hot environments were investigated (**Paper V** and **Paper VI**). The PHS model was validated by those human trials. Some suggestions on how to revise this model in order to achieve wider applicability were discussed and proposed.

The results showed that the prevailing method for the calculation of evaporative resistance can generate an error of up to 35.9% on the boundary air layer's evaporative resistance R_{ea} . In contrast, it introduced an error of up to 23.7% to the clothing total evaporative resistance R_{et} . The error was dependent on the value of the clothing intrinsic evaporative resistance R_{ecl} . The isothermal condition is the most preferred test condition for measurements of clothing evaporative resistance; the isothermal mass loss method is always the correct option to calculate evaporative resistance. The reduction equations developed for localised clothing evaporative resistance have demonstrated that a total evaporative resistance value provided very limited information for local clothing properties and thus, localised values should be reported. The skin temperatures predicted by the PHS model were greatly overestimated in light clothing and high humidity environments ($RH > 80\%$). Similarly, the predicted core temperatures in protective clothing FIRE in warm and hot environments were also largely overestimated. The predicted evaporation rate was always much lower than the observed data. Therefore, a further revision of this model is required. This can be achieved by performing more human subject tests and applying more sensitive mathematical equations.

Keywords: sweating thermal manikin, protective clothing, evaporative resistance, localised evaporative resistance, thermophysiological response, heat stress, heat strain, the PHS model

List of publications and author's contribution

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

I Wang F, Kuklane K, Gao C and Holmér I.

Effect of temperature difference between manikin and wet fabric surfaces on clothing evaporative resistance: how much error is there? *Int. J. Biometeorol.* doi: 10.1007/s00484-011-0411-z (2011)

I conducted the experiments, analysed the data and wrote the paper. My supervisors made comments and replied to some of the questions raised by reviewers.

II Wang F, Kuklane K, Gao C and Holmér I.

Development and validity of a universal empirical equation to predict skin surface temperature on thermal manikins. *J. Therm. Biol.* 35:197-203 (2010)

I conducted all experiments, analysed the data and wrote the paper. My supervisors made comments and replied to some of the questions raised by reviewers.

III Wang F, Gao C, Kuklane K and Holmér I.

Determination of clothing evaporative resistance on a sweating thermal manikin in an isothermal condition: heat loss method or mass loss method? *Ann. Occup. Hyg.* 55:775-85 (2011)

I designed the test protocols, performed the experiments, analysed the data and wrote the paper. My supervisors commented on the manuscript and replied to some of the questions raised by reviewers.

IV Wang F, Ribeiro M, Mayor TS, Lin LY, del Ferraro S, Molinaro V, Gao C, Kuklane K and Holmér I.

Localised boundary air layer and clothing evaporative resistance for local body segments. Submitted to *Ergonomics*, manuscript number TERG-2011-0252

I developed the idea, designed the test protocol, and performed all experiments with Miguel at CeNTI, Simona and Vincenzo at INAIL. I carried out all data analysis and wrote the paper. My supervisors made comments.

V Wang F, Kuklane K, Gao C and Holmér I.

Can the PHS model (ISO7933) predict reasonable thermophysiological responses while wearing protective clothing in hot environments?. *Physiol. Meas.* 32:239-49 (2011)

I conducted all human trials with Kalev and Chuansi. I analysed the data and wrote the paper. We had several discussions before the paper submission.

VI Wang F, Gao C, Kuklane K and Holmér I.

Effects of various protective garments and thermal environments on physiological heat strain of unacclimated men: the PHS model (ISO 7933) revisited. To be submitted for publication

I conducted all human trials with Kalev and Chuansi. I analysed the data and wrote the paper. We had several discussions as well.

Papers I, II, III and V have been reprinted with kind permissions from the following publishers:

Paper I: Springer, Berlin;

Paper II: Elsevier, Amsterdam;

Paper III: Oxford University Press, Oxford;

Paper V: IOP (Institute of Physics), London.

Additional papers, not included in the thesis

Journal papers

1. Wang F, Gao C, Kuklane K, Holmér I. (2009) A study on evaporative resistance of two new skins designed for thermal manikin ‘Tore’ under different environmental conditions. *J. Fiber Bioeng. Inform.* **1**: 301-5
2. Wang F, Zhou X, Wang S. (2009) Development processes and property measurements of moisture absorption and quick dry fabrics. *Fibers Text. East. Eur.* **17**: 46-9
3. Wang F. (2010) Comparisons on thermal and evaporative resistances of kapok coats and traditional down coats. *Fibers Text. East. Eur.* **18**:75-8
4. Wang F, Gao C, Kuklane K, Holmér I. (2010) A review on technology of personal heating garments. *Int. J. Occup. Safety Ergo. (JOSE)* **16**: 387-404
5. Wang F, Lee H. (2010) Evaluation of an electrically heated vest (EHV) using thermal manikin in cold environments. *Ann. Occup. Hyg.* **54**:117-24
6. Wang F, Wang S. (2010) Characterization on pore size of honeycomb-patterned micro-porous PET fibers using image processing techniques. *Ind. Textila* **61**: 66-9
7. Wang F, Ji E, Zhou X, Wang S. (2010) Empirical equations for intrinsic and effective evaporative resistances of multi-layer clothing ensembles. *Ind. Textila* **61**:176-80
8. Wang F, Gao C, Holmér I. (2010) Effects of air velocity and clothing combination on heating efficiency of an electrically heated vest (EHV): a pilot study. *J. Occup. Environ. Hyg.* **7**: 501-5
9. Wang F, Kuklane K, Gao C, Holmér I, Havenith G. (2010) Development and validation of an empirical equation to predict wet fabric skin surface temperature of thermal manikins. *J. Fiber Bioeng. Inform.* **3**: 9-15
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11. Gao C, Kuklane K, Wang F, Holmér I. (2011) Personal cooling with phase change materials to improve thermal comfort from a heat wave perspective. *Indoor Air* submitted, manuscript number INA-11-08-158

Conference papers

1. Wang F. A comparative introduction on thermal manikins “Newton” and “Walter”. *Proceedings of the 7th International Thermal Manikin and Modelling Meeting (7I3M)*, University of Coimbra, Portugal, Sept. 3-5, 2008
2. Wang F. Comparisons on thermal and evaporative resistances of traditional down coats and kapok coats. *The 4th European Conference on Protective Clothing (ECPC)*, Arnhem, Netherlands, June 10-12, 2009
3. Wang F, Gao C, Kuklane K, Holmér I. A study on evaporative resistance of two new skins designed for thermal manikin ‘Tore’ under different environmental conditions. *The 4th European Conference on Protective Clothing (ECPC)*, Arnhem, Netherlands, June 10-12, 2009
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15. Gao C, Wang F, Kuklane K, Holmér I. Personal cooling with phase change materials in a very hot environment. *Proceedings of the 4th International Conference on Human-Environment System (ICHE 2011)*, Hokkaido University, Sapporo, Japan, Oct. 3-6, 2011
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17. Gao C, Wang F, Sakoi T. Ventilated evaporative cooling as a preventive measure when confronted with climate changes. *The 55th Nordic Work Environment Meeting (NAM 2011)*, Lund, Sweden, Oct.17-19, 2011

Licentiate thesis

Wang F. Evaluation of the Performances of Electrically Heated Clothing. ISBN: 978-91-7473-016-6, E-husets Tryckeri Press, Lund, Sweden, Sept. 2010

Technical reports

1. A report for a Vinnova (Swedish Government Agency for Innovation Systems) project entitled “Development of clothing for extreme environments, and assessment model of thermal protection for different work situations”, 2010
2. A report for the Taiwan Textile Research Institute (TTRI) contract entitled “Evaluation of cold protective clothing”, 2010
3. A report for the Taiwan Textile Research Institute (TTRI) contract entitled “An Investigation of sleeping bags using thermal manikins and human subjects”, 2011, in preparation

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Eleven years ago, in 2001, I was a teenager entering my first term as a college freshman. This was the first time that I had lived in a big city and I was struggling with my future dream—to be a researcher. It wasn't that easy. Today, eleven years later, I am completing my PhD studies at Lund University but am not that young any more. Fortunately, I am now approaching the fulfilment of my early dream.

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Faming Wang

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Hässleholm

Nomenclature

Symbol	Meaning	SI units
A	surface area	m^2
A_D	DuBios body surface area	m^2
A_{du}	body surface area	m^2
A_i	surface area of the segment, i	m^2
A_r	body surface area participating in radiant heat exchange	m^2
a	coefficient for Eq. (4-3)	-
B	coefficient for Eq. (1-11)	-
b	coefficient for Eq. (1-11)	-
C	convective heat transfer	W/m^2
C_b	specific heat of the human body	$W \cdot h / (^{\circ}C \cdot kg)$
$Corr$	correction factor for localised resultant evaporative resistance	-
c	coefficient for Eq. (4-3)	-
d	coefficient for Eq. (4-3)	-
\bar{d}	mean thickness of discs of the hot plate	m
E	evaporative heat exchange	W/m^2
E_{dif}	evaporative heat loss through moisture diffusion	W/m^2
E_{res}	respiratory heat exchange	W/m^2
E_{rsw}	evaporative heat loss through sweating	W/m^2
E_{sk}	evaporation from skin surface	W/m^2
e	coefficient for Eq. (4-3)	-
f_{cl}	clothing area factor	-
H_b	body height	m
H_d	total dry heat loss	W/m^2
H_{dry}	total dry heat transfer	W
H_e	evaporative heat loss	W/m^2
$H_{e,env}$	evaporative heat taken from the air in a so called isothermal	W

	condition	
$H_{e,heat}$	observed evaporative heat loss from the sweating thermal manikin in a so called isothermal condition	W/m^2
$H_{e,i}$	segmental evaporative heat loss of the segment, i	W/m^2
$H_{e,mass}$	evaporative heat loss calculated from the observed mass loss rate in a so called isothermal condition	W/m^2
HL	total observed heat loss from the sweating thermal manikin	W/m^2
h_c	convective heat transfer coefficient	$W/(m^2 \cdot ^\circ C)$
h_e	evaporative heat transfer coefficient	$W/(kPa \cdot m^2)$
h_{fg}	latent heat of water evaporation	$W \cdot h/g$
h_r	radiant heat transfer coefficient	$W/(m^2 \cdot ^\circ C)$
I_T	clothing total thermal insulation	$K \cdot m^2/W$
i	segment number of the sweating thermal manikin	-
K	conductive heat transfer	W/m^2
LR	Lewis relation	K/kPa
M	body metabolism	W
M_{sk}	net metabolic heat	W
m	clothing weight	kg
m	mass loss	kg
\dot{m}	body weight change per unit area	kg/h
m_i	mass loss at the segment, i	kg
p	probability	-
p_a	partial water vapour pressure in the air	kPa
p_s	saturated water vapour pressure	kPa
p_{sk}	water vapour pressure on skin surface	kPa
$p_{sk,i}$	water vapour pressure on skin surface at the segment, i	kPa
q	heating power	W
R	radiant heat transfer	W/m^2
R_a	boundary air layer's thermal resistance	$K \cdot m^2/W$

R_{cl}	clothing/fabric intrinsic thermal resistance	$K \cdot m^2/W$
R_{ct}	fabric total thermal resistance	$K \cdot m^2/W$
R_{ea}	boundary air layer's evaporative resistance	$kPa \cdot m^2/W$
R_{ecl}	clothing intrinsic evaporative resistance	$kPa \cdot m^2/W$
R_{et}	clothing total evaporative resistance	$kPa \cdot m^2/W$
R_{et_heat}	clothing total evaporative resistance calculated by the heat loss method (ASTM F2370 [2010])	$kPa \cdot m^2/W$
$R_{et,i}$	clothing total evaporative resistance of the segment, i	$kPa \cdot m^2/W$
$R_{eti,r}$	clothing total resultant evaporative resistance at the segment, i	$kPa \cdot m^2/W$
$R_{eti,ref}$	clothing total evaporative resistance of the segment, i , determined at reference condition	$kPa \cdot m^2/W$
R_{et_mass}	clothing total evaporative resistance calculated by the mass loss method (ASTM F2370 [2010])	$kPa \cdot m^2/W$
R_{et_p1}	clothing total evaporative resistance calculated from predicted wet fabric skin temperature by Eq. (4-1)	$kPa \cdot m^2/W$
R_{et_p2}	clothing total evaporative resistance calculated from predicted wet fabric skin temperature by Eq. (4-2)	$kPa \cdot m^2/W$
R_{etr}	clothing total resultant evaporative resistance	$kPa \cdot m^2/W$
RH	relative humidity	%
RH_a	relative humidity in the air	%
RH_{sk}	relative humidity on skin surface	%
S	body heat storage rate	J/m^2
T_a	air temperature	$^{\circ}C$
\bar{T}_b	mean body temperature	$^{\circ}C$
$T_{manikin}$	thermal manikin surface temperature	$^{\circ}C$
T_r	radiant temperature	$^{\circ}C$
T_{re}	rectal temperature	$^{\circ}C$
T_{re_p}	predicted rectal temperature by the PHS model	$^{\circ}C$

T_s	temperature of the plate surface of the hot plate	°C
T_{sk}	human skin surface temperature	°C
$T_{sk,f}$	fabric skin surface temperature	°C
T_{sk_p}	predicted human skin temperature by the PHS model	°C
T_{sk_p1}	predicted fabric skin temperature by Eq. (4-1)	°C
T_{sk_p2}	predicted fabric skin temperature by Eq. (4-2)	°C
T_1	temperature of the plate 1 of the hot plate	°C
T_2	temperature of the plate 2 of the hot plate	°C
t	time	h
t_{cl}	clothing surface temperature	°C
\bar{t}_r	mean radiant temperature	°C
v_a	air velocity	m/s
W	external work rate	W
W_b	body weight	kg
W_f	fabric weight	g/m ²
w	walking speed	m/s
w_s	skin wettedness	-

Greek letters

Symbol	Meaning	SI units
λ	heat of vapourisation of water	J/g
λ_i	heat of vapourisation of water at the segment, i	J/g
λ_T	thermal conductivity	W/(m·K)
σ	Stefan-Boltzman constant	W/(m ² ·K ⁴)

Subscripts

dif	diffusion
$heat$	heat loss method
$mass$	mass loss method
ref	reference condition

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1. Literature review

1.1 Brief introduction

Clothing is the second skin of human beings (Horn and Gurel 1981) and it serves several functions: adornment, status, modesty and protection (Li and Wong 2006). By wearing fashionable and aesthetic garments with proper adornments, one can reach his or her mental comfort. In some societies, clothing reflects the wearer's social rank or status. In ancient Rome, for example, only senators were allowed to wear clothing dyed with Tyrian purple (Reinhold 1971). Regarding the protective function, clothing plays two primary roles (Li and Wong 2006): helping the human body maintain body core temperature; and protecting the body from injury from abrasion, scratches, fire, radiations, chemical toxic substances, electricity and insect bites. Goldman summarised four primary factors in clothing comfort, and identified as the "4Fs of comfort": fashion, feel, fit and function (Goldman 2005). Definitely, clothing plays an important role between the human body and its surrounding environments in determining subjective and objective perceptions of comfort. In order to understand the mechanisms behind these perceptions, the interaction among the human body, clothing and the environment should be clearly investigated (Goldman and Kampmann 2007).

1.2 Protective clothing

Protective garments are designed to prevent harmful exposures to various hazards in the environment. These include fire, extreme heat and cold, water, chemicals, particulates, blood-borne pathogens, biological agents, electrical power, radioactive materials, physical force or impact (e.g., bullets, bomb fragments, sports and work equipment, falling debris), and ultraviolet light. The protection must be sufficient but allow performing tasks; otherwise, it may put the wearer in a dangerous condition. Generally, the protective function of a protective garments

is highlighted as oppose to other aspects such as fashion. That is why protective clothing is usually made with specialised materials, innovative finishing, and unique designs (Li and Wong 2006; Holmér 2006). The performance of a protective clothing system depends mainly on the textile structure, clothing moisture permeability, fibre wicking, absorption and desorption properties as well as on the course of heat and mass transfer processes within clothing (Yarborough and Nelson 2005; Li and Wong 2006). For a well-designed protective garment, the gains in a high level of protection should not be compromised by increased physiological or mental strain, reduced performance or other negative factors such as increased discomfort (Holmér 2006). The design of protective clothing systems should consider such ergonomic requirements as not constricting body movement and not being too heavy (Huck 1988; Havenith and Heus 2004).

1.3 Clothing thermal comfort evaluation

Umbach (1983) suggested that clothing performance could be adequately predicted based on physiological measurements and subjective data. Such data may be obtained from either climatic chamber tests or field studies. Human subject tests, however, are time and labour intensive; cost and ethical issues may be involved. Instead measurements of clothing thermal comfort have been carried out on objective apparatuses, such as hot plates, skin simulators and thermal manikins (Kenney *et al.* 1987; Holmér and Nilsson 1995). With regard to clothing thermal comfort, thermal insulation (or thermal resistance) and evaporative resistance (or moisture vapour resistance) are the two most important physical parameters (Holmér 1995; Fan and Chen 2002; Qian and Fan 2006; Wu and Fan 2009; Yu *et al.* 2011). Thus, determination of these two physical factors is the main focus for objective assessments of clothing thermal comfort. Many objective evaluation apparatuses have been developed over the past 30 years. Hot plates, simple skin simulators and thermal manikins are the most innovative instruments (Bankvall

1973; Gibson *et al.* 1994; Mattle 2000; Meinander 2000; Richards and Mattle 2001; Fan and Qian 2004; Psikuta *et al.* 2008a, b).

1.3.1 Hot plate

The hot plate was first developed by Lee in England in 1898 (Brown 2006). At that time, it was an unguarded hot plate: a pair of thin circular discs was clamped between three copper plates. The heat was electrically generated in the central plate and conducted in the axial direction through the discs to the outer two plates. The temperature of the discs was assumed equal to the temperature of the plates. The temperature was measured using thermocouples. The thermal conductivity λ_T could be computed by (Salmon 2001)

$$\lambda_T = \frac{q\bar{d}}{2A(T_1 - T_2)} \quad \text{Eq.(1-1)}$$

where, q is the supplied heating power, W; $T_1 - T_2$ is the mean temperature difference between the plates, °C; \bar{d} is the mean thickness of the discs, mm; A is the cross-sectional area of the plates, m².

The sweating guarded hot plate, also referred to as the ‘skin model’, is able to simulate both heat and moisture transfer from skin surface through a piece of cloth to the ambient environment. A schematic drawing of a typical sweating guarded hot plate is displayed in Fig.1.1.

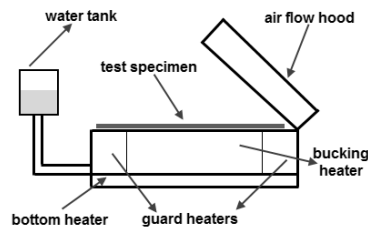


Fig.1.1 Schematic drawing of sweating guarded hot plate.

Generally, the sweating guarded hot plate consists of three main units (McCullough *et al.* 2003; Huang 2006): a measuring unit, a temperature controlling unit and a water supply unit. The measuring unit is fixed to a metal block embedded with heating elements. The plate test section is surrounded by a guard section. The guard heaters are applied to eliminate lateral heat flow to/from the main heater. The bottom heater serves the function of preventing downward heat loss from the test section and guard heaters. Such a design forces both the heat and moisture transfer upward only, (i.e., they transfer perpendicularly to the test specimen's surface). The test specimen is placed on the heated porous plate, which is normally heated to a constant temperature to represent the normal human skin temperature (e.g., 35.0 °C). Temperature sensors detect the temperature of the plate. The heating power is recorded throughout the measurement. For the evaporative resistance measurement, distilled water is fed to the heated porous plate from a dosing unit. This unit is activated when the water level in the plate is 1 mm below the plate's surface. Water was preheated when flowing through the guard heater zone. A piece of waterproof but permeable membrane is placed on the plate. Air bubbles and wrinkles may exist under this piece of membrane, thus, cautions has to be used to ensure that such bubbles and wrinkles are totally removed. The test specimen is directly placed above the membrane.

Under the steady-state, the fabric's total thermal resistance R_{ct} and evaporative resistance R_{et} can be calculated by Eq.(1-2) and Eq.(1-3), respectively.

$$R_{ct} = \frac{A(T_s - T_a)}{H_d} \quad \text{Eq.(1-2)}$$

$$R_{et} = \frac{A(p_s - p_a)}{H_e} \quad \text{Eq.(1-3)}$$

where, A is the surface area of the plate test section, m^2 ; T_s and T_a are the temperatures on the plate surface and in the ambient air, respectively, $^{\circ}C$; H_d and H_e are the total dry heat loss and evaporative heat loss, respectively, W ; p_s and p_a are the water vapour pressures at the plate surface and in the ambient air, respectively, kPa .

The boundary air layer's thermal resistance R_a and evaporative resistance R_{ea} can be determined by conducting tests on the bare plate. The fabric's intrinsic thermal resistance R_{cl} and intrinsic evaporative resistance R_{ecl} can be determined by Eq.(1-4) and Eq.(1-5), respectively.

$$R_{cl} = R_{ct} - R_a \quad \text{Eq.(1-4)}$$

$$R_{ecl} = R_{et} - R_{ea} \quad \text{Eq.(1-5)}$$

It should be pointed out that the aforementioned guarded hot plate is a 'flat' apparatus. It cannot provide information critical to clothing design and cannot detect the effects of clothing fit, joining, seaming and pumping effects from body movement and articulation (Song 2011). Also, such measurements do not account for the effects of air volume inside the clothing. Thus, those fabric measurements provided limited information.

1.3.2 Skin simulator

A skin simulator (i.e., sweating torso) has a cylindrical shape that is similar to the human trunk (Camenzind *et al.* 2001; Keiser *et al.* 2008). It is mainly used to study clothing fabrics as well as sleeping bags. A stretchable skin layer fabric is used to mimic the human skin layer. The torso can be run in several modes: constant temperature mode, constant power mode, and physiological control mode (Zimmerli and Weder 1997; Keiser *et al.* 2008; Psikuta 2009). Take the EMPA's sweating torso (see Fig.1.2) for example, where there were 54 sweating outlets

spread on the torso to produce sweat. Different human activities can also be simulated by changing predefined phase sequences. The torso surface temperature and weight are recorded during the testing.

A single-section torso has solved many of the problems that were left by guarded hot plates: it has the size and shape of the human trunk; it can also mimic different thicknesses of homogeneous air gaps between adjacent cloth layers (Kim *et al.* 2003). Nevertheless, it cannot simulate human movement. Such simulators are unable to mimic realistic microclimate air gaps inside a clothing system. Hence, sweating torso measurements disregard the non-uniform heat and moisture transfer (Frackiewicz-Kaczmarek *et al.* 2011). To study the effects of different body diameters and movements as well as non-homogeneous air gaps on localised heat and moisture transfer through clothing ensembles, a multi-segment sweating and moveable thermal manikin is required.



Fig.1.2 Sweating torso at EMPA, Switzerland (©Keiser 2007)

1.3.3 Thermal manikin

Thermal manikins are essential tools to evaluate clothing comfort, automobile environments as well as to assess the effect of heating, ventilation and air conditioning (HVAC) systems on humans. The thermal manikin measurement

meets basic thermo-physiological requirements of whole body exchange. It can detect clothing layer and dynamic movement effects, clothing drape, fit, and body covering area. Therefore, measurements performed on a full-size thermal manikin are realistic, fast, accurate, reproducible, cost-effective and provide baseline values for standards and models (Holmér and Nilsson 1995).

More than 100 thermal manikins are in service worldwide (Holmér 2004). The number is expanding every year. The development of heated thermal manikins started in 1945 (Zimmerli 2000), when the US Army Research Institute of Environmental Medicine (also known as “USARIEM”) built a manually controlled, one-section copper thermal manikin. Afterwards, researchers from England, France, Denmark, Sweden, Finland, Germany and the Kansas State University (KSU) headed the development, and advanced computer controlled, multi-segment and moveable manikins were built (Wyon 1989; Holmér 2004). In 1989, the first female plastic manikin was developed by the Danish researchers (Madsen 1989).

The first continuous sweating thermal manikin, ‘Coppelius’, was developed at the VTT Technical Research Centre of Finland in a Scandinavian project concerned with thermal comfort (Meinander 1992, 1997). ‘Coppelius’ has a total of 18 segments and 187 sweating glands. It does not sweat at the head, hands and feet. An inner nonwoven material is applied to help water distribution. The outer membrane layer is used to prevent water drip and to hold excessive water. Almost 10 years later, in 2001, the Swiss multi-segmental sweating agile thermal manikin ‘SAM’ was developed (Richards and Mattle 2001). ‘SAM’ has a total of 30 body segments and 125 sweat outlets. This manikin can simulate both vapourous and liquid sweating over the whole body and over any local body segment, with variable sweating rates from 0 to 4 l/(m²·h). In addition, ‘SAM’ has moveable joints, which allows it to perform even complicated 2D movements of each limb. It can reach a walking speed of 3.0 km/h.

In 2002, an inexpensively priced, one-segment sweating fabric thermal manikin, ‘Walter’, was developed in Hong Kong (Fan and Chen 2002). This manikin has a waterproof but water vapour permeable Gore-Tex skin. It can only simulate gaseous perspiration. ‘Walter’ can determine clothing thermal insulation and evaporative resistance in one step. Moreover, it is the first manikin that has consistency in sweating over the entire body. Although ‘Walter’ addressed many problems of other sweating manikins, it did not provide a method for determining localised thermal comfort properties, nor did it mimic liquid sweating. In addition, the use of a Gore-Tex fabric skin layer may change the driving force for water evaporation due to the low permeability of the Gore-Tex skin.



Fig.1.3 Sweating thermal manikin at INAIL, Italy (Newton, MTNW, Seattle, WA)

Because current sweating thermal manikins are unable to simulate the transient thermal responses of humans, the recent development of thermophysiological model controlled multi-segment sweating thermal manikins has become a main trend (Richards *et al.* 2006; Psikuta *et al.* 2008a,b; Burke *et al.* 2010; Blood and Burke 2010; Redortier and Voelcker 2010, 2011). At present, commercial physiological controlled ‘Newton’ sweating thermal manikins (see Fig.1.3) are available from MTNW (Measurement Technology Northwest) Inc. (2011). Nevertheless, the reported results obtained on such physiological model controlled

thermal manikins have shown large discrepancies in human subject data. Some possible reasons accounting for these large differences are the incorrect system operation over the application range and manikin configuration issues such as the use of thick fabric skin (Redortier and Voelcker 2011).

1.4 Human heat balance equation

To investigate heat exchange from the human body to its surrounding environment, the heat balance equation (Gagge and Gonzalez 1996) is an essential guideline. It may be written as

$$S = M \pm W \pm (R + C + K) \pm E \quad \text{Eq.(1-6)}$$

where, S is the body heat storage rate; M is the body metabolism; W is the work rate (+ for work against external forces); R is the radiant heat exchange (+ for a gain); C is the convective heat transfer (+ for a gain); K is the conductive heat transfer (+ for a gain); E is the evaporative heat transfer (- for a loss).

The equation of heat exchange at the human skin surface can also be simplified as

$$S = M_{sk} \pm H_{dry} \pm E_{sk} \quad \text{Eq.(1-7)}$$

where, M_{sk} is the net metabolic heat; H_{dry} is the total dry heat transfer from skin surface through radiation, convection and conduction; E_{sk} is the evaporation from skin surface (- for a loss).

The units of all the above rate of energy gains or losses are energy per second; J/s or watt (W). In fact, the rate of energy change per unit time and per body surface area is used more often (Holmér 2004): $W \cdot s/m^2$. The human body surface area is usually determined by the DuBois and DuBois equation (1916)

$$A_D = 0.202 \times W_b^{0.425} \times H_b^{0.725} \quad \text{Eq.(1-8)}$$

where, A_D is the DuBois body surface area, m^2 ; W_b is the body weight, kg; H_b is the body height, m.

For a body to be in heat balance, the body heat storage S should be equal to zero. If $S > 0$, the body temperature will rise. On the contrary, if $S < 0$, the heat storage will be negative and the body temperature will drop. The rate of body heat storage is directly associated with the mean body temperature change, which can be expressed as

$$S = (C_b \times \frac{W_b}{A_D}) \times \frac{\Delta \bar{T}_b}{\Delta t} \quad \text{Eq.(1-9)}$$

where, C_b is the specific heat of the body, $C_b = 0.965 \text{ W}\cdot\text{h} / (\text{°C}\cdot\text{kg})$; $\Delta \bar{T}_b / \Delta t$ is the mean body temperature change rate per unit time, °C/h .

1.4.1 Convective heat transfer

The convective heat transfer C between a clothed body and the environment may be written as

$$C = h_c \times f_{cl} \times (t_{cl} - t_a) \quad \text{Eq.(1-10)}$$

where, h_c is the convective heat transfer coefficient, $\text{W}/(\text{m}^2\cdot\text{°C})$; f_{cl} is the clothing area factor (dimensionless), which may be determined by body segment circumference measurement, by photograph technology or by a 3D body scanner (Anttonen *et al.* 2004; McCullough *et al.* 2005; Gao *et al.* 2005; Apeageyi 2010); t_{cl} and t_a are the mean clothing surface temperature and the mean air temperature, respectively, °C .

The convective heat transfer coefficient h_c varies with air velocity and walking speed due to convection is caused by air and body movements. Many researchers have defined the convective heat transfer coefficient (see Table 1.1) through either

human tests or thermal manikin measurements, a universal expression for the convective heat transfer coefficient may be read as

$$h_c = B \times v_a^b \quad \text{Eq.(1-11)}$$

where, B and b are coefficients; v_a is the air velocity, m/s.

Table 1.1 Empirical equations for estimating convective heat transfer coefficient.

Equation	Range of v_a	Condition	Reference
$h_c=12.1 v_a^{0.5}$	0.05-2.64	semi-reclining	Winslow <i>et al.</i> (1939)
$h_c=8.16 v_a^{0.5}$	0.15-3.04	nude, standing	Nelson <i>et al.</i> (1947)
$h_c=2.7+8.7 v_a^{0.7}$	0.20-1.20	nude, reclining	Colin <i>et al.</i> (1967)
$h_c=7.25 v_a^{0.6}$	0.67-4.94	nude, sitting	Mitchell <i>et al.</i> (1969)
$h_c=8.6 v_a^{0.5}$	0.10-1.78	clothed, walking	Nishi <i>et al.</i> (1970)
$h_c=12.2 v_a^{0.4}$	0.05-1.20	seated manikin	Ichihara <i>et al.</i> (1997)
$h_c=10.1 v_a^{0.43}$	0.10-1.10	standing manikin	Mochida <i>et al.</i> (1998)
$h_c=3.4+6.9 v_a^{0.9}$	0.10-4.70	standing manikin	Kuwabara <i>et al.</i> (2005)

1.4.2 Radiative heat transfer

The radiative heat exchange R between a clothed body and its exposed environment is generally calculated by

$$R = h_r \times f_{cl} \times (t_{cl} - \bar{t}_r) \quad \text{Eq.(1-12)}$$

where, h_r is the radiative heat transfer coefficient, a typical value at room temperature is $4.5 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$; \bar{t}_r is the mean radiant temperature, $^\circ\text{C}$.

The radiative heat transfer coefficient is computed by Eq.(1-13)

$$h_r = 4\sigma\varepsilon \times \left(\frac{t_{cl} + t_r}{2} + 273 \right)^3 \times \frac{A_r}{A_{du}} \quad \text{Eq.(1-13)}$$

where, σ is the Stefan-Boltzman constant, $\nu=5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$; ε is the emissivity of the clothed body surface (dimensionless). The emissivity is normally close to unity (about 0.95), unless reflective materials are used or high-temperature

sources are applied (ASHRAE 1997). A_r/A_{du} is the effective surface area participating in the radiative heat exchange (dimensionless). The ratio A_r/A_{du} equals 0.70 for a sitting person and 0.73 for a standing person (Fanger 1967).

1.4.3 Evaporative heat transfer

The total evaporative heat loss E (latent heat) can be determined by both direct calorimetry and partitional calorimetry (Holmér and Elnäs 1981; Gagge and Gonzalez 1996). E may be given by

$$E = E_{sk} + E_{res} = \dot{m} \times \frac{h_{fg}}{A_D} \quad \text{Eq.(1-14)}$$

where, E_{sk} and E_{res} are the evaporative heat loss of sweat from skin and respiratory evaporative heat loss, respectively, W/m^2 ; \dot{m} is the body weight change per unit time, g/h ; h_{fg} is the latent heat of sweat evaporation ($h_{fg}=40.8 \text{ W}\cdot\text{h/g}$ [Snellen *et al.* 1970]).

It should be noted that Eq.(1-14) is only valid on humans during light or moderate exercise. For humans during heavy exercise, a correction should be made for the change rate of CO_2 loss over O_2 gain (Gagge and Gonzalez 1996).

Under steady-state, the evaporative heat exchange E_{sk} of sweat from skin to the environment can be expressed as (Holmér 1995; ASHRAE 1997; Parsons 2003)

$$E_{sk} = E_{rsw} + E_{dif} = \frac{w_s(p_{sk} - p_a)}{R_{et}} = \frac{w_s(p_{sk} - p_a)}{(R_{ecl} + \frac{1}{f_{cl}h_e})} \quad \text{Eq.(1-15)}$$

where, E_{rsw} and E_{dif} are the evaporative heat losses from the skin through sweating and through moisture diffusion, respectively, W/m^2 ; w_s is the skin wettedness factor (dimensionless); p_{sk} and p_a are the water vapour pressures on the skin surface and in the air, respectively, kPa ; R_{et} is the clothing total evaporative

resistance, $\text{kPa}\cdot\text{m}^2/\text{W}$; R_{ecl} is the clothing intrinsic evaporative resistance, $\text{kPa}\cdot\text{m}^2/\text{W}$; h_e is the evaporative heat transfer coefficient, $\text{W}/(\text{m}^2\cdot\text{kPa})$, it can be derived from the Lewis Relation

$$h_e = LR \times h_c \quad \text{Eq.(1-16)}$$

where, $LR=16.5 \text{ K/kPa}$ at standard environment ($25 \text{ }^\circ\text{C}$, $\text{RH}=50\%$, at the sea level).

1.5 Heat stress and development of body heat strain

Heat stress is the net heat load to which a person may be exposed from combined factors such as metabolic rate, air temperature, relative humidity, air velocity, radiation and such clothing factors as thermal insulation and evaporative resistance (Beshir *et al.* 1981; ACGIH 2001). A mild or moderate heat stress may cause discomfort and a deterioration of performance (Azer *et al.* 1972; McMorris *et al.* 2006). If the heat stress level reaches human tolerance limits, heat-related illnesses such as heat syncope, heat cramp, heat exhaustion and heat stroke may occur (Knochel 1989; Parsons 2003).

Generally, sweating occurs after a core temperature increase of about 0.2 to 0.3 $^\circ\text{C}$ from a baseline body core temperature of $37.0\pm 0.5 \text{ }^\circ\text{C}$ (Gagge and Gonzalez 1996). With continued body heat storage, an increase of sweat production occurs in proportion to core temperature change rate. Dripping of sweat takes place as sweating becomes more and more profuse. Unfortunately, dripping sweat makes no contribution to cooling the body. If the sweat is absorbed by the clothing and transported to the clothing's outer surface, the cooling power of produced sweat will be reduced (Havenith *et al.* 2009). On the other hand, protective clothing ensembles are used to eliminate or reduce the effects of environmental stress factors such as heat, cold and contamination (Holmér 2006). They are often impermeable to water vapour. Therefore, sweat evaporation is largely constricted by such clothing. This adds extra heat stress to the wearers. Combined with the largely restricted sweat evaporation caused by the protective

clothing, an accelerated rise in body core temperature will probably occur. The probability of heat exhaustion when the core temperature reaches 39.0-40.0 °C becomes very high (Glazer 2005). Classic heat stroke occurs when the core temperature is beyond 40.0-41.0 °C (LoVecchio *et al.* 2007). Finally, the degradation of body protein will appear when the core temperature exceeds 42.0-43.0 °C (Jay and Kenny 2010).

1.6 Heat stress assessment and heat strain prediction

The heat stress evaluation may be performed by measuring physical thermal environment parameters and following the evaluation of their impacts on the human body by using a single index or more. Many attempts have been made to assess/predict physiological heat strain and to combine various heat stress parameters into an empirical index, such as the wet-bulb globe temperature (WBGT) index (ISO7243 [1994]). Givoni and Goldman (1972) developed a model for prediction of core body temperature response and found that a theoretical equilibrium core body temperature matches the skin temperature at any given combinations of the environment, metabolism and clothing ensemble. The USARIEM developed a heat strain model (Cadarette *et al.* 1999) that has now been incorporated into a heat strain decision aid (Xu and Santee 2011). This empirical model predicts core temperature, maximum work times, sustainable work/rest cycles, water requirements and heat casualties.

Many rational models (Brake and Bates 2002) have been also developed for predicting heat strain in the past 60 years, such as the heat strain index (HSI), the index of thermal stress (ITS) and the required sweat rate index *SWreq* (ISO79338 [1989]). A rational model called Predicted Heat Strain (PHS) model was developed in the BIOMED project (Malchaire *et al.* 2001). It was derived from an in-depth revision of the previous required sweat rate index (Malchaire *et al.* 2000). In this model, new algorithms were created based on scientific literature concerning, convection, evaporative heat transfer, rectal and skin temperatures.

This model was developed based on the human heat balance equation, which made the predicted physiological parameters consistent with heat transfer theory. This rational model was later adopted by the ISO standard (ISO7933 [2004]) and has been used as a tool to predict the human thermophysiological responses of a standard person exposed to hot environments.

Many advanced human thermoregulatory models have been developed in the past three decades. These models are rather complicated and most of them were derived from previous fundamental research carried out by Stolwijk and Hardy (1977). They have become valuable tools for researchers to understand thermal regulation processes. Unfortunately, they have yet to gain widespread applications yet. Currently, the most influential and popular thermoregulatory models are Wissler model, Xu and Werner model, Fiala Model and Tanabe model (Wissler 1985; Werner 1989; Xu and Werner 1997; Fiala *et al.* 1999; Tanabe *et al.* 2002).

2. Objectives

The previous round robin study on the determination of clothing evaporative resistance using sweating thermal manikins (McCullough 2001; Richards and McCullough 2005) showed great variations of 50-100%. The large discrepancy was mainly due to variations in the measurement techniques, test conditions and sweating system constructions of the manikins. Different calculation methods (Havenith *et al.* 2008b; Wang, Gao, Kuklane and Holmér 2011) may also have contributed to those great variations. In order to contribute to enhancing the measurement repeatability as well as its reproducibility, the research presented in this thesis has examined several main issues that cause large errors in clothing evaporative resistance. Further, because total evaporative resistance provides very limited information for the local body areas, localised evaporative resistance was also investigated through an inter-laboratory study. Finally, an example application of using clothing evaporative resistance for predicting body heat strain was demonstrated. A validation of the predicted heat strain (PHS) model was also performed. The main objectives of the research presented were

- a) To examine the errors in using manikin surface temperature instead of wet fabric skin temperature to calculate the evaporative resistances of the boundary air layer and clothing.
- b) To measure the wet fabric skin surface temperature by applying additional temperature sensors and to develop a universal empirical skin temperature prediction equation for the sweating thermal manikin ‘Tore’.
- c) To study how to choose from two calculation options of clothing evaporative resistance for measurements conducted in a so-called “isothermal” condition ($T_{manikin} = T_a = T_r$).

- d) To determine the amount of heat taken from the surrounding environment for the wet fabric skin evaporation in a so-called isothermal condition ($T_{manikin} = T_a = T_r$) by performing manikin experiments.
- e) To investigate the combined effects of air and body movements on localised clothing evaporative resistance and to develop empirical equations for local body segments.
- f) To demonstrate the application of evaporative resistance in a heat strain model and to check thermophysiological responses of human subjects wearing different protective clothing in various moderate warm and hot environments.
- g) To validate the Predicted Heat Strain (PHS) model (ISO 7933) and to point out potential improvements in order to gain better applicability in the relevant scientific research field and in the practical work situations.

3. Methods

3.1 Experimental design

The experimental conditions of all studies included in Papers **I-VI** are displayed in Table 3.1. For all manikin measurements, the experimental conditions were selected to ensure that both the thermal manikin and the climatic chamber were well regulated throughout all the experimental periods. For human trials, the experimental conditions were selected mainly based on both operation range of the predicted heat strain (PHS) model (ISO 7933) and capacity of the climatic chamber.

Table 3.1 Experimental conditions selected in Papers **I-VI**.

T_a °C	RH_a %	p_a kPa	v_a m/s	w m/s
Study 1 (Paper I)				
34.0	39	2.0	0.33±0.09	0
	44	2.4		
	53	2.8		
	72	3.8		
30.0	55	2.3	0.33±0.09	0
	59	2.5		
	69	2.9		
25.0	61	1.9	0.33±0.09	0
	70	2.2		
20.0	51	1.2	0.33±0.09	0
	70	1.6		
Study 2(Paper II)-equation development part				
34.0	25	1.4	0.33±0.09	0
	40	2.2		
	52	2.8		
	72	3.8		
30.0	55	2.3	0.33±0.09	0
	59	2.5		
	69	2.9		
25.0	62	2.0	0.33±0.09	0
	70	2.2		
Study 2(Paper II)-equation validation part				
34.0	46	2.5	0.33±0.10	0

30.0	63	2.7	0.33±0.10	0
25.0	67	2.2	0.33±0.10	0
Study 3(Paper III)				
34.0	38	2.1	0.33±0.10	0
Study 4(Paper IV)- boundary air layer study (local)				
34.0	38	2.1	0.18±0.03	0
				0.96
				1.17
			0.48±0.05	0
				0.96
				1.17
			0.78±0.05	0
				0.96
				1.17
Study 4(Paper IV)-clothing study (local)				
34.0	38	2.1	0.13±0.03	0
				0.96
				1.17
			0.48±0.05	0
				0.96
				1.17
			0.70±0.04	0
				0.96
				1.17
Study 5 (Paper V)-human trials (hot environments)				
40.0	30	2.3	0.33±0.05	1.25
	45	3.4		
Study 6 (Paper VI)-human trials (warm environments)				
20.0	86	2.1	0.33±0.05	1.25
30.0	47	2.0		

Notes: T_a , air temperature; RH_a , relative humidity in the air; p_a , air water vapour pressure; v_a , air velocity; w , walking speed. A 'Tore' thermal manikin was used in Papers **I-III**, while in **Paper IV**, 'Newton' type thermal manikins were used for experiments. The manikin surface temperature of all studies was controlled at 34.0 °C except for some of the experiments used in **Paper III** (some were performed without heating power). All tests were repeated at least twice for each test scenario.

The first study (**Paper I**) was designed to examine the temperature difference between controlled manikin surface temperature and uncontrolled wet fabric skin surface temperature. The experimental conditions were selected to demonstrate that this temperature difference is determined by evaporation rate. The higher the evaporation rate from the wet fabric skin, the larger the temperature difference. On the other hand, the evaporation rate is mainly determined by the water vapour pressure gradient between skin surface and environment, and air velocity. It can be

seen from Table 3.1 that the selected ambient water vapour pressure ranges from 1.20 to 3.83 kPa.

In study 2 (**Paper II**), a universal equation for wet skin temperature prediction was developed. All skin experiments were conducted at a temperature range of 25.0-34.0 °C. Different levels of relative humidity (RH) were selected at each temperature level. In the validation experiments, additional clothing ensembles were dressed on the manikin. The measured wet fabric skin temperature and predicted wet skin temperature were compared.

A so-called isothermal condition ($T_{manikin}=T_a=T_r=34.0$ °C) was chosen for experiments in study 3 (**Paper III**). The air velocity was kept at a constant value: 0.33 ± 0.10 m/s. In order to determine the amount of heat taken from the environment by the wet fabric skin, the manikin was disconnected from its power source (i.e., unheated). Other experiments were performed with a constant temperature mode (i.e., $T_{manikin}=34.0$ °C).

Because a clothing total evaporative resistance value provides very limited information for clothing local body segments, in study 4 (**Paper IV**), the experimental conditions were selected to examine the effects of walking and air speed on localised evaporative resistance. Three levels of air speed and three levels of walking speed were used in both the boundary air layer study and clothing study. Because all experiments were conducted randomly at three different laboratories, the air velocity levels for the boundary air layer study were not exactly the same as those for the clothing study.

In studies 5 and 6 (**Papers V and VI**), three levels of air temperature were chosen: 20.0, 30.0 and 40.0 °C, representing different heat stress levels. The water vapour pressure inside the chamber was intended to be kept at either 2.0 or 3.0 kPa. However, the observed values varied with external weather conditions and subject sweating levels.

3.2 Clothing ensembles

Various vocational clothing ensembles were used in the series of studies. The characteristics of all clothing ensembles are described in Table 3.2.

Table 3.2 Clothing ensembles used in **Papers I-VI**.

Testing code	Garment Component	I_t °C·m ² /W	R_{et}^* kPa·m ² /W	m kg
SKIN	cotton fabric skin, knitted	-	-	0.325
L	t-shirt, briefs, short pants, socks, sports shoes	0.163	0.0169	1.692
HV	t-shirt, briefs, long trousers with 3M reflective materials, socks, sports shoes	0.186	0.0229	2.211
MIL	jacket, long trousers, net t-shirt, briefs, socks, sports shoes	0.256	0.0391	2.132
CLM	polyamide overall laminated with Gore-Tex membrane, t-shirt, briefs, socks, sports shoes	0.260	0.0629	3.570
PERM	permeable overall (hydrophobic layer laminated with inner PTFE membrane)	0.237	0.0380	0.586
IMP	impermeable overall (PA webbing coated with PVC)	0.248	∞	0.680
FIRE	RB90 firefighting clothes, underwear, t-shirt, briefs, socks, sports shoes	0.399	0.1139	6.446

*Notes: I_t , total thermal resistance; R_{et} , total evaporative resistance; m , clothing total weight.*the evaporative resistance values presented in the table were calculated based on the mass loss option.*

3.3 Experimental protocols

All thermal manikin wet experiments were performed in controlled climatic chambers. The ASTM F2370 (2010) standard was selected as the main guideline. In order to simulate sweating, a pre-wetted fabric skin was dressed on the dry heated manikin ‘Tore’. There was no covering on the head, hands and feet. This method was not a continued sweating setup; the fabric skin would then dry out in less than 50 minutes. Nevertheless, it functions well and is easy to perform.

Prior to performing studies 1 and 2, there were two main plausible options for attaching the temperature sensors to determine wet fabric skin temperature: either on the manikin surface to measure the wet fabric skin inner temperature or on the wet fabric skin surface to acquire the skin outer surface temperature (see Fig.3.1).



Fig.3.1 Sensor attachments applied in the study. [Reprinted with permissions]

The first option was easy to perform, and each sensor had a standard fixed position. Since temperature sensors were fixed on the manikin surface, there was no need to attach them again when taking off the fabric skin for another cycle of rinse. The second option was quite time-consuming, and all sensors had to be removed and attached again for each new experiment. In this matter a comparison of the wet skin inner temperature and the outer surface temperature was made. The statistical analyses indicated that there were no significant differences between skin inner and outer temperatures (Wang, Kuklane, Gao, Holmér and Havenith, 2010). Therefore, in studies 1 and 2, twelve temperature sensors (Sensirion SHT75, Sensirion AG, Switzerland) were attached to the manikin surface to measure wet fabric skin inner surface temperature. In studies 3 and 4, the wet fabric skin outer surface temperatures were determined by attaching sensors to the wet fabric outer surface using thread rings. In study 4, thermocouples (tip diameter: ~ 0.5 mm, copper-constantan) with a data logger (Testo 177 T4, Testo AG, Germany) were used for skin temperature acquisition.

All physiological testing followed the following protocol: each separate garment, equipment, and subject were weighed on a weighing scale during preparation (Mettler-Toledo Inc., Switzerland, precision: ± 2 g). Afterwards, subjects came into the chamber and walked on a treadmill (Exercise™ X Track Elite, Norway) at a speed of 4.5 km/h. The subjects were weighed again after 30

min of exposure to collect the first 30 min sweat rate (normally the sweating reached steady state after 30 min). The heart rate, the rectal (T_{re}) and skin (T_{sk}) temperatures were recorded throughout the trials. Test sessions were terminated when one of the following four criteria was reached: (a) subjects felt the conditions were intolerable and were unable to continue, (b) the rectal temperature T_{re} reached 38.5 °C, (c) test leaders decided to stop the test, or d) subjects completed 70 min exposure.

Once the test session was finished, the subject was weighed again. They took off equipment and garments. Each garment was weighed separately after the subject removed them. Right after the subjects were undressed and the measuring equipment was removed, they were weighed wearing just briefs and the rectal sensor to get post-exercise nude body weight.

3.4 Physiological measurement parameters

The body core temperature (i.e., rectal temperature) was measured using a rectal temperature probe (YSI 401, Yellow Spring Instrument, Measurement Specialties Inc., USA, accuracy ± 0.1 °C) at a depth of 10 cm above the anal sphincter. Four skin temperature thermistors (ACC-001, NTC, temperature matched, Rhopoint Components Ltd., UK, accuracy ± 0.2 °C) were taped on the left four body sites (chest, upper arm, thigh and calf) of the subject's skin surface to acquire mean skin temperature. The well-established Ramanathan's four-point formula was applied to calculate the mean skin temperature (Ramanathan 1964). The oxygen uptake was continuously measured with a MetaMax I instrument (Cortex Biophysik GmbH, Germany) for 5 minutes from the 10th minute of the exposure until the 15th min. The heart rate was tracked with a pulse monitor (Sport Tester, Polar Electro Oy, Finland) throughout the experiment.

3.5 Calculations

For calculations of saturated water vapour pressure on a fully wet fabric skin surface p_{sk} and partial water vapour pressure in the ambient air p_a , the Antoine's equation was applied

$$p_{sk} = \exp\left(18.956 - \frac{4030.18}{T_{sk,f} + 235}\right) \times RH_{sk} \quad \text{Eq.(3-1)}$$

$$p_a = \exp\left(18.956 - \frac{4030.18}{T_a + 235}\right) \times RH_a \quad \text{Eq.(3-2)}$$

where, $T_{sk,f}$ and T_a are the wet fabric skin surface temperature and the ambient temperature, respectively, °C; RH_{sk} and RH_a are the relative humidities at the wet fabric skin surface and in the ambient, respectively, %. The relative humidity on the saturated wet textile fabric surface RH_{sk} was assumed to be 100%.

The clothing evaporative resistance R_{et} (ASTM F2370 [2010]) can be calculated by either the heat loss method (i.e., Eq.(3-3)) or mass loss method (i.e., Eq.(3-4)):

$$R_{et} = \frac{(p_{sk} - p_a)A}{H_e} \quad \text{Eq.(3-3)}$$

$$R_{et} = \frac{(p_{sk} - p_a)A}{\lambda \frac{dm}{dt}} \quad \text{Eq.(3-4)}$$

where, A is the sweating fabric skin surface area, m^2 , in all four studies, A was assumed to be equal to the manikin's skin-covered surface area because the textile fabric skin is quite thin and tight fitting around the manikin body shape; H_e is the evaporative heat loss from the manikin, W; λ is the heat of water vapourisation at

the measured skin temperature, J/g; the ratio of dm/dt is the evaporation rate of moisture leaving the manikin-clothing system, g/h.

The intrinsic evaporative resistance of a clothing ensemble R_{ecl} is defined as

$$R_{ecl} = R_{et} - \frac{R_{ea}}{f_{cl}} \quad \text{Eq.(3-5)}$$

Similarly, the localised clothing evaporative resistance R_{eti} may be determined by either the heat loss method or mass loss method

$$R_{eti} = \frac{(p_{sk,i} - p_a)A_i}{H_{e,i}} \quad \text{Eq.(3-6)}$$

$$R_{eti} = \frac{(p_{sk,i} - p_a)A_i}{\lambda_i \frac{dm_i}{dt}} \quad \text{Eq.(3-7)}$$

where, $p_{sk,i}$ is the localised water vapour pressure on the wet fabric skin at the segment i , kPa; p_a is the water vapour pressure in the air, kPa; $H_{e,i}$ is the localised evaporative heat loss at the segment i , W/m², λ_i is the heat of vapourisation at the skin temperature at the segment i , J/g; dm_i/dt is the mass loss rate at the segment i , g/h.

The correction factor $Corr$ for localised resultant evaporative resistance (caused mainly by air and body movement) may be expressed as

$$Corr = \frac{R_{eti,r}}{R_{eti,ref}} \quad \text{Eq.(3-8)}$$

where, $R_{eti,r}$ is the localised resultant evaporative resistance at the segment i , kPa·m²/W; $R_{eti,ref}$ is the localised evaporative resistance of the segment i

determined at reference condition (in studies presented in **Paper IV**, the reference condition is defined as: $v_a=0.18\pm0.05$ m/s, $w=0$ m/s, $p_a=2.1$ kPa), $\text{kPa}\cdot\text{m}^2/\text{W}$.

As shown in Eq.(3-3), Eq.(3-4), Eq.(3-6) and Eq.(3-7), the (local) wet fabric skin temperature should be measured and used when calculating evaporative resistance. Nevertheless, very few reported thermal manikin experiments (Fan and Chen 2002; Meinander 1992; Wang, Kuklane, Gao and Homlér 2010, 2011a) actually measured the fabric skin temperature due to the complexity of applying additional sensors to determine fabric skin temperature. Therefore, the prevailing method uses the manikin temperature instead of the wet fabric skin temperature to calculate clothing evaporative resistance. For studies presented in Papers **I** and **II**, both methods (the prevailing method and the real method [i.e., the wet fabric skin temperature was used for calculations]) were used and compared. While in other studies presented in **Papers III** and **IV**, only the real method was applied for calculations.

3.6 Data analyses

In **Paper I**, the repeated measures ANOVA (Analysis of Variance) was performed for within-subject comparison of the effect of temperature differences ($T_{manikin}$ vs. $T_{sk,f}$) on the measured boundary air layer's evaporative resistance. This was achieved using the SPSS version 16.0 (SPSS, Chicago, IL). In **Paper II**, RMSD (root mean square deviation) was used to examine the prediction of the developed universal skin temperature equation.

Multiple nonlinear regression analysis was applied in **Paper IV** to develop empirical correction equations for the localised resultant evaporative resistance of each segment. Such analyses were performed using the software XLSTAT version 2011 (Addinsoft Inc., Brooklyn, NY).

In **Paper V**, RMSD was applied to examine the prediction acceptance of physiological factors such as core temperature and skin temperature produced by the PHS model.

For physiological testing (**Paper VI**), repeated measures ANOVA was also used to determine whether there were significant differences in the metabolism, heart rate, subjective sensations, sweat rate and the evaporative rate for different clothing and thermal environments. The statistical significance was set at $p < 0.05$.

4. Results and discussion

4.1 Effect of temperature difference between $T_{manikin}$ and $T_{sk,f}$ on evaporative resistance (Paper I)

4.1.1 Boundary air layer's evaporative resistance

The wet fabric skin temperatures observed were 0.46 to 3.47 °C lower than the manikin surface temperatures due to water evaporation (in non-isothermal conditions, the dry heat loss also contributed to these reductions). The temperature difference was dependent on evaporation rate (i.e., water vapour pressure gradient between wet fabric skin surface and ambient air, and air velocity). The real evaporative resistances (i.e., calculated from the wet skin temperature) were lower than the evaporative resistances calculated from the manikin surface temperature (hereafter referred to as prevailing evaporative resistance). The mean real boundary air layer's evaporative resistance was 0.0287 kPa·m²/W. The average prevailing evaporative resistance was 0.0355 kPa·m²/W. Statistical results showed a highly significant difference between the real evaporative resistances and prevailing evaporative resistances ($p < 0.001$). Therefore, calculations based on the manikin surface temperature produced errors in the evaporative resistance ranging from 9.9 to 35.9%.

4.1.2 Clothing total evaporative resistance

The temperature difference between $T_{manikin}$ and $T_{sk,f}$ in clothing total evaporative resistance was examined by mathematic deduction. It was found that the prevailing calculation overestimated the real clothing total evaporative resistance by 3.8 to 23.7%. Additionally, the prevailing calculation generated a much larger error on permeable clothing than on semi-permeable/impermeable clothing at the same test condition. This was mainly because a permeable garment usually has a relatively low intrinsic evaporative resistance (it was assumed that the boundary air layer's evaporative resistance and clothing area factor were constant). For

impermeable clothing such as chemical or CBRN (chemical, biological, radiological, nuclear) protection clothing, the error introduced by the temperature difference might be neglected because such clothing usually has a very high intrinsic evaporative resistance (e.g., R_{et} value could be $0.50 \text{ kPa}\cdot\text{m}^2/\text{W}$ or even higher).

The conclusions of **Paper I** were that the evaporative resistance should be calculated based on the wet fabric skin temperature rather than the manikin surface temperature. In order to determine the real evaporative resistance, the wet skin temperature and climatic conditions should be measured using temperature/RH sensors with good measurement accuracy (e.g., temperature: $\pm 0.1 \text{ }^\circ\text{C}$; RH: $\pm 2\%$). Finally, it was concluded that the major errors in calculating the real evaporative resistance of clothing came from the use of the manikin temperature instead of the real wet fabric skin temperature and the control accuracy of the RH value inside the test house.

4.2 Development of a universal empirical equation for wet skin temperature prediction (Paper II)

Due to the complexity of measuring wet fabric skin temperature, it was useful to develop a universal empirical equation to predict this temperature. The relationships between wet fabric skin temperature and total heat loss of the manikin are illustrated in Fig.4.1. Considering the fact that the skin surfaces will not cool down if there is no evaporation, a linear regression equation with an intercept ($0, T_{manikin}$) was developed accordingly.

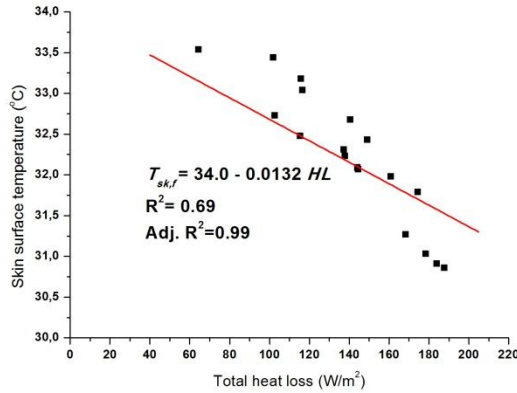


Fig.4.1 The universal empirical equation for wet fabric skin temperature prediction at an ambient temperature range between 25.0 and 34.0 °C. [Reprinted with permission]

The universal skin temperature prediction equation developed at an environmental temperature range of 25.0-34.0 °C is written as

$$T_{sk,f} = 34.00 - 0.0132HL \quad \text{Eq.(4-1)}$$

where, $T_{sk,f}$ is the skin surface temperature, °C; HL is the total heat loss observed from the thermal manikin, W/m^2 .

Havenith (Havenith, Kuklane & Ueno, personal communications, 2007) studied the wet fabric skin temperature on a Newton manikin (Havenith *et al.* 2008a) by the infrared camera immediately after stripping clothing. The skin temperature prediction equation on their type manikin determined at 34.0 °C is read as

$$T_{sk} = 34.13 - 0.012HL \quad \text{Eq.(4-2)}$$

It should be noted that the universal skin temperature equation (Eq.4-1) was developed based on nude measurements. Therefore, validation experiments with several clothing ensembles were performed. The observed and predicted wet skin temperature data for each test condition were plotted in Fig. 4.2.

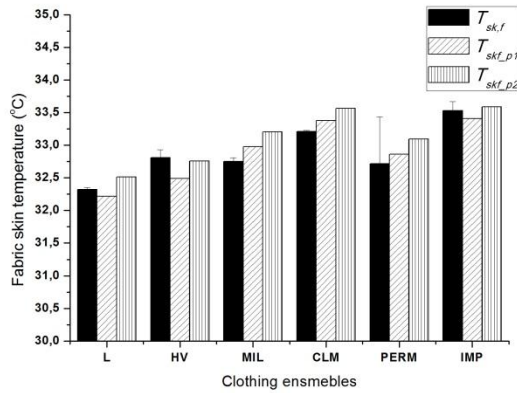


Fig.4.2 Observed and predicted fabric skin temperatures for 6 clothing ensembles. $T_{sk,f}$, the observed fabric skin temperature; T_{skf_p1} , the predicted fabric skin temperature by Eq.(4-1); T_{skf_p2} , the predicted fabric skin temperature by Eq.(4-2). [Reprinted with permission]

The RMSD values have demonstrated that Eq.(4-1) has a prediction accuracy of ± 0.3 °C. In contrast, the prediction accuracy of Eq.(4-2) fell within the ± 0.5 °C range.

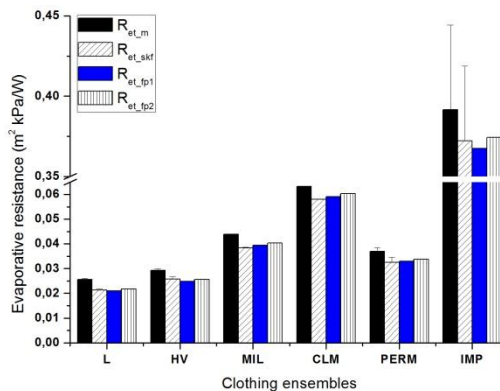


Fig.4.3 The clothing evaporative resistances of 6 clothing ensembles calculated based on 4 different temperatures (mass loss method). R_{et_m} , the evaporative resistance calculated

based on the prevailing method; R_{et_skf} , the calculated evaporative resistance by Eq.(3-4); R_{et_fp1} , the calculated evaporative resistance based on the predicted fabric skin temperature by Eq.(4-1); R_{et_fp2} , the calculated evaporative resistance based on the predicted fabric skin temperature by Eq.(4-2). [Reprinted with permission]

The clothing total evaporative resistances of all 6 clothing ensembles calculated using different temperatures (skin temperature, manikin temperature or predicted skin temperature) are presented in Fig.4.3. The calculated clothing evaporative resistances by Eq.(3-4) (i.e., mass loss method, experimental skin temperature was used for calculation) ranged from 0.0213 to 0.3721 kPa·m²/W. It was evident that the prevailing calculation method (i.e., mass loss method, manikin temperature was used for calculation) produced greater values than the data calculated from Eq.(3-4). On the other hand, the evaporative resistances of all 6 clothing ensembles calculated based on the predicted skin temperatures by Eq.(4-1) and Eq.(4-2) were relatively good. Thus, compared with the prevailing method, the accuracy of clothing evaporative resistance calculation was further enhanced by the empirical equations developed in our study and in Havenith's study (Havenith, Kuklane, and Wang, Personal communications).

The conclusion of **Paper II** was that the accuracy of clothing evaporative resistance was further enhanced by using the predicted wet skin temperature generated from a newly developed universal empirical equation. Nevertheless, it should be pointed out that this empirical equation was developed from the 'Tore' thermal manikin, it is not clear whether it is valid on other sweating thermal manikins.

4.3 Determination of evaporative heat taken from the ambient: selection of calculation options (Paper III)

In a so-called isothermal condition ($T_{manikin}=T_{sk,f}=T_r$, Havenith *et al.* 2008a,b), the evaporative resistances of the boundary air layer and five clothing ensembles

calculated by two options (i.e., heat loss and mass loss method) are displayed in Fig 4.4. The heat loss method produced greater values than those by the mass loss method. The evaporative resistance values for the boundary air layer and clothing L, HV, MIL, CLM, and FIRE based on the heat loss method were 37.1, 30.8, 25.9, 21.5, 12.7, and 11.2%, respectively, greater than those based on the mass loss option.

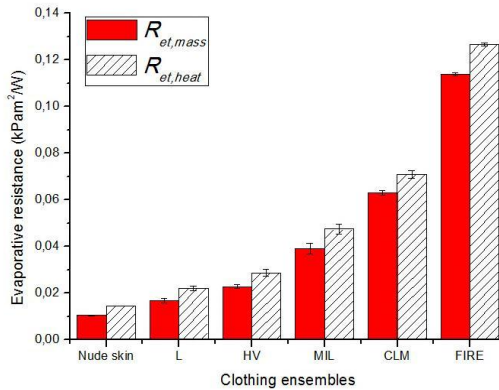


Fig. 4.4 The evaporative resistances of the boundary air layer and five clothing ensembles calculated by the mass loss method and heat loss method at a so-called isothermal condition ($T_{manikin}=T_a=T_r=34.0\text{ }^{\circ}\text{C}$). [Reprinted with permission]

The evaporative heat taken from the environment accounts for 10.9-23.8% of the total calculated evaporative heat loss. The real evaporative cooling efficiency ranged from 0.762 to 0.891 accordingly. Moreover, the theoretical evaporative heat energy taken from the environment (i.e., $H_{e, mass}-H_{e, heat}$) was consistent with the observed heat loss $H_{e, env}$ (the differences were 7.4, 8.2, 3.5, -2.0, 0.3 and 0.6 W/m^2 for the nude skin, L, HV, MIL, CLM and FIRE, respectively, which were perhaps mainly caused by measurement error, for example the weighing scale's drift).

A second finding was that the higher the thermal insulation of a clothing ensemble dressed on top of the wet textile skin, the less evaporative heat energy

taken from the environment. This was mainly because high insulation clothing prevented the wet textile skin from absorbing heat energy from the ambient environment. The firefighter's clothing FIRE, for instance, provides a thermal insulation of 2.58 clo, the calculated clothing evaporative resistance by the heat loss method is only 11.2% greater than that based on the mass loss method. In contrast, if there was no clothing dressed on top of the pre-wetted textile skin, the difference between those two evaporative resistance values rose to 37.1%. It was thus concluded that the real evaporative cooling efficiency was higher if a higher insulation garment was used. However, the total amount of evaporation leaving the manikin-clothing system would be greatly impeded by the clothing. Consequently, the real evaporative cooling efficiency was not always necessarily high and the amount of sweat evaporation per unit time leaving the manikin-clothing system was more important.

Third, the selection of evaporative resistance calculation options depends on the manikin construction and design. For the 'Newton' type thermal manikin, the heat loss method was widely used. Sweating thermal manikins such as 'Walter', 'KEM' and 'Coppelius' use the mass loss method. Hence, different calculation options may generate large deviations in evaporative resistance. In order to make these results comparable, a correction of the real evaporative heat loss (i.e., the observed value from the sweating thermal manikin) has to be made. One possible approach to correcting the real evaporative heat loss is to add the amount of heat energy taken from the environment $H_{e,env}$. An alternative method is to use the real evaporative cooling efficiency to correct the real evaporative heat loss.

The conclusion of **Paper III** was that the determination of clothing evaporative resistance on a thermal manikin should be preferably conducted in a real isothermal condition ($T_{manikin} > T_{sk,f} = T_a = T_r = 34.0$ °C). This can avoid complicated heat transfer processes such as dry heat loss, and possible condensation inside clothing. The mass loss method was always the correct option for clothing

evaporative resistance testing conducted under isothermal conditions. The isothermal heat loss method can be used provided that a correction is made on the real evaporative heat loss or the measurement is performed in a real isothermal condition (in such a condition both the heat loss and mass loss methods should give the same evaporative resistance).

4.4 Localised boundary air layer and clothing evaporative resistance for local body segments (Paper IV)

4.4.1 Individual effects on localised boundary air layer's evaporative resistance

At an air velocity range of 0.18 to 0.78 m/s, the localised boundary air layer's evaporative resistance decreases linearly with the increasing air velocity (walking speed $w=0$ m/s). However, its reduction rate differs significantly at different body segments. Reduction rates at the face, upper arm, hand and foot at an air velocity of 0.78 m/s are the lowest, ranging from 48.6 to 55.9%. The head, shoulders, back and thigh have the greatest reduction, ranging from 72.5 to 86.9%.

The individual walking effect on localised evaporative resistance at a reference air velocity of 0.18 m/s was also examined. It was found that the walking speed decreases localised evaporative resistance at the extremities much more than on other segments. Interestingly, the reduction rate at the thigh was the greatest, when the manikin was walking at 1.17 m/s compared with a standing posture (reduction: 64.8%, i.e., $0.0297 \text{ kPa}\cdot\text{m}^2/\text{W}$). The reduction of localised evaporative resistances at segments such as the face, head and chest were less than 10% of that on the thigh. Moreover, the reduction of localised evaporative resistance at the forearm was greater than that on the upper arm. This was mainly because the arm swing created a local turbulent air flow which led to a stronger decrease in the evaporative resistance at the manikin torso (e.g., shoulders and back) than at face.

It was also found that the smaller the diameter of a local segment (such as the hand, forearm, calf and foot), the smaller the localised evaporative resistance (i.e.,

the higher the localised evaporative heat transfer coefficient, the greater the evaporative capacity). The results were consistent with Belghazi *et al.*'s findings (2005), where the effect of air velocity on whole body and regional evaporative heat transfer coefficients was examined in neonates using a baby manikin. The intersegment differences between upper limbs and the torso ranged from 75-100%. Belghazi *et al.* (2005) observed that the differences were 30% on their baby manikin. One possible reason for this could be that their baby manikin has a relatively small body surface area compared with the adult manikins used in this study. The evaporative heat transfer coefficients at those extremities had greater values than those at the torso. Thus, the evaporative resistances at segments such as the hands, feet, and limbs were smaller than those at the torso such as the back, shoulders, waist, and chest. The results presented in this study showed good agreement with De Dear *et al.*'s study (1997), where the convective heat transfer coefficients of the hands, feet and peripheral limbs were found higher than the central torso regions.

Localised convective heat transfer coefficients at the anterior body segments were much greater than those at the posterior segments due to laminar air flows from the front wall facing the manikin's anterior segments to the back wall. The localised evaporative heat transfer coefficients were greater at the front than those at the back accordingly. Hence, localised evaporative resistances at the front segments were smaller than those at the back. The data determined at the reference condition ($v_a=0.18$ m/s, $w=0$ m/s) were in good agreement with the above theoretical analysis. The localised evaporative resistances at the chest, stomach, and waist were 0.0240, 0.0212 and 0.0213 kPa·m²/W, respectively. In contrast, localised evaporative resistances at the shoulders and back were 0.0486 and 0.0404 kPa·m²/W respectively. They were 168-229% greater than those observed at the anterior body segments.

4.4.2 Combined effect on localised boundary air layer's evaporative resistance

It was observed that body movement has greater influence on the extremities such as the forearm, hand, thigh, calf and foot than on the torso. At high wind speeds, body movement has very little effect on the localised evaporative resistance. At higher walking speeds, the wind has a smaller effect than at lower walking speeds. This trend became even more obvious at the body extremities such as the hands, feet, thigh, and arms. These findings are line with the findings of Havenith *et al.* (1990), where the changes of clothing vapour resistance with posture, movement and wind were investigated on human subjects.

4.4.3 Combined effect on localised clothing evaporative resistance

The relation between air velocity, walking speed, and fabric weight and correction factors for localised clothing evaporative resistance was determined by multiple non-linear regressions. The correction equation can be written as

$$R_{etr} = Corr \times R_{et} = \exp \left\{ \left(a \times (v_a - 0.13) + b \times (v_a - 0.13)^2 + c \times w + d \times w^2 \right) \times W_f^e \right\} \times R_{et} \quad \text{Eq.(4-3)}$$

where, a , b , c , d and e are coefficients; v_a is the wind speed relative to the manikin inside the climatic chamber, m/s (range: 0.13-0.71 m/s); w is the walking speed, m/s, (range:0-1.17 m/s); W_f is the fabric weight (range: 179-239 g/m²).

The coefficients a , b , c , d and e , correlation factor R^2 , and SEE (standard errors of the estimate) values for each local body segment are displayed in Table 4.1.

Table 4.1 Coefficients, correlation factors and SEE values of the reduction equations (localised clothing evaporative resistance).

Segment	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>R</i> ²	<i>SEE</i>
Chest	-0.013	-0.050	-0.003	-0.003	0.686	0.960	0.037
Shoulders	-1.469	-1.468	-0.488	-0.167	-0.066	0.976	0.029
Stomach	-17.970	-31.213	-32.990	24.598	-0.423	0.948	0.054
Back	-2.376	0.410	-2.356	1.560	0.037	0.947	0.051
Upper arm	0.025	-0.592	-0.440	0.320	0.341	0.892	0.073
Forearm	-0.320	0.350	-0.041	-0.023	0.412	0.949	0.043
Waist	-6.574	-21.618	-10.284	5.484	-0.353	0.909	0.069
Hip	-0.810	-3.425	-3.446	2.475	0.032	0.969	0.042
Thigh	0.035	-0.333	-0.226	0.137	0.464	0.966	0.046
Calf	-0.069	-0.350	-0.369	0.147	0.230	0.952	0.050

Moisture transfer became more complex when clothing ensembles were involved. The clothing ventilation caused by body posture, body movement, wind, air gap and apertures of clothing (open/close) can greatly affect localised clothing evaporative resistance. The observed reductions at the limbs such as upper arm, forearm, thigh and calf were greater than those generated by the empirical equation given in the ISO 9920 (2007) standard. On the other hand, reductions at some local body segments, such as the chest and shoulders, were smaller than those produced by this equation. Therefore, the empirical equation (i.e., Eq.38) presented in the ISO 9920 (2007) standard may not be suitable for estimating localised clothing evaporative resistance. The empirical equations presented in this study provide a good alternative for its estimation.

The conclusion of **Paper IV** was that the local moisture transfer property inside clothing should be characterised by localised evaporative resistance rather than by clothing total evaporative resistance. The total evaporative resistance provided very limited information. In addition, the localised resultant evaporative resistance caused by air and body movement varied considerably, which depended on local body shape, position and local ventilation characteristics. It was thus concluded that the localised evaporative resistance was important for the study of local body thermal comfort and for human-clothing-environment modelling.

4.5 Application of clothing evaporative resistance in the PHS model (Papers V and VI)

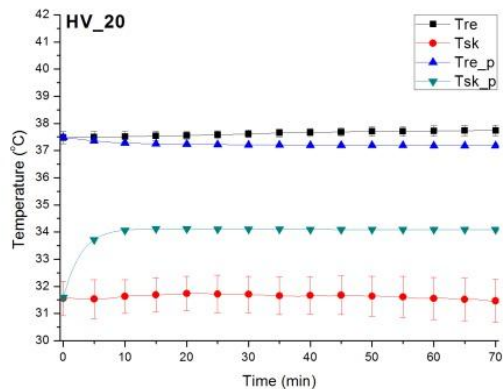
4.5.1 Comparison of predicted and observed physiological data

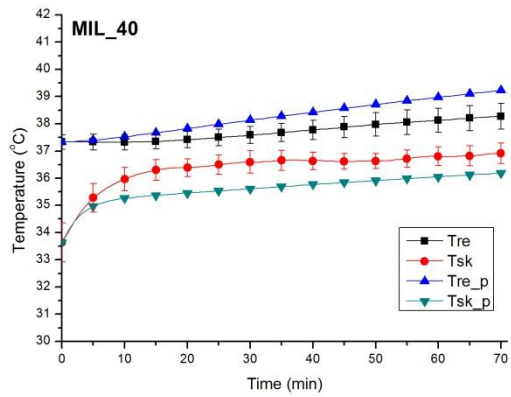
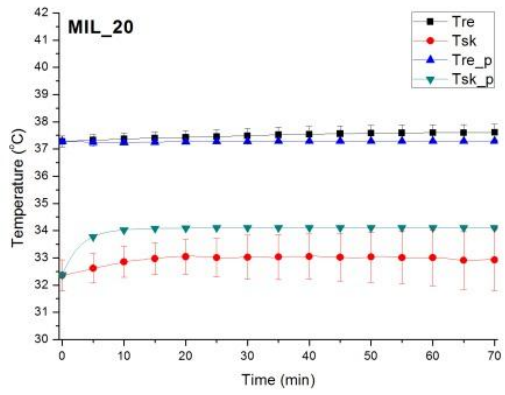
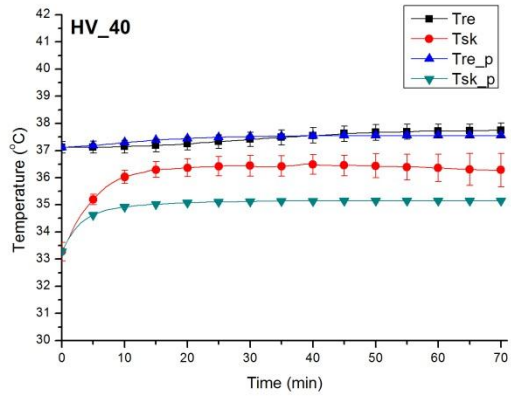
A PHS model program developed by Malchaire (2009, version 26-3-09) was used in **Paper V**. In the study presented in **Paper VI**, this PHS program was firstly modified and later applied to generate predictions. The main modification was that the starting rectal and skin temperatures in the program were set equal to pre-exercise experimental values observed at each test scenario. In order to ensure that all input data were accurate, input values were precisely determined using relevant equipment.

The predicted sweat rates in clothing ensembles MIL, CLM and FIRE at both 20.0 and 30.0 °C were significantly greater than the observed values ($p<0.05$). In contrast, the predicted evaporation rates were significantly underestimated for all test scenarios except for clothing ensemble L and HV at WBGT=19.0 °C ($p<0.05$). Nevertheless, the predicted sweat rates in L and HV at those two temperatures were in close agreement with the experimental data. The sweat accumulation in HV, MIL, and CLM after 70 min in the warm and high humidity environment (i.e., 20.0 °C, RH=87%) were 53, 70 and 127 g, respectively (expressed as the percentage of produced sweat: 25.1, 29.6, and 43.6%). Similarly, for all clothing ensembles at 30.0 °C, the sweat accumulations were 92, 56, 78, 216 and 364 g for clothing ensembles L, HV, MIL, CLM and FIRE (expressed as the percentage of produced sweat: 22.1, 13.5, 17.9, 39.8, and 52.7%), respectively. No differences in sweat accumulation were registered in clothing ensembles L, HV and MIL at those two thermal environments. However, there was a much higher percentage of sweat accumulation in CLM and FIRE. At 40.0 °C, the subjects were significantly dehydrated during FIRE ($p<0.01$), with a mean body weight loss of 0.96 kg, which accounted for about 1.2 % of their total body weight. The predicted sweat rate during HV was significantly higher than the experimental data. The predicted

values in clothing MIL and FIRE fell within the observed range. The mean evaporation rate for all three clothing ensembles (i.e., HV, MIL, FIRE) remained at the same level. The predicted evaporative rate for all three scenarios was still much lower than the experimental data.

The PHS model (ISO 7933) demonstrated good performance in predicting the skin temperature for clothing MIL and CLM at both 20.0 and 30.0 °C. Nevertheless, there was a large discrepancy between the predicted and observed skin temperatures in light clothing such as HV. The predicted skin temperature curve showed an initial rate of rise much greater than the experimental data in the first 10 min, and then adopted a relatively constant temperature plateau. The predicted post-exercise skin temperature was 2.01 °C higher than the experimental data.





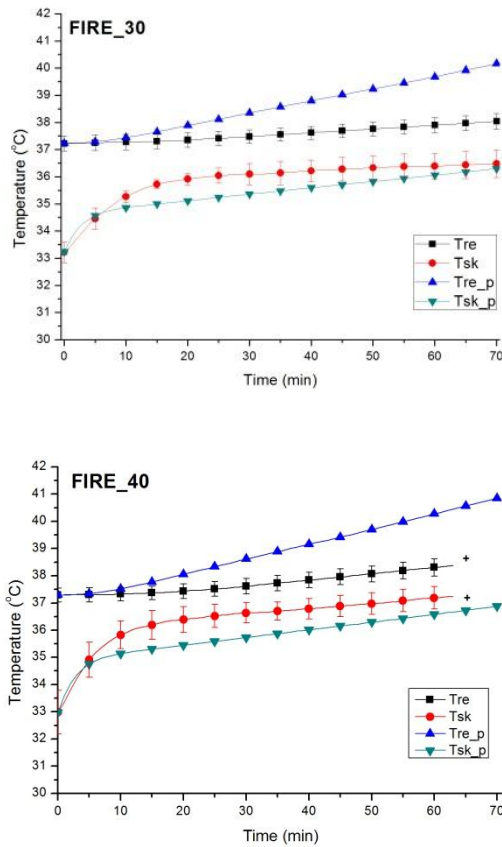


Fig.4.5 Some weak predictions generated by the PHS model. [Reprinted with permission]

The predicted rectal temperature curves in clothing ensembles MIL and CLM at 20.0 °C closely followed the experimental curves. However, for clothing HV at 20.0 °C, the post-exercise rectal temperature was 0.56 °C lower than the observed value (see Fig.4.5). Moreover, the predicted rectal temperature curves at 30.0 °C in clothing ensembles L, HV and MIL also showed good predictions; nevertheless, the predicted rectal temperature curves in CLM rose above the observed curve after about 45 min. Similarly, the predicted rectal temperature curve stayed above the still rising experimental curve after 15 min. Finally, the predicted post-exercise

rectal temperatures in CLM and FIRE at 30.0 °C were 0.92 and 2.12 °C higher than the observed values. In the hot environment (i.e., 40.0 °C), the predicted core temperature curves in HV and MIL followed the observed curves, although the initial rate of rise was slightly greater than experimental curves because different initial starting points were used. However, the core temperature prediction curve for FIRE showed a much greater rise than the observed curve. The predicted rectal temperature after 63 min was 1.8 °C higher than the observed value. For all predicted skin temperature curves at 40.0 °C, there was a much shallower rise during the first 30 min and the predicted values were continuously lower than the still rising observed curves.

Table 4.2 The RMSD and mean SD of experimental data.

T_a (°C)	20.0			30.0				40.0			
Cloth.	HV	MIL	CLM	L	HV	MIL	CLM	FIRE	HV	MIL	FIRE
RMSD (T_{re})	0.42	0.23	0.23	0.13	0.17	0.16	0.49	1.18	0.10	0.37	1.05
SD	0.17	0.26	0.24	0.26	0.18	0.23	0.39	0.27	0.26	0.36	0.28
RMSD (T_{sk})	2.39	1.09	0.51	0.47	0.29	0.23	0.45	0.56	1.21	1.01	0.92
SD	0.70	0.80	0.52	0.60	0.45	0.69	0.57	0.37	0.38	0.38	0.45

The root mean standard deviation (RMSD) was used to examine the prediction accuracy of the PHS model (see Table 4.2). Generally, if the RMSD is greater than the average mean standard deviation (SD) of the experimental data (i.e., RMSD>SD), the prediction will be treated as unreasonable. It can be deduced from Table 4.2 that the PHS model performed well in clothing ensemble CLM at 20.0 °C, and clothing ensembles L, HV and MIL at 30.0 °C. However, for the other 7 test scenarios, the PHS model generated either unreasonable rectal temperature or unreasonable skin temperature. In particular, the PHS model had both unreasonable rectal and skin temperatures for test scenarios involving FIRE at 30.0 and 40.0 °C. The reason was obvious: the thermal insulation of the

protective clothing FIRE lies well beyond the application range of the model (the PHS model has only a valid thermal insulation range of 0.1-1.0 clo). Since the PHS model excludes almost all protective clothing and people who wear such clothing are more often suffer great heat strain, there is a great need for the improvement of the PHS model in order to include such high insulation protective garments.

Although test scenarios such as HV at both 20.0 and 40.0 °C were well within the valid range of the PHS model, it still generated unreasonable predictions. One possible reason was that the skin temperature prediction formula used in the PHS model has the poorest and lowest correlation when a clothed subject exercised at a humidity level above 2.0 kPa (Mehnert *et al.* 2000). Thus, a further revision of the PHS model was required to gain better applicability and wider acceptance.

4.5.2 *Suggestions on further revision of the PHS model*

The **Paper V** (Wang *et al.* 2011b) has clearly demonstrated that the PHS model was inapplicable for protective clothing and those trials conducted in high humidity conditions (RH>80%). The model generated relatively conservative data on the evaporation rate and the duration limited exposure and thus, the worker's productivity was highly reduced. In order to maximise the worker's productivity but keep them safe, it is necessary to revise the current PHS model and extend its applicability. Firstly, the skin temperature equation was developed from a purely statistical manner; some clothing factors such as insulation, evaporative resistance and condensation were removed from the equation. Thus it cannot reflect all heat transfer characteristics (Sakoi *et al.* 2006). The low predictive ability of the skin temperature also introduced a large error into the calculation of the heat exchange between the human body and environments. Secondly, the calculation of the maximal evaporation rate in the PHS model was deduced from the water vapour pressure gradient between the skin surface and the environment and dynamic clothing evaporative resistance. This neglected the effect of absorbed sweat on

clothing. The liquid sweat may be absorbed by garments and transported from the skin surface to the outer clothing surface. Thus, the amount of liquid transported to the clothing outer surface should not be restricted by the clothing. The sweat also wet the clothing and reduced the resultant evaporative resistance. Consequently, the predicted evaporation rate was underestimated while the body core temperature was overestimated.

Clothing input data such as the thermal insulation and permeability index should not be taken from tables because such data were far from accurate. One of the most reliable ways was to measure such inputs on a sweating thermal manikin. However, it was suggested that the evaporative resistance could be used to replace the permeability index. In addition, a correction of the wind and body effects on dynamic evaporative resistance may be used. Similarly, the metabolic rate was usually taken from the reference table specified in ISO 7933 (2004). This kind of estimation may be inaccurate too. Previous studies showed that estimation of the metabolic rate can introduce an error of up to 60% (NIOSH 1986; ISO8996 [2004]; Dorman 2007). The best way was to measure the oxygen uptake using a cardiopulmonary instrument and the measurement error can be reduced to $\pm 5\%$.

5. Extended discussion

Currently, there are two international standards describing thermal manikin measurements or estimations of clothing evaporative resistance: ISO 9920 (2007) and ASTM F2370 (2010). ISO 9920 offers two basic estimation options: using tables with data determined on standing thermal manikins or deducing from thermal resistance through the Lewis relation. In addition, the measurement of clothing evaporative resistance on sweating manikins is summarised in this standard as an annex. However, no detailed test protocol is given. In contrast, the ASTM F2370 (2010) is the only standard presenting a detailed test protocol on manikin measurement of clothing evaporative resistance.

In the aforementioned two standards, many open details need to be clarified. Apart from the open issue on different sweating simulation options, how to select a reasonable calculation option between the two is not well described in the standard. Similar to calculation options listed in clothing thermal insulation standards (e.g., ISO 15831[2004]; EN 342[2004]), both the ISO 9920 and ASFM F2370 provide two calculation options. No recommendation has been made for researchers and industrial technicians on how to select one based on testing environment and tested garments. This definitely adds difficulty to select a reasonable value for both models and standards dealing with heat stress.

How to select a calculation option for clothing evaporative resistance measurements performed in a so-called isothermal condition was addressed in **Paper III**. It should be noted that conclusions were made from a purely physical point of view. Basically, evaporative resistance is an inherent physical parameter; it would always be good to have a baseline value. For measurements conducted in ‘real’ isothermal condition ($T_{sk,f}=T_a=T_r$), the mass loss and heat loss should generate the same value. Therefore, both methods can be selected for calculation. The value determined under such a condition should be reported by industrial

firms when informing the consumers. At present, it seems very difficult to create a real isothermal condition for sweating thermal manikins. All reported experiments have treated the so called condition of $T_{manikin}=T_a=T_r$ as an isothermal condition. It can be learnt from the **Paper III** that the mass loss option should be used for calculation because the heat loss option overestimated the evaporative resistance. However, from a physiological point of view, the mass loss method underestimated much more heat stress compared with the heat loss method. This is mainly because, in real cases, the evaporative heat used for sweat evaporation usually comes from both the environment and the body. Thus, if clothing evaporative resistance is intended to be used as an input in heat stress models, the isothermal heat loss method should be used.

Under non-isothermal conditions, complicated heat and mass transfer processes made comparison of the two calculation options even more difficult. Previous studies (Havenith *et al.* 2008a; Wang *et al.* 2009; Kuklane, Gao and Wang, personal communications 2011) have shown that the two calculation options may generate totally different values. Generally, the difference becomes even more obvious in impermeable clothing in cool environments (Havenith *et al.* 2008b). The mass loss method may produce a higher value than the heat loss method due to that it can only detect part of the heat loss leaving the manikin-clothing system. Nevertheless, the amount of moisture participating in condensation will not leave the clothing system but does take away heat from the thermal manikin to the environment. Therefore, the mass loss overestimates the heat stress from a physiological point of view.

In summary, the clothing evaporative resistance determined in a condition can only represent the garment characteristics at that specific condition. The data determined in some non-isothermal conditions may be treated as apparent evaporative resistance. Further, the mass loss method may not be suitable for calculating apparent evaporative resistance from a physiological point of view.

6. Conclusions

This thesis presents the results of extensive thermal manikin studies and human subject studies that were performed to describe clothing evaporative resistance measurements using sweating thermal manikins and its application in the heat strain model. The main findings of this thesis are summarised as follows:

- The use of manikin surface temperature instead of wet fabric skin temperature can introduce an error of up to 35.9% on the boundary air layer's evaporative resistance R_{ea} . In contrast, its use generated an error of up to 23.7% on the clothing total evaporative resistance R_{et} , which was dependent on the clothing intrinsic evaporative resistance R_{ecl} . It was also found that the prevailing calculation method for evaporative resistance causes greater error on permeable clothing than on impermeable clothing.
- The universal equation for the prediction of sweating skin temperature on the 'Tore' thermal manikin was $T_{sk,f}=34.0-0.0132HL$.
- Isothermal was the most preferred test condition for measurements of clothing evaporative resistance. From a physical point of view, the isothermal mass loss method was always the correct calculation option for calculating clothing evaporative resistance.
- Localised evaporative resistances at segments such as the hands, feet, and limbs were smaller than those at the torso such as the back, shoulders, waist, and chest.
- Localised convective heat transfer coefficients at the anterior body segments were much greater than those at the posterior body segments. Thus the localised evaporative resistances at the anterior segments were smaller than those at the posterior segments.
- Body movement has a greater influence on the extremities (such as the forearm, hand, thigh, calf and foot) than on the torso. At high wind speeds, body movement has very little effect on localised evaporative resistance. At higher walking speeds, wind has a smaller effect than at lower walking speeds.

- The reduction equations developed for localised clothing evaporative resistance have demonstrated that a total evaporative resistance value cannot always characterise the local clothing property. Thus, the localised value should be used instead of a total value when reporting results.
- The PHS model (ISO 7933) was not applicable for the prediction of core and skin temperatures for high insulation protective clothing. Although the predicted sweat rate was well within the observed ranges, the predicted evaporation rate was greatly underestimated.
- The PHS model (ISO 7933) should be revised by performing more human subject tests or applying sensitive mathematical equations in order to gain wide acceptance.

7. Future study

Most of the current thermal manikin technology on sweating simulation separates the fabric skin from the manikin controlling system, which means that the wet fabric skin surface temperature is always lower than the manikin surface temperature (due to water evaporation). A further step would be to establish a feedback system as a bridge between the wet fabric skin and the manikin controlling system. The local information on the wet skin can be obtained by embedding flexible temperature sensors and relative humidity sensors. The data collected from these temperature and RH sensors can be used as feedback. In addition, such a feedback system can also be used to control the skin wettedness. Since our bodies seldom have fully wet skin in our daily life and work, this improvement would be very useful in order to mimic different levels of the human skin wettedness.

Another future study will focus on creating a real isothermal testing condition by setting and regulating the wet fabric skin surface temperature to the air temperature and the mean radiant temperature ($T_{sk,f}=T_a=T_r$). In such a testing condition, both the heat loss option and mass loss option will be used to calculate clothing evaporative resistance, which in turn can be used as a reference value for both garment manufacturers and wearers. Such a test condition may also be deemed as the most ideal test environment for measurements of clothing evaporative resistance using a sweating thermal manikin.

More thermal manikin experiments are required to further improve the applicability of the empirical equations developed for localised clothing resultant evaporative resistance. More garments should be included in order to achieve better prediction accuracy on possible testing conditions. In order to extend the applicability of empirical equations developed in **Paper IV**, experiments in greater

wind speed environments need to be added because the normal outdoor air speed is above 1.0 m/s at most of workplaces.

Furthermore, a round robin study on the determination of clothing evaporative resistance using different sweating thermal manikins at different laboratories may be required to examine the data reproducibility. The same strict protocol would be used and preferably, the conduction of all measurement would be supervised by the same researcher together with local researchers at different laboratories.

Regarding the PHS model (ISO 7933), it should be further improved by conducting more human subject tests. The empirical equations such as the mean skin temperature prediction equation might be replaced by several equations for different situations. For instance, the equation when $T_{sk} < T_a$ should be different than when $T_{sk} > T_a$ because the radiative heat transfer direction is totally different under these two conditions. The predicted evaporation rate should also be improved because it is highly underestimated by the equation adapted in the model.

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Appendix I: Glossary of terms

Apparent total evaporative resistance

The total evaporative resistance of the garment, liquid barrier and boundary air layer determined under a condition that condensation may occur within the garment (non-isothermal conditions) or the total evaporative resistance of the wetted clothing by either sweat, water or rain and boundary air layer.

Boundary air layer's evaporative resistance

The evaporative resistance of the surrounding air layer on the sweating fabric skin surface of the nude thermal manikin measured under isothermal conditions.

Clothing area factor

The ratio of the surface area of a clothed human body to the surface area of the nude body. It may be determined by a photograph method or on a 3D body scanner.

Condensation

Condensation occurs when the temperature of a vapour is reduced below its saturation temperature (Cengel 2002). In real cases, condensation can be easily achieved by bringing the vapour into contact with a solid surface whose temperature is below the vapour's saturation temperature. Condensation may also occur on the free surface of a liquid or even in gases when the temperature of the liquid or the gas to which the vapour is exposed is below the vapour's saturation temperature.

Conduction

The energy transfers from the more energetic particles of an object to the adjacent less energetic ones as a result of interactions between the particles. It can take place in solids, liquids or gases. In solids conduction is driven by combinations of molecules' vibration in a lattice and the energy is transported by free electrons. In contrast,

conduction occurs in liquids and gases due to collisions and diffusion of the molecules during their random motion.

Convection

The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion. It involves the combined effects of conduction and fluid motion.

Intrinsic evaporative resistance

The resistance to transport moisture vapour from one side of the garment to another side with a lower water vapour pressure (normally determined under isothermal conditions).

Localised/regional evaporative resistance

The clothing segmental evaporative resistance determined on the multi-segment sweating manikin.

Localised resultant evaporative resistance

The clothing localised evaporative resistance determined on a sweating thermal manikin under a condition where air and/or body movement is involved.

Radiation

Electromagnetic radiation emitted from a heat or light source due to its temperature. It consists of ultraviolet, visible and infrared radiation.

Resultant evaporative resistance

The clothing evaporative resistance determined on the sweating thermal manikin at a condition where air and/or body movement is involved.

Total evaporative resistance

The clothing evaporative resistance of the garment and the boundary air layer around the sweating thermal manikin determined under isothermal conditions.

Effect of temperature difference between manikin and wet fabric skin surfaces on clothing evaporative resistance: how much error is there?

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Abstract Clothing evaporative resistance is one of the inherent factors that impede heat exchange by sweating evaporation. It is widely used as a basic input in physiological heat strain models. Previous studies showed a large variability in clothing evaporative resistance both at intra-laboratory and inter-laboratory testing. The errors in evaporative resistance may cause severe problems in the determination of heat stress level of the wearers. In this paper, the effect of temperature difference between the manikin nude surface and wet textile skin surface on clothing evaporative resistance was investigated by both theoretical analysis and thermal manikin measurements. It was found that the temperature difference between the skin surface and the manikin nude surface could lead to an error of up to 35.9% in evaporative resistance of the boundary air layer. Similarly, this temperature difference could also introduce an error of up to 23.7% in the real clothing total evaporative resistance ($R_{et,real} < 0.1287$ kPa m²/W). Finally, it is evident that one major error in the calculation of evaporative resistance comes from the use of the manikin surface temperature instead of the wet textile fabric skin temperature.

Keywords Evaporative resistance · Thermal manikin · Heat stress · Thermoregulatory model · Wet fabric skin temperature

Introduction

Protective clothing ensembles can greatly impede the heat exchange by sweat evaporation, one of the most important mechanisms that regulate a human body core temperature in hot environments. A vital limiting inherent factor of the clothing is its evaporative resistance. For the same amount of external work load, the greater the evaporative resistance of the clothing worn, the lesser the ability to cool the human body by sweat evaporation. Further, an evaporative resistance value means that a rational method, such as the predicted heat strain (PHS) model, can be used to assess the heat stress exposure (ISO 7933 2004; Malchaire 2006). Moreover, the evaporative resistance is used to calculate the body heat balance and model the heat exchange between the human body and its environment. Finally, such modelling can provide useful information about the rate of the body core temperature rise and the heat exposure safety time limit (Fiala et al. 1999; Gonzalez et al. 1997; Kellett et al. 2001).

Currently, there are three main approaches to measure the evaporative resistance of a piece of textile fabric or a garment (ASTM 2009, 2010; Holmér and Elnäs 1981; ISO 11092 1993): sweating guarded hotplate, sweating thermal manikin and human subjects. A previous study (Ross 2005) has clearly demonstrated that the thermal manikin measurement provides a more realistic value than that determined by a sweating guarded hotplate. This is mainly because the thermal manikin test could evaluate the effect of garments' boundary air layers and examine the contribution of clothing design features to the clothing evaporative resistance. The third approach mentioned above can be achieved by measuring the water vapour pressure gradient between the human skin and ambient air and the steady state rate of the evaporative heat loss (Holmér and Elnäs 1981). However, human trials are costly, and ethical issues

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are always involved. Therefore, the sweating thermal manikin is a perfect intermediate tool to bridge the gap between the sweating hot plate and physiological testing.

A round-robin laboratory study on measurement of clothing evaporative resistance using different sweating thermal manikins has revealed a large variability in both intra- and inter-laboratory studies (McCullough 2001; Richards and McCullough 2005). The intra-laboratory repeatability of clothing intrinsic evaporative resistance was 0.002–0.005 kPa m²/W for relatively permeable clothing. For impermeable clothing, the variability was 0.059–0.086 kPa m²/W. The inter-laboratory reproducibility of intrinsic evaporative resistance for permeable clothing was 0.010–0.018 kPa m²/W (i.e., 6–17% of the averaged values), and 0.207–0.219 kPa m²/W (i.e., 39–46% of the mean values) for impermeable clothing ensembles. Those large discrepancies might be reasonably attributed to the limited capacity of climatic chambers, different manikin configurations, various sweating simulation methods and differences in detailed test setups and protocols.

Although ASTM (2010) specifies that the calculation of clothing evaporative resistance should be based on the wet skin surface temperature rather than the manikin nude surface temperature, laboratory testing seldom measures the wet textile skin surface temperature by using sensors attached to the wet textile skin surface. It seems that the prevailing calculation on clothing evaporative resistance is based on the thermal manikin surface temperature (Wang et al. 2010). This might be attributed to the technical difficulty and complexity in putting temperature sensors on a wet textile fabric surface. In addition, the distance between wet textile fabric skin surface and the sensing point of the sensor greatly influences the observed temperature values (Fan and Chen 2002). Moreover, those values are highly dependent on the tightness of sensor attachment and which side of the temperature sensor is against the textile skin. Hence, very little work has been published on attaching temperature sensors to the wet textile fabric surface to measure its surface temperature. Recently, we conducted a series of skin experiments and developed a universal empirical equation to predict the wet textile skin surface temperature (Wang et al. 2010). It was found that the prevailing calculation method generated higher values than those calculated from the wet textile skin surface temperature. The error introduced by the temperature difference between manikin surface and wet textile skin surface, however, has not been thoroughly investigated.

The main aim of this study was to examine the error in the temperature difference between the manikin nude surface and the wet textile surface and its effect on the evaporative resistance. The evaporative resistance of the boundary air layer was measured on a dry heated thermal manikin covered with a pre-wetted textile skin. In addition, the effect of the error

introduced by the temperature difference between the manikin and wet textile skin surfaces on clothing total evaporative resistance was analysed theoretically. Finally, some suggestions on how to improve the measurement accuracy of the clothing evaporative resistance are summarised.

Materials and methods

Calculation on evaporative resistance

At present, there is a single standard that describes the measurement of clothing evaporative resistance on a sweating thermal manikin (ASTM 2010; Huang 2007a). It specifies the configuration of the thermal manikin and the test protocol as well as the test conditions. The sweating simulation for thermal manikins is still open because of the limited techniques for sweating simulation. This standard describes two options to calculate clothing evaporative resistance: the heat loss option and the mass loss option. These two calculation options are determined by Eqs. (1) and (2).

Heat loss option:

$$R_{et} = \frac{(p_{sk} - p_a)A}{H_e} \quad (1)$$

Mass loss option:

$$R_{et} = \frac{(p_{sk} - p_a)A}{\lambda \frac{dm}{dt}} \quad (2)$$

where, R_{et} is the total evaporative resistance of the clothing, kPa m²/W; p_{sk} is the saturated water vapour pressure at the wet textile skin surface, kPa; p_a is the partial water vapour pressure in the environment, kPa; A is the wet textile skin surface area, m² (in this study, the surface area of the textile skin was assumed equal to the manikin surface area due to the textile skin is pretty thin and fits tightly over the manikin body); H_e is the observed evaporative heat loss from the manikin, W; λ is the heat of vaporization of water at the measured textile skin temperature, kJ/kg; the ratio of dm/dt is the evaporation rate of moisture leaving the manikin-clothing system, kg/h.

The saturated water vapour pressure at wet textile skin surface and the partial vapour pressure in the air can be expressed by the so-called Antoine's equation (e.g.s. Huang 2007b; Parsons 2003)

$$p_{sk} = 0.1333 \times \exp\left(18.6686 - \frac{4030.183}{t_{sk} + 235}\right) \quad (3)$$

$$p_a = 0.1333 \times \exp\left(18.6686 - \frac{4030.183}{t_a + 235}\right) \times RH_a \quad (4)$$

where, t_{sk} is the mean fabric skin temperature, °C; t_a is the air temperature, °C; RH_a is the relative humidity in the ambient air, %.

In order to examine the effect of temperature difference between the manikin surface and the wet textile skin surface on clothing evaporative resistance, two evaporative resistances were calculated. One was calculated based on the thermal manikin nude surface temperature (i.e., the prevailing method), and another was based on the wet textile skin temperature (i.e., the real evaporative resistance).

Test procedures

Twenty-two wet tests were conducted on a thermal manikin 'Tore' (Wang et al. 2009) to examine the effect of temperature difference between the manikin nude surface and wet skin surface on the evaporative resistance. Fourteen dry tests were performed to measure the dry heat losses under non-isothermal conditions (i.e., $t_a = 30.0, 25.0,$ or 20.0°C). All dry and wet experiments were repeated twice in each environmental condition, with the results averaged. For wet skin experiments to determine the evaporative resistance of the boundary air layer, the manikin was covered with a knit cotton fabric skin (fabric mass per unit area: 228 g/m^2) and wetted with tap water to simulate sweat-saturated skin. There were no coverings on the manikin's head, hands and feet. Thus, the total sweating surface area was 1.426 m^2 . The manikin surface temperature was controlled at 34.0°C (accuracy: $\pm 0.1^\circ\text{C}$). The total or dry heat loss from the thermal manikin was continuously recorded by a MS DOS program (Nilsson 2004). The heat loss option (i.e., Eq. (1)) was used to calculate the evaporative resistance.

Our recent thermal manikin studies (Wang et al. 2010) have demonstrated that there was no significant temperature difference between the wet textile skin inner surface and its outer surface. By attaching sensors on the manikin surface using waterproof surgical tapes (3M, USA) to measure the wet skin inner surface temperature, measurements are simplified but the accuracy is maintained. Thus, in this study, 12 temperature sensors (Sensirion SHT75, Switzerland; temperature accuracy: $\pm 0.3^\circ\text{C}$; RH accuracy: $\pm 1.8 \%$; response time: 8 s) were placed at 12 different manikin body sites (left upper arm, left lower arm, right lower arm, right upper arm, right scapula, right lower chest, left upper chest, left lower buttocks, right shin, left calf, right posterior thigh, and left anterior thigh) to measure the wet textile fabric skin inner surface temperature. The size of the temperature sensor is $6.4 \times 3.7 \times 3.1 \text{ mm}^3$ (length \times width \times thickness). The thermistor sensing point was faced to the wet fabric skin side. Thus, the measured value comes from the wet

fabric skin side. Three temperature and RH integrated sensors (Sensirion SHT75, Switzerland) set at heights of 0.1, 1.1 and 1.7 m were used to monitor the ambient temperature and relative humidity in the climatic chamber. The air inlets in the climatic chamber are from the mesh ceiling and air outlets are through the lower mesh part of one side wall. The air velocity for all dry and wet experiments was maintained at $0.33 \pm 0.09 \text{ m/s}$. The test conditions are illustrated in Table 1.

Statistical analysis

The Repeated Measures ANOVA (Analysis of Variance) was applied for within-subject comparison of the effect of temperature difference on the evaporative resistance. This was performed on the software SPSS version 16.0 (SPSS, Chicago, IL, USA). The statistical significance level was set at $P < 0.05$.

Results and discussion

Evaporative resistance of the boundary air layer

The calculated evaporative resistance values of the boundary air layer are displayed in Fig. 1. The observed wet textile skin temperatures were $0.46\text{--}3.47^\circ\text{C}$ lower than the manikin nude surface temperature (e.g. Fig. 2a–c) because of the water evaporation (in non-isothermal conditions, dry heat loss also contributes to those reductions). As expected, the real evaporative resistances

Table 1 Eleven test conditions used in the wet skin study

t_a (°C)	RH_{real} (%)	P_{real} (Pa)	V_a (m/s)
34.0	39.2	2,085	0.33 ± 0.09
	44.3	2,356	
	53.1	2,825	
	72.0	3,830	
30.0	55.1	2,338	0.33 ± 0.09
	59.2	2,512	
	69.0	2,927	
25.0	61.4	1,944	0.33 ± 0.09
	70.1	2,220	
20.0	51.5	1,203	0.33 ± 0.09
	70.3	1,643	

The water vapour pressure in the climatic chamber was calculated from the temperature and RH values. It should be noted that the RH value set on the control panel should not be used to calculate clothing evaporative resistance. Otherwise, it may generate a large error on the calculated evaporative resistance. RH_{real} The real observed RH value in the climatic chamber, P_{real} the real water vapour pressure in the climatic chamber, V_a the air velocity in the climatic chamber

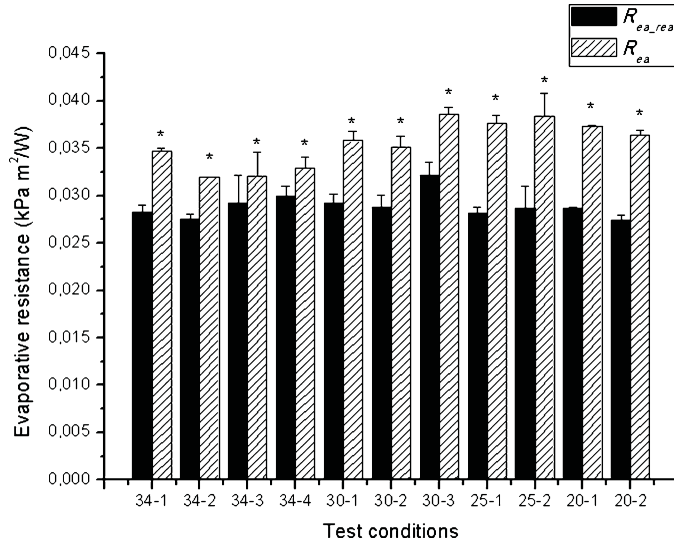


Fig. 1 The evaporative resistances of the boundary air layer calculated from the manikin nude surface temperature and the wet textile skin surface temperature (by the heat loss option). R_{ea_real} The real evaporative resistance of the air layer calculated from the wet skin

surface temperature; R_{ea} the evaporative resistance of the air layer calculated from the manikin nude surface temperature; 34, 30, 25 and 20 are ambient temperatures (°C); 1, 2, 3 and 4 are the set partial water vapour pressures in the climatic chamber (kPa); * $P < 0.05$

were much lower than the calculated evaporative resistances from the manikin nude surface temperature. The mean real evaporative resistance of the boundary air layer was 0.0287 kPa m²/W. The averaged evaporative resistance calculated from the manikin surface temperature was 0.0355 kPa m²/W. The statistical results showed a highly significant difference between the real evaporative resistances and evaporative resistances calculated from the manikin surface temperatures ($P < 0.001$, Partial Eta Square = 0.887, $n = 22$). The calculation based on the manikin nude surface temperature produced errors on the evaporative resistance ranged from 9.9 to 35.9%.

McCullough (2001) published a previous inter-laboratory study report on the determination of clothing evaporative resistance using six different sweating thermal manikins. In this report, the evaporative resistance of the boundary air layer around the nude manikin ranged from 0.011 to 0.020 kPa m²/W for four laboratories except the other two laboratories at the North Carolina State University (NCSU, NC) and VTT Technical Research Centre in Finland. The two laboratories at NCSU and VTT used the same type of manikin that did not sweat in the head, hands and feet. The evaporative resistances of the boundary air layer were accordingly slightly higher at 0.032 kPa m²/W. Similarly, the sweating thermal manikin 'Tore' used in this study also did not sweat in the head, hands and feet. The mean real

evaporative resistance of the boundary air layer presented in our study stays below this value.

Clothing total evaporative resistance

The clothing total evaporative resistance R_{et} is the sum of the clothing intrinsic evaporative resistance R_{ecl} and the evaporative resistance of the boundary surface air layer R_{ea} (ASTM 2010), which is expressed by Eq. (5). The unit is kPa m²/W.

$$R_{et} = R_{ecl} + \frac{R_{ea}}{f_{cl}} \quad (5)$$

where, f_{cl} is the clothing area factor, non-dimensional.

Similarly, the real clothing total evaporative resistance R_{et_real} (the total evaporative resistance calculated from the wet fabric skin surface temperature, kPa m²/W) is defined by Eq. (6):

$$R_{et_real} = R_{ecl} + \frac{R_{ea_real}}{f_{cl}} \quad (6)$$

It is assumed that the clothing intrinsic evaporative resistance R_{ecl} is a constant value and also, that the measurement of clothing total evaporative resistance on a sweating thermal manikin will not introduce further errors on R_{ecl} . Therefore, the error introduced by the temperature

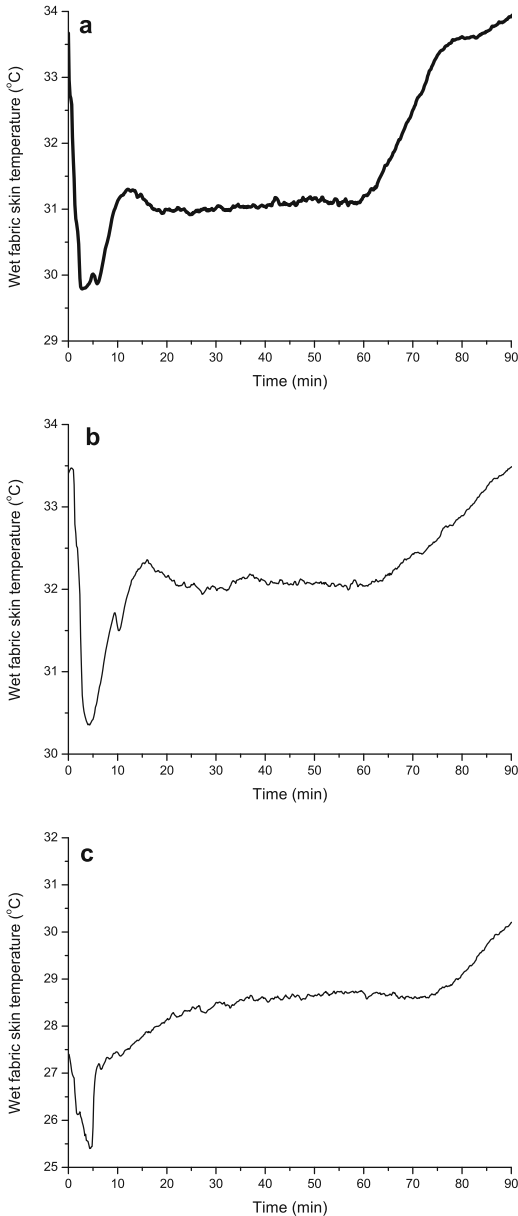


Fig. 2 The mean inner surface temperature of the wet textile fabric skin at different test conditions. **a** Isothermal condition, $t_a=34.0^\circ\text{C}$, $RH=44.3\%$; **b** non-isothermal condition, $t_a=30.0^\circ\text{C}$, $RH=59.2\%$; **c** non-isothermal condition, $t_a=20.0^\circ\text{C}$, $RH=51.5\%$. The wet textile fabric skin started to dry out after about 50 min. Thus, only the stable-state data (e.g. 30 min data) can be used for the calculation

difference between the wet fabric skin and manikin surface on clothing evaporative resistance can be calculated by Eq. (7).

$$Err = \frac{(R_{et_real} - R_{et})}{R_{et_real}} \quad (7)$$

By using Eqs. (5) and (6) and the two calculated mean evaporative resistances of the boundary air layer (i.e., $R_{ea}=0.0355 \text{ kPa m}^2/\text{W}$, $R_{ea_real}=0.0287 \text{ kPa m}^2/\text{W}$), Eq. (7) can be written as

$$Err = \frac{|R_{ea_real} - R_{ea}|}{R_{ecf_{cl}} + R_{ea_real}} = \frac{0.0068}{R_{ecf_{cl}} + 0.0287} \times 100\% \quad (8)$$

Many previous studies (Caravello et al. 2007; McCullough et al. 1989; McCullough 2001; McCullough and Kenney 2003; Richards and McCullough 2005; Wang et al. 2010) have demonstrated that the total evaporative resistance of most permeable and semi-permeable vocational clothing was below $0.10 \text{ kPa m}^2/\text{W}$. Based on these findings, we assume that the intrinsic evaporative resistance of most clothing ensembles ranged from 0 to $0.10 \text{ kPa m}^2/\text{W}$, and the corresponding clothing area factor ranged from 1.0 to 1.5 (McCullough et al. 1989). Thus, one has

$$0 < R_{ecf_{cl}} \cdot f_{cl} \leq 0.15 \quad (9)$$

Finally, the solution of Eq. (8) is given by

$$3.8\% \leq Err < 23.7\% \quad (10)$$

It is evident that the prevailing calculation based on the manikin nude surface temperature overestimates the real clothing total evaporative resistance by up from 3.8 to 23.7%. It should also be noted that the prevailing calculation generates a much larger error on permeable clothing than semi-permeable clothing or impermeable clothing. This is because the permeable clothing ensembles have low intrinsic evaporative resistance values. For impermeable clothing such as chemical protection clothing, the error introduced by the temperature difference might be neglected due to it having a relative high intrinsic evaporative resistance (i.e., the measured value could be $0.50 \text{ kPa m}^2/\text{W}$ or even higher; e.g. Gao and Holmér 2006).

Generally, the required ambient air temperature could be attained rapidly and be accurately maintained by the current climatic chamber technology ($\pm 0.5^\circ\text{C}$). The ability of relative humidity control in the climatic chamber is mainly determined by the capacity of the dehumidifying and humidifying equipment in the chamber controlling system. In addition, the total and dry heat losses (or the mass loss rate) from the thermal manikin could be measured accurately by the manikin control program (or a weighing scale with a high enough accuracy, e.g. $\pm 1 \text{ g}$). The evaporative heat loss could be calculated by deducting the dry heat loss from the total heat loss. Therefore,

it can be easily deduced that major errors in calculating clothing evaporative resistance come from the measurement of wet skin surface temperature and the control accuracy of the RH value in the climatic chamber.

Conclusions

In summary, the wet textile skin temperature at each sweating thermal manikin's body segment should be measured by at least one temperature sensor in order to reduce the calculation error on clothing evaporative resistance. Also, better measurement techniques in testing the wet textile skin temperature will be available in the future, e.g. flexible distributed temperature sensors embedded in the textile fabric skin. The measurement accuracy will definitely be further enhanced if such solutions are available. The RH value in the climatic chamber should be measured by at least two RH sensors. Additionally, wet experiments must be performed in a climatic chamber where the RH value can be controlled within a reasonable range of the control value ($\pm 5\%$). The two calculation options presented in Eqs. (1) and (2) must be chosen according to the test conditions (Havenith et al. 2008). Moreover, clothing ensembles with different permeability properties need different test durations because the time taken by different clothing ensembles to reach the equilibrium condition is different (Gao and Holmér 2006). Finally, the determination of clothing evaporative resistance is a complicated process, and one of the main errors comes from the calculation of evaporative resistance using the manikin surface temperature.

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Conflict of interest The authors declare no conflict of interest.

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Development and validity of a universal empirical equation to predict skin surface temperature on thermal manikins

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ABSTRACT

Clothing evaporative resistance is an important input in thermal comfort models. Thermal manikin tests give the most accurate and reliable evaporative resistance values for clothing. The calculation methods of clothing evaporative resistance require the sweating skin surface temperature (i.e., options 1 and 2). However, prevailing calculation methods of clothing evaporative resistance (i.e., options 3 and 4) are based on the controlled nude manikin surface temperature due to the sensory measurement difficulty. In order to overcome the difficulty of attaching temperature sensors to the wet skin surface and to enhance the calculation accuracy on evaporative resistance, we conducted an intensive skin study on a thermal manikin 'Tore'. The relationship among the nude manikin surface temperature, the total heat loss and the wet skin surface temperature in three ambient conditions was investigated. A universal empirical equation to predict the wet skin surface temperature of a sweating thermal manikin was developed and validated on the manikin dressed in six different clothing ensembles. The skin surface temperature prediction equation in an ambient temperature range between 25.0 and 34.0 °C is $T_{sk} = 34.0 - 0.0132HL$. It is demonstrated that the universal empirical equation is a good alternative to predicting the wet skin surface temperature and facilitates calculating the evaporative resistance of permeable clothing ensembles. Further studies on the validation of the empirical equation on different thermal manikins are needed however.

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1. Introduction

Skin is the largest external organ of the human body. It consists of several layers and protects the human body when the environmental temperature is within the normal physiological range (Xu et al., 2008). Skin surface temperature is one of the most important parameters in heat exchanges between the human body and its environment. The level of skin surface temperature affects the heat and mass transfer by convection, radiation and evaporation (Mairiaux et al., 1987). Therefore, skin temperature plays a fundamental role in thermoregulation (Lichtenbelt et al., 2006). The prediction of skin surface temperature is very important for the human heat balance. Similar to human beings, the skin surface temperature of a sweating thermal manikin directly determines the clothing evaporative resistance, one of the most important parameters used in thermal comfort models.

Thermal manikins have served research and development purposes for about 70 years (Holmér, 2004). It is well known that thermal manikins are one of the most ideal instruments for

measuring the thermal insulation and evaporative resistance of clothing ensembles. The calculations of clothing thermal insulation and evaporative resistance require the skin surface temperature (EN ISO 15831, 2004; ASTM F 2370, 2005). Currently, there is only one reported thermal manikin can measure the clothing thermal insulation and evaporative resistance in one step (Fan and Chen, 2002). Most of the other thermal manikins require two steps to determine clothing evaporative resistance under non-isothermal conditions, a dry test and a wet test (Wyon, 1989; Richards and Mattle, 2002; Wang, 2008; Celcar and Meinander, 2008). For dry tests to determine clothing thermal insulation, a dry heated thermal manikin can be used to achieve this. However, to measure clothing evaporative resistance, a wet test is needed, and an additional fabric 'skin' should be put on top of the dry heated thermal manikin to simulate sweating. As it is the manikin's nude surface temperature that is controlled, and not the wet fabric skin, the evaporation cooling of the wet skin layer may generate a big temperature difference between the wet fabric skin surface and the controlled nude manikin surface. It is anticipated that this temperature difference is related to the total heat loss of the manikin in non-isothermal conditions (in isothermal conditions, the evaporative heat loss theoretically equals to the total heat loss, the dry heat loss might exist due to the temperature differences among the skin surface, manikin and

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the environment). To some extent, the accuracy of measurement of the wet skin fabric surface temperature determines the calculation accuracy of clothing evaporative resistance. However, no data have been published on putting temperature sensors on the wet skin surface to measure the actual skin surface temperature under a wide range of environmental conditions. Informally, various laboratories have reported attempts at this using surface sensors (Redortier, Havenith, Ueno, Kuklane, Burke; personal communications at ICEE, 2007), but with limited success. Havenith (personal communication, 2008) studied this phenomenon using an infrared camera and developed some prediction equations, though this was not published either. In a recent skin study (Wang et al., 2010), we developed and validated an empirical equation to predict the skin surface temperature in an isothermal condition ($t_{\text{manikin}} = t_a = t_{\text{radiant}} = 34\text{ }^{\circ}\text{C}$) based on the total heat loss and the nude manikin surface temperature. However, the empirical equation should be extended to a wide range of ambient temperatures in order to get more applications. Thus, it was deemed more useful to perform a study to measure wet skin surface temperatures and develop a universal skin temperature prediction equation relating the wet fabric skin temperature to the nude manikin surface temperature and the total heat loss. Ideally, with such a skin equation, we could predict the wet skin surface temperature without even using temperature sensors, avoiding a lot of technical issues. In addition, such a skin temperature prediction equation could also be expected to predict the skin surface temperature for the wet skin with clothing ensembles worn on the top. Finally, the predicted wet fabric skin temperature could be used to calculate the clothing evaporative resistance.

In this paper, a well-fitted knit cotton fabric 'skin' was placed on top of a dry heated thermal manikin 'Tore' to simulate a skin wetted by sweating. The wet skin inner surface temperatures and outer surface temperatures were pre-measured on an undressed manikin by totally 18 temperature sensors at 34.0 and 25.0 °C. The temperature differences between the skin inner and outer surfaces were statistically compared and a suitable sensor attachment method was chosen for the tests conducted in the equation development and validation parts. A universal skin temperature empirical equation was developed based on the observed skin temperature, nude manikin surface temperature and the total heat loss at three different ambient temperatures: 34.0, 30.0 and 25.0 °C. Moreover, the empirical equation for skin surface temperature prediction was validated on the manikin while this was dressed in 6 different clothing ensembles. The calculated evaporative resistances of 6 clothing ensembles by 2 options (as shown later by options 2 and 4) were compared in order to check the practicability of the universal empirical equation. Finally, further studies on how to extend the application of the prediction equation to different types of thermal manikins were discussed.

2. Methods

2.1. Thermal manikin

A Swedish 17 segments thermal manikin 'Tore' was used in this study (Fig. 1). 'Tore' is made of plastic foam with a metal frame inside to support body parts and for joints (Kuklane et al., 2006). It is the size of an average Swedish male of 1980s. Its height is 170 cm, chest and waist circumferences are 94 and 88 cm, respectively, with a total heated body area of 1.774 m². The wire temperature sensors used for measuring nude manikin surface temperatures were evenly embedded on each area. The manikin surface temperature can be independently controlled,

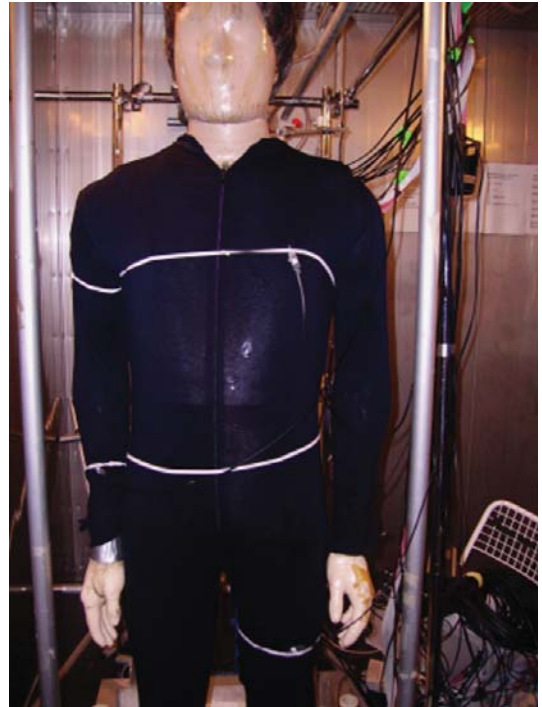


Fig. 1. The thermal manikin 'Tore' in the climatic chamber.

and the total heat input required to achieve this was recorded by a specially designed computer program. The heat input is a direct measure of the heat loss from the manikin (Wang, 2008; Havenith et al., 2008). The entire thermal manikin was placed in a climatic chamber, where various ambient conditions can be simulated.

2.2. Skin layer

A knit cotton fabric 'skin' (fabric mass per unit area: 228 g/m²) was used in this study. The skin was specially designed for the thermal manikin 'Tore' and fits it tight. Before each wet test, the cotton skin was rinsed in a washing machine (Electrolux W3015H, Sweden) for 4 min and then centrifuged 4 s to ensure water would not drip from the skin.

2.3. Temperature sensor

The CMOS type temperature sensors (Pin SHT75, Sensirion AG, Switzerland) were used to record the skin surface temperature values. The temperature accuracy is $\pm 0.3\text{ }^{\circ}\text{C}$. The size of a sensor is $6.4 \times 3.7 \times 3.1\text{ mm}^3$ (length \times width \times thickness). The temperature sensor and attachment are presented in Fig. 2. As to the thermistor point was faced to the skin inner surface side, the observed temperature values come from the wet skin inner surface rather than the nude manikin surface.

2.4. Test conditions

The skin tests presented in this paper consisted of three parts: the skin temperature comparison tests to determine the sensor attachment (on the skin surface or under the skin surface, totally

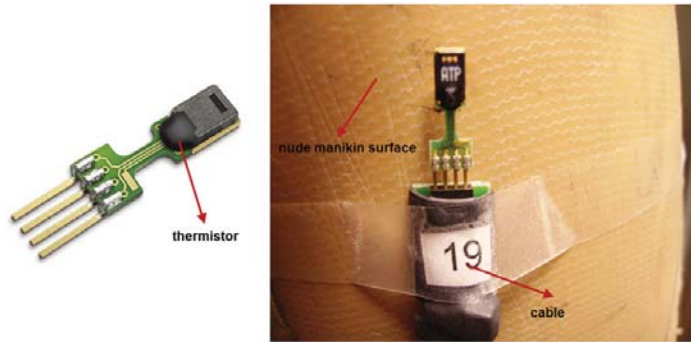


Fig. 2. The CMOS temperature sensor and a sensor attachment to the nude manikin surface.

Table 1
Test conditions (equation development and validation sections).

Temperature t_a (°C)	Equation development part			Equation validation part		
	RH (%)	P_a (kPa)	v_a (m/s)	RH (%)	P_a (kPa)	v_a (m/s)
34.0	25.6	1363	0.33 ± 0.09	46.4	2470	0.33 ± 0.10
	40.9	2177				
	52.5	2794				
	72.2	3843				
30.0	55.1	2333	0.33 ± 0.09	63.2	2726	0.33 ± 0.10
	59.2	2503				
	69.5	2927				
25.0	62.3	1963	0.33 ± 0.09	67.4	2164	0.33 ± 0.10
	70.1	2216				

4 tests), development tests of skin temperature prediction equations (18 tests) and validation tests on skin temperature prediction equations (16 tests). The nude thermal manikin surface temperature was set to 34.0 °C for all 38 tests. Three platinum air temperature sensors set at the height of 0.1, 1.1 and 1.7 m were used to record the ambient temperatures. The air inlets in the climatic chamber are from the mesh ceiling and air outlets are through the lower mesh part of one side wall. The skin temperature comparison tests were performed at two ambient temperatures, 34.0 °C, 40% RH and 25.0 °C, 45% RH. The air velocity was controlled at 0.33 ± 0.09 m/s. In the temperature comparison part, 18 digital temperature sensors were used to record the skin inner and outer surface temperatures. Twelve sensors were attached to the nude manikin surface at 12 positions (the left upper arm, left lower arm, right lower arm, right upper arm, right scapula, right lower chest, left upper chest, left lower buttocks, right shin, left calf, right posterior thigh and the left anterior thigh) using waterproof surgical tapes (3M, USA). Other six sensors were attached to the wet skin outer surface at 6 sites (the left anterior thigh, left upper chest, left lower buttock, right upper arm, right lower arm and the right upper back) using white thread rings (Resårband Gummilitze Elastic Braid, Sweden). The equation development and validation tests were conducted at three environmental conditions, where the ambient temperatures were 34.0, 30.0 and 25.0 °C, respectively. The RHs and partial water vapour pressures in the climatic chamber at these three temperatures are listed in Table 1. In the equation development and validation sections, 12 sensors were used to measure the skin inner surface temperatures. Furthermore, six different working clothing ensembles were selected to validate the empirical equation. The details of all 6 clothing ensembles are displayed in Table 2.

In the equation validation section, it was assumed that the RH on the wet skin surface was 100%. Eight thermal manikin validation tests in clothing ensembles L, HV, MIL and CLM were conducted at 34.0 °C and 46.4% RH. Other 8 validation measurements in two permeable and impermeable overalls were conducted at two environmental conditions: 30.0 °C, 63.2% RH and 25.0 °C, 67.4% RH. The air velocity for all 16 validation tests was controlled to 0.33 ± 0.10 m/s. Finally, the calculated total evaporative resistances of all 6 clothing ensembles by two calculation options (as shown later by options 2 and 4) were presented and compared.

2.5. Calculation of clothing evaporative resistance

ASTM F 2370 (2005) specifies the following two options to calculate the clothing evaporative resistance:

$$\text{Option 1 : } R_{et} = \frac{(p_{sk} - p_a)A}{H_e} = \frac{[(e^{18.956 - (4030.18/t_{sk} + 235)})RH_{sk} - (e^{18.956 - (4030.18/t_a + 235)})RH_a]A}{H_e}$$

$$\text{Option 2 : } R_{et} = \frac{(p_{sk} - p_a)A}{\lambda(dm/dt)} = \frac{[(e^{18.956 - (4030.18/t_{sk} + 235)})RH_{sk} - (e^{18.956 - (4030.18/t_a + 235)})RH_a]A}{\lambda(dm/dt)}$$

where, R_{et} is the total evaporative resistance of clothing ensemble, $kPa \text{ m}^2/W$; p_{sk} and p_a are the saturated and partial water vapour pressures at the manikin sweating skin surface and the environment, respectively, kPa ; A is the area of manikin's surface that is sweating, m^2 , for thermal manikin 'Tore', $A = 1.4257 \text{ m}^2$; H_e is the evaporative heat loss from the manikin, W ; t_{sk} and t_a are the sweating skin surface temperature and the air temperature, respectively, °C; RH_{sk} and RH_a are the relative humidities of the sweating skin surface and in the air, respectively, %; λ is the heat of vaporization of water at the measured skin surface temperature, W ; dm/dt is the evaporation rate of moisture leaving the manikin's sweating surface, kg/h .

Due to the difficulty of attaching sensors on the sweating skin surface and the limited sensory technology, the prevailing methods to calculate clothing evaporative resistance are

$$\text{Option 3 : } R_{et} = \frac{(p_{sk} - p_a)A}{H_e} = \frac{[(e^{18.956 - (4030.18/t_{manikin} + 235)})RH_{sk} - (e^{18.956 - (4030.18/t_a + 235)})RH_a]A}{H_e}$$

Table 2
Details of six clothing ensembles (the equation validation section).

Code	Garment components	W (g)	It (°Cm ² /W)
L	T-shirt, briefs, short pants, socks, sports shoes	1692	0.163
HV	T-shirt, briefs, long trousers with 3 M [®] reflective materials, socks, sports shoes	2211	0.186
MIL	Jacket, long trousers, net t-shirt, briefs, socks, sports shoes	2132	0.256
CLM	Polyamide overall laminated with Gore-tex [®] membrane, t-shirt, briefs, socks, sports shoes	3570	0.260
PERM	Permeable overall (hydrophobic layer laminated with inner PTFE membrane)	586	0.025 ^a
IMP	Impermeable overall (PA webbing coated with PVC)	680	0.007 ^a

Note: L: light series clothing; HV: high vision series clothing; MIL: military series clothing; CLM: climber series clothing; IMP, impermeable; PERM, permeable. W: total weight of the clothing ensemble; It: thermal resistance of clothing ensemble or fabric material.

^a The data come from the fabric material, which are measured on a sweating hot plate according to ISO 11092 (Havenith et al., 2008).

$$\text{Option 4: } R_{\text{et}} = \frac{(p_{\text{sk}} - p_a)A}{\lambda(dm/dt)}$$

$$= \frac{[(e^{18.956 - (4030.18/t_{\text{manikin}} + 235)})RH_{\text{sk}} - (e^{18.956 - (4030.18/t_a + 235)})RH_a]A}{\lambda(dm/dt)}$$

where t_{manikin} is the temperature on the nude thermal manikin surface, °C. For the thermal manikin 'Tore', it is the paint layer surface temperature. There are a resin covering heating wires, a copper layer and a paint layer on top of the plastic foam.

3. Results and discussion

3.1. Determination of temperature sensor attachment

The attachment of temperature sensors using thread rings to the wet skin outer surface was difficult and time consuming. The sensors should be attached to the skin outer surface before each test and removed after the test. On the other hand, the distance to the skin surface greatly affects the temperature values. Besides, the impermeable sticky tapes cannot be applied on the wet surface as they might restrict the evaporation and may malfunction when attached to the wet flat surface. It is also difficult to determine standard measurement points on the fabric skin surface for each separate test. An alternative to solve these problems is that all the sensors were attached on the nude manikin surface to measure the wet skin inner surface temperature. If no significant temperature differences were observed, then the measurement of the wet skin inner surface temperatures could be performed instead to replace its outer surface temperatures. For these reasons, we conducted a temperature pre-comparison study before the development of the skin empirical equations. Considering the temperature difference between inner and outer surfaces might be bigger at a low ambient temperature, we conducted 4 tests at both 34.0 and 25.0 °C. The main aims of the current study were to simplify the measurement and save the preparation time as the wet skin will dry out after 40–50 min. The comparison can also improve the measurement accuracy by keeping sensors in standard positions processed to the skin. In addition, the temperature data could be used to calculate the water vapour pressure on the skin surface, and the evaporative resistance of clothing ensembles could be determined accordingly.

The mean skin inner and outer surface temperatures were calculated based on each 3-min data during the stable state period of each test condition. The total sample size was 32. The paired-samples *t*-test was performed using SPSS (v.16.0, Chicago, IL, USA) to determine whether there are significant mean temperature differences between the skin inner surface and outer surface. The significant level was set at 0.05 and the *P* value [i.e., Sig (2-tailed)] was 0.350. Therefore, the null hypothesis should be accepted accordingly, i.e., there were no significant temperature differences between the wet skin inner surface and

outer surface. Therefore, the temperatures measured on the skin inner surface can be deemed as values measured on the skin outer surface. This simplifies the measurement and most important, the measurement accuracy is the same.

3.2. Development of equations to predict wet skin surface temperature

A special MS-DOS program (Nilsson, 2004) was used to record the total heat loss from the undressed manikin (only with the wet fabric skin). The temperatures and relative humidities of the wet skin inner surface were recorded every 10 s by the Sensirion program (Sensirion AG, Switzerland). The tests were performed twice at each test condition. The test stopped when an obvious decrease in the heat loss from the thermal manikin was observed. The data selected from the stable state of the test period were used for analysis. Based on the data of the thermal nude manikin surface temperature, wet fabric skin surface temperature and the total heat loss, a scatter chart with markers was plotted at each testing temperature. Considering the fact that the skin surfaces will not cool down if there is no evaporative heat loss, a linear regression equation with a forced point (0, t_{manikin}) was developed accordingly. The averaged nude manikin surface temperatures t_{manikin} was 34.0 °C. Hence, it is evident that the heating power provided for the thermal manikin 'Tore' could maintain the desired manikin surface temperature (i.e., 34.0 °C) at ambient temperatures ranged from 34.0 to 25.0 °C.

It can be deduced from Fig. 3 that the linear equation fits all 18 scatters well and the correlation factor *R* is 0.83. The universal skin temperature prediction equation developed at an environmental temperature range between 25.0 and 34.0 °C is defined as

$$T_{\text{sk}} = 34.00 - 0.0132HL \quad (1)$$

where T_{sk} is the mean skin surface temperature, °C; HL is the total sweating area heat loss from the thermal manikin, W/m².

Moreover, Havenith (personal communication, 2008) analysed wet skin surface temperatures of a thermal manikin 'Newton' (Havenith et al., 2008) by a thermal infrared camera immediately after stripping clothing. The skin temperature prediction equation on the thermal manikin 'Newton' at an ambient temperatures 34.0 °C was

$$T_{\text{sk}} = 34.13 - 0.012HL \quad (2)$$

3.3. Validity of skin temperature prediction equations

Two overalls and 4 working clothing ensembles were used in this section for the validation of the skin temperature prediction equations. The observed and predicted wet skin surface temperatures for each clothing ensemble at three different ambient temperatures were plotted in Fig. 4.

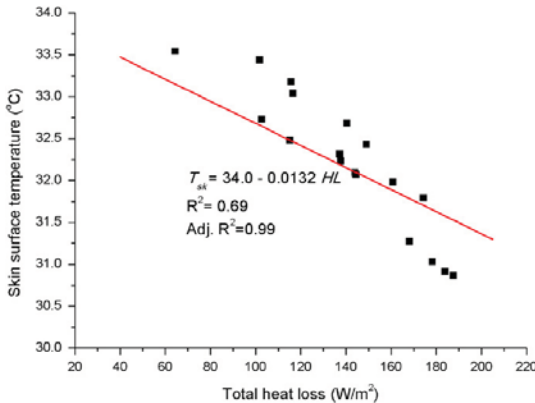


Fig. 3. The universal empirical equation for prediction of the wet skin surface temperature at an ambient temperature range between 25.0 and 34.0 °C (equation development part).

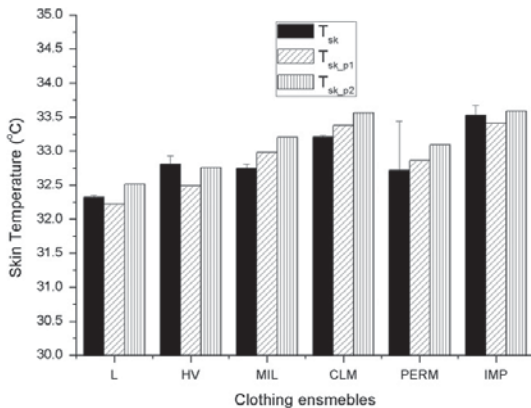


Fig. 4. Predicted and observed skin surface temperatures for 6 clothing ensembles (equation validation part). T_{sk} , the observed skin surface temperature; $T_{sk,p1}$, the predicted skin surface temperature by Eq. (1); $T_{sk,p2}$, the predicted skin surface temperature by Eq. (2).

The root mean squared deviation (RMSD) was used to compare the statistical evaluation between the predicted values and observed data. The RMSD is a frequently used measure of differences between values predicted by a model and the values actually observed from the thing being modelled or estimated (Castellani et al., 2007). The best prediction value is that which gives the minimal RMSD. The RMSD is defined as

$$RMSD = \sqrt{\frac{\sum_{i=1}^n x_i^2}{n}} \quad (3)$$

where x_i is the difference between the predicted and observed at each test condition; n is the number of comparisons.

The heat loss values observed from the thermal manikin ‘Tore’ during the stable state of the 12 validation tests ranged from 25.1 to 135.9 W/m². The RMSD values of those two empirical equations at each test are displayed in Table 3. Table 3 also presents the averaged standard deviation from the observed mean skin surface temperature over the time of each 16 test conditions. This provides the capability to examine the prediction accuracy of

Table 3

The calculated RMSD values for four prediction equations in each 16 test conditions (the equation validation section).

	Eq. (1)	Eq. (2)
L	0.105	0.195
Average mean SD	0.028	0.028
HV	0.319	0.083
Average mean SD	0.152	0.152
MIL	0.239	0.460
Average mean SD	0.064	0.064
CLM	0.176	0.362
Average mean SD	0.021	0.021
PERM	0.217	0.378
Average mean SD	0.067	0.067
IMP	0.179	0.150
Average mean SD	0.106	0.106

these two prediction equations. For the empirical Eq. (1), the RMSD values in all 6 clothing ensembles ranged from 1.54 to 8.32 times greater than the mean standard deviation. For Eq. (2), the RMSD values ranged from 0.69 to 17.0 times greater than the mean standard deviation. In general, the predicted temperature values from any model are more than two times greater than the mean standard deviation of the observed data which indicates that the prediction of the model fall outside of the 95% of an average population (Cadarette et al., 1999). The six test conditions with the most favourable comparisons between observed data and the estimated values with Eqs. (1) and (2) occurred in HV and IMP. However, the predicted values in other 4 test clothing ensembles from Eqs. (1) and (2) are 3.72 to 17.0 times greater than the mean standard deviation. From a statistical point of view, the prediction values by these two equations in clothing ensembles L, MIL, CLM and PERM are not accurate enough. In the real situation, considering the skin temperature values were recorded with a precision of ± 0.3 °C, agreement of predicted value with the observed data to this precision level would always be the acceptance accuracy. However, lesser level such as ± 0.5 °C of precision will also be useful. The predicted skin temperatures by Eq. (1) in L, HV and IMP were 0.10, 0.31 and 0.12 °C greater than the observed values, while the predicted data in clothing ensembles MIL, CLM and PERM were 0.23, 0.17 and 0.11 °C lesser than the observed data. All predicted values by Eq. (1) are well within acceptable levels. Similarly, the predicted skin temperatures by Eq. (2) in all clothing ensembles except HV were ranged 0.06–0.46 °C lesser than the observed temperatures. For clothing ensemble HV, the predicted temperature value was 0.04 °C greater than measured skin temperature. Thus, the developed empirical equation from another type of the thermal manikin could predict the wet skin temperatures within the ± 0.5 °C precision level. It should also be noted that Eq. (2) was developed based on only one ambient temperature (i.e., 34.0 °C). Higher accuracy on the predicted values is expected if the empirical equation could be developed based on a wide range of environmental conditions.

The total evaporative resistances of all 6 clothing ensembles calculated by options 2 and 4 are described in Fig. 5. The calculated clothing evaporative resistances by option 2 were ranged from 21.3 to 372.1 Pa m²/W. It is evident that the prevailing calculation method (i.e., option 4) produces greater values than the data calculated from the standard option listed in ASTM F2370 (i.e., option 2). In addition, the calculated mean evaporative resistances of all 6 clothing ensembles based on the predicted skin surface temperatures by Eqs. (1) and (2) are relatively good. Therefore, the accuracy of clothing evaporative resistance is highly enhanced by these two empirical equations.

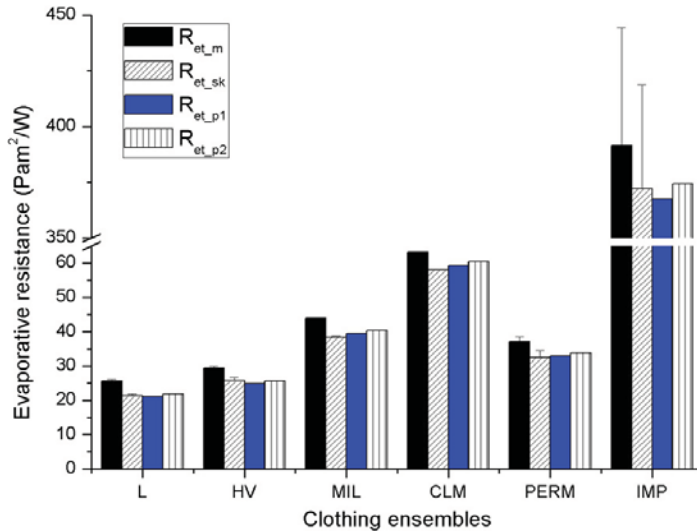


Fig. 5. The clothing evaporative resistances of 6 clothing ensembles calculated based on 4 different temperatures. $R_{et,m}$, the calculated evaporative resistance based on the prevailing method, i.e., option 4; $R_{et,sk}$, the calculated evaporative resistance by option 2; $R_{et,p1}$, the calculated evaporative resistance based on the predicted skin temperature by Eq. (1); $R_{et,p2}$, the calculated evaporative resistance based on the predicted skin temperature by Eq. (2).

In this study, a universal empirical equation for the prediction of sweating fabric skin surface temperature on a thermal manikin was developed and validated. It should be noted that the empirical equation was obtained from a specific thermal manikin. The prediction equations developed from different thermal manikins may be slightly different due to different data analysis and operation methods. Further interlaboratory studies will be performed on different thermal manikins by using the same temperature measurement technology and test protocol. In addition, the effect of wicking and condensation inside multi-layer clothing ensembles should be examined in order to enhance the prediction accuracy. A correction for the empirical equation might be needed at some specific test scenarios.

4. Conclusions

We developed a universal empirical equation for the prediction of wet fabric skin surface temperature of a thermal manikin 'Tore' in an ambient temperature range between 25.0 and 34.0 °C. The empirical equation was validated on 6 clothing ensembles under three different environmental conditions. It is evident from the acceptable precision levels that the empirical equation is a good alternative to predict the wet skin surface temperature for the thermal manikin dressed in various clothing ensembles. The empirical equation for prediction of sweating skin surface temperatures is $T_{sk} = 34.00 - 0.0132 HL$.

In this paper, we only validated the universal empirical equation on a specific thermal manikin. The empirical equation obtained from another thermal manikin showed a slightly low precision on the predicted skin temperature values. Future validation studies should therefore focus on other thermal manikins, such as the sweating thermal manikin Newton, and possibly on other types of fabric skins and extensions in wider ambient temperature ranges. Meanwhile, a further investigation might be needed to examine the effects of wicking and condensation on the predicted skin temperature at low ambient temperatures inside multi-layer clothing ensembles.

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Determination of Clothing Evaporative Resistance on a Sweating Thermal Manikin in an Isothermal Condition: Heat Loss Method or Mass Loss Method?

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This paper addresses selection between two calculation options, i.e. heat loss option and mass loss option, for thermal manikin measurements on clothing evaporative resistance conducted in an isothermal condition ($T_{\text{manikin}} = T_a = T_r$). Five vocational clothing ensembles with a thermal insulation range of 1.05–2.58 clo were selected and measured on a sweating thermal manikin ‘Tore’. The reasons why the isothermal heat loss method generates a higher evaporative resistance than that of the mass loss method were thoroughly investigated. In addition, an indirect approach was applied to determine the amount of evaporative heat energy taken from the environment. It was found that clothing evaporative resistance values by the heat loss option were 11.2–37.1% greater than those based on the mass loss option. The percentage of evaporative heat loss taken from the environment ($H_{e,\text{env}}$) for all test scenarios ranged from 10.9 to 23.8%. The real evaporative cooling efficiency ranged from 0.762 to 0.891, respectively. Furthermore, it is evident that the evaporative heat loss difference introduced by those two options was equal to the heat energy taken from the environment. In order to eliminate the combined effects of dry heat transfer, condensation, and heat pipe on clothing evaporative resistance, it is suggested that manikin measurements on the determination of clothing evaporative resistance should be performed in an isothermal condition. Moreover, the mass loss method should be applied to calculate clothing evaporative resistance. The isothermal heat loss method would appear to overestimate heat stress and thus should be corrected before use.

Keywords: ASTM F2370; evaporative cooling efficiency; evaporative resistance; heat stress; isothermal; thermal manikin

INTRODUCTION

Clothing acts as a moisture barrier between the wearer’s body and environment (Havenith *et al.*, 1999). With regard to heat stress, one of the most important physical parameters is its evaporative resistance (Bernard and Matheen, 1999; Fan and Chen, 2002; Holmér, 2006; Caravello *et al.*, 2008). The clothing evaporative resistance determines the amount of sweat evaporation from the wearer’s body to the surrounding environment

(Caravello, 2004). For any type of clothing ensemble, a low evaporative resistance value is always preferred to a high value (Wang, 2010). On the other hand, clothing evaporative resistance is needed in both heat strain prediction and thermoregulatory models (Kolka *et al.*, 1994; Gonzalez *et al.*, 1997; Gallagher, 2009). Such mathematical modelling could provide invaluable data on the development of body core temperature and thermophysiological duration limited exposure for industrial and occupational hygienists (Malchaire *et al.*, 2000; Besnard *et al.*, 2004; Cain, 2006).

Previous studies have demonstrated that inter- and intra-laboratory measurements of clothing thermal

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insulation on various dry heated thermal manikins are highly reproducible (Anttonen *et al.*, 2004; Kuklane *et al.*, 2005; Gao *et al.*, 2006). However, laboratory tests on the determination of clothing evaporative resistance showed a great variation among different types of sweating thermal manikins (McCullough, 2001; Richards and McCullough, 2005). Some possible reasons to account for the big discrepancy may include different sweating simulation methods, limited controlling capacity of climatic chambers, different manikin configurations, differences in detailed testing protocols, and calculation options (Richards and McCullough, 2005; Huang, 2007; Havenith *et al.*, 2008b; Wang *et al.*, 2010a,b). ASTM F2370 (2010) is the only published standard describing the determination of clothing evaporative resistance using a sweating thermal manikin. In this standard, two calculation options are provided: heat loss method (i.e. Option 1) and mass loss method (i.e. Option 2). Both methods require the water vapour pressure gradient between the sweating skin and ambient environment. The heat loss method uses the area-weighted real evaporative heat loss observed from the sweating thermal manikin to calculate evaporative resistance. The mass loss method calculates the mass loss rate first and then converts it to the evaporative heat loss by multiplying the latent heat of vapourization of water.

Very little investigative work has been published concerning the effect of different calculation methods on clothing evaporative resistance. Havenith *et al.* (2008a) pointed out that the isothermal heat loss method underestimated the evaporative heat loss. Thus, the evaporative resistance generated by this method was higher than the clothing evaporative resistance acquired by the mass loss option in the isothermal condition. If this value were used as an input in a heat strain/thermoregulatory model, the heat stress was overestimated (Havenith *et al.*, 2008a). However, up to now, the evaporative heat loss difference introduced by those two methods has not yet been thoroughly investigated. The reasons behind this evaporative heat loss difference in isothermal condition have not been discussed either.

In this paper, the clothing evaporative resistances calculated by two calculation options were compared and analysed. The amount of evaporative heat energy difference introduced by the heat loss method and by the mass loss rate was verified by thermal manikin measurements. Moreover, the percentages of evaporation heat taken from the manikin body and the ambient environment were calculated. Some suggestions on how to choose between those two calculation methods were finally discussed.

METHODS

Calculation of evaporative resistance

In an isothermal condition, there is no dry heat exchange (i.e. conductive, convective, and radiative heat losses are equal to zero) between the manikin surface and the environment because $T_{\text{manikin}} = T_a = T_r$ (the air temperature T_a equals to the manikin temperature T_{manikin} and both values equal to the radiant temperature T_r). Also, theoretically, condensation inside clothing will never take place. Therefore, the isothermal condition is the most preferable condition for measuring clothing evaporative resistance (Havenith *et al.*, 2008b; ASTM F2370, 2010). In such a condition, the clothing evaporative resistance could be calculated by isothermal heat loss method or mass loss method (ASTM F2370, 2010).

$$R_{\text{et,heat}} = \frac{\Delta p_{\text{iso}} \cdot A}{H_{\text{e,heat}}}, \quad (1)$$

$$R_{\text{et,mass}} = \frac{\Delta p_{\text{iso}} \cdot A}{H_{\text{e,mass}}} = \frac{\Delta p_{\text{iso}} \cdot A}{\lambda \cdot \frac{dm}{dt}}, \quad (2)$$

where $R_{\text{et,heat}}$ is the total clothing evaporative resistance calculated by the heat loss method, kilopascal square metres per watt; Δp_{iso} is the water vapour pressure gradient between the wet/sweating textile skin surface and in the environment at the isothermal condition, kilopascal; A is the sweating surface area, square metre; in this study, the pre-wetted skin's surface area was assumed to be equal to the manikin surface area because the skin is pretty thin and it fits tightly around the manikin body shape, $A = 1.4257 \text{ m}^2$. $H_{\text{e,heat}}$ is the real evaporative heat loss observed from the sweating thermal manikin, watt; $R_{\text{et,mass}}$ is the total clothing evaporative resistance calculated by the mass loss method, kilopascal square metres per watt; $H_{\text{e,mass}}$ is the calculated evaporative heat loss from the mass loss rate, watt; λ is the heat of vaporization of water at the measured skin temperature, watt hours per gram; in this study, $\lambda = 0.673 \text{ W} \cdot \text{h g}^{-1}$ at 34.0°C ; the ratio of dm/dt is the evaporation rate of moisture from the wet textile skin leaving the manikin-clothing system, grams per hour.

Since there was an evaporative heat loss difference between those two calculation methods (Havenith *et al.*, 2008a; Wang *et al.*, 2009), the amount of heat energy required for water evaporation should both come from the thermal manikin and from its environment. Otherwise, no evaporative heat loss difference could be observed.

Apparently, the observed real evaporative heat energy $H_{e,heat}$ from the manikin body is a part of the total heat energy used for sweat evaporation. Thus, the following formula is valid

$$H_{e,mass} > H_{e,heat} \quad (3)$$

With equations (1) and (2) and formula (3), we can easily find

$$R_{et,heat} > R_{et,mass} \quad (4)$$

The amount of heat energy $H_{e,mass}$ calculated from the mass loss rate of the manikin-clothing system could also be expressed as

$$H_{e,mass} = H_{e,heat} + H_{e,env} \quad (5)$$

where $H_{e,env}$ is the amount of evaporative heat energy taken from the environment.

Determination of $H_{e,env}$

With current technology, it is difficult to determine $H_{e,env}$ by the thermal manikin testing in one step. This is probably because there is no feasible approach that could force the wet textile skin to absorb heat from only the environment at an isothermal condition. Even if there is a feasible method that could make the wet skin to absorb heat from the environment only, the skin temperature will not be the same as that in the isothermal condition. The pre-wetted textile skin temperature is dependent on both the manikin surface temperature and the whole manikin-clothing system's evaporation rate (Wang *et al.*, 2010b). In order to determine the amount of evaporative heat taken from the environment $H_{e,env}$, an indirect method was applied. The manikin was placed in a climatic chamber but not heated. The pre-wetted textile fabric skin was dressed on the manikin surface. An equilibrium condition will be reached when the following two conditions are observed (ASTM F2370, 2010):

1. the manikin surface temperature $T_{manikin}$ remains constant ($\pm 3\%$) and
2. the wet textile skin temperature T_{sk} reached stable and it varies within $\pm 1.0^\circ\text{C}$.

It is anticipated that the manikin surface temperature is lower than the pre-wetted textile skin surface temperature. Therefore, the heat energy required for sweat evaporation comes purely from the ambient. The mass loss rate of the manikin-clothing system could be determined by weighing. Then, the amount of evaporative heat energy $H'_{e,env}$ at such a condition may be determined by the equation (6):

$$H'_{e,env} = \lambda \cdot \left. \frac{dm}{dt} \right|_{no,heat} \quad (6)$$

where $H'_{e,env}$ is the heat energy taken from the environment when the manikin is not heated at an ambient temperature of 34.0°C , watt; $\left. \frac{dm}{dt} \right|_{no,heat}$ is the mass loss rate of the pre-wetted textile skin when the manikin is not heated, grams per hour. It should be also noted that the water vapour pressure gradient at the above test condition is different with that in the isothermal condition (i.e. the manikin is heated and the air temperature is kept the same). Therefore, this mass loss rate is not equal to that at the isothermal condition. However, it could be derived from a method described below.

Kucera (1954) investigated the relationship of evaporation rate to the vapour pressure deficit and low wind velocity and found that the relationship between the evaporation rate and the vapour pressure deficit appears to be linear. Brebner *et al.* (1956) studied the diffusion of water vapour through the human skin and found that the sweat loss rate has a linear relation with the water vapour pressure gradient between the saturated skin and the ambient. Bernard and Matheen (1999) also commented that the evaporation rate mainly depends on the water vapour pressure gradient between the human skin and ambient air. Based on these findings, the mass loss rate at a specific water vapour pressure gradient might be calculated by equation (7):

$$\frac{dm}{dt} = k \cdot \Delta p, \quad (7)$$

where k is a constant, which is related to the permeability of the wet textile skin (Brebner *et al.*, 1956). Δp is the water vapour pressure gradient between the saturated wet textile skin and the environment at any specified condition, kilopascal.

Thus, the amount of evaporative heat energy taken from the environment $H_{e,env}$ at the isothermal condition may be calculated by equation (8):

$$H_{e,env} = \frac{\Delta p_{iso}}{\Delta p} H'_{e,env} \quad (8)$$

It can be deduced from equations (5), (6), and (8) that

$$H_{e,mass} = H_{e,heat} + \frac{\Delta p_{iso}}{\Delta p} \lambda \cdot \left. \frac{dm}{dt} \right|_{no,heat} \quad (9)$$

Test procedures

A 17-segment dry heated thermal manikin 'Tore' was used in this study (Kuklane *et al.*, 2004).

A pre-wetted cotton knitted textile skin (dry/conditioned weight per unit area: 228 g m^{-2} ; moisture content: $\sim 163\%$ of the initial mass) was placed on top of the thermal manikin to simulate a skin wetted by sweating. It covers in all 12 segments and excludes the manikin's head, hands, and feet. There was no moisture migration from pre-wetted skin to non-covered manikin surface areas due to the non-absorbent surface of the manikin. The textile skin was rinsed with tap water in a washing machine (W3015H; Electrolux Inc., Sweden) for 4 min and then centrifuged 4 s to ensure no water dripped. Five sets of garments (Table 1) were selected and balanced in a climatic chamber at least 24 h before testing. The testing on clothing evaporative resistance followed the American standard ASTM F2370 (2010). The measurements of clothing evaporative resistance were performed at an isothermal condition, where the air temperature was 34.0°C . The relative humidity was controlled to 38.0% . The ambient temperature and relative humidity were measured by three digital temperature and relative humidity sensors (SHT75; Sensirion AG, Switzerland) set at heights of 0.1, 1.1, and 1.7 m. Twelve temperature sensors (SHT75; Sensirion AG) were attached on the wet textile skin surface using thread rings to measure its surface temperatures. The whole manikin system was placed on a weighing scale (KC240; Mettler-Toledo Inc., Switzerland, accuracy: $\pm 2 \text{ g}$). The mass loss rate of the whole system could be easily determined accordingly. The air velocity was maintained at $0.33 \pm 0.10 \text{ m s}^{-1}$. For testing on the determination of $H'_{e,env}$, the manikin was disconnected from the heating power supply box. The ambient conditions were kept the same as described above.

RESULTS

The evaporative resistances of the boundary air layer and five vocational clothing ensembles calcu-

lated by the heat loss method and mass loss method were displayed in Fig 1. As expected, the heat loss method produced greater clothing evaporative resistances than those calculated from the mass loss method. The results are in accordance with the formula (4). The evaporative resistance values for the boundary air layer, clothing ensembles L, HV, MIL, CLM, and FIRE based on the heat loss method were 37.1, 30.8, 25.9, 21.5, 12.7, and 11.2% greater than those based on the mass loss option.

The observed wet textile skin temperature and manikin surface temperature when the manikin was not heated for all six test scenarios are presented in Fig 2. The observed manikin surface temperature was $0.4\text{--}2.2^\circ\text{C}$ lower than the wet textile skin surface temperature. See the supplementary data at *Annals of Occupational Hygiene* online for further details on wet fabric skin temperatures when manikin was heated, wet skin surface vapour pressure and water vapour pressure gradient between wet skin and environment. In addition, the observed dew point at those six test conditions was always lower than the manikin surface temperature, which indicates that there was no condensation during the testing period. Thus, it is evident that the heat energy used for sweat evaporation $H'_{e,env}$ at such a condition comes only from the environment. Consequently, the real evaporative heat energy taken from the environment at the isothermal condition could be determined by the equation (8).

Table 2 presents the amount of evaporative heat losses taken from the manikin and the environment, respectively. The evaporative heat energy taken from the environment accounts for $10.9\text{--}23.8\%$ of the total calculated evaporative heat loss. The real evaporative cooling efficiency ranged from 0.762 to 0.891, respectively. On the other hand, the theoretical evaporative heat energy taken from the environment (i.e. $H_{e,mass} - H_{e,heat}$) was almost equal to the observed heat loss $H_{e,env}$ (the differences are 7.4, 8.2, 3.5,

Table 1. Details of five vocational clothing ensembles

Code	Garment components	I_r , clo	I_{cl} , clo	W^a , g
L	Short sleeve tee-shirt, briefs, short pants, socks, sports shoes	1.05	0.48	1692
HV	Short sleeve tee-shirt, briefs, long trousers with reflective materials, socks, sports shoes	1.20	0.63	2211
MIL	Jacket, long trousers, net t-shirt, briefs, socks, sports shoes	1.65	1.08	2132
CLM	Polyamide overall laminated with Gore-tex membrane, short sleeve tee-shirt, briefs, socks, sports shoes	1.68	1.11	3570
FIRE	RB90 firefighting clothes, underwear, short sleeve tee-shirt, briefs, socks, sports shoes	2.58	2.01	6446

L, light clothing; HV, high-visibility clothing; MIL, military clothing; CLM, climber overall; FIRE, firefighting clothing; I_r , total clothing thermal insulation, clo; I_{cl} , clothing intrinsic thermal insulation, clo; W, total clothing weight, grams.

^aClothing weight may vary a lot among different sizes; in this study, all garments have a unique size of large.

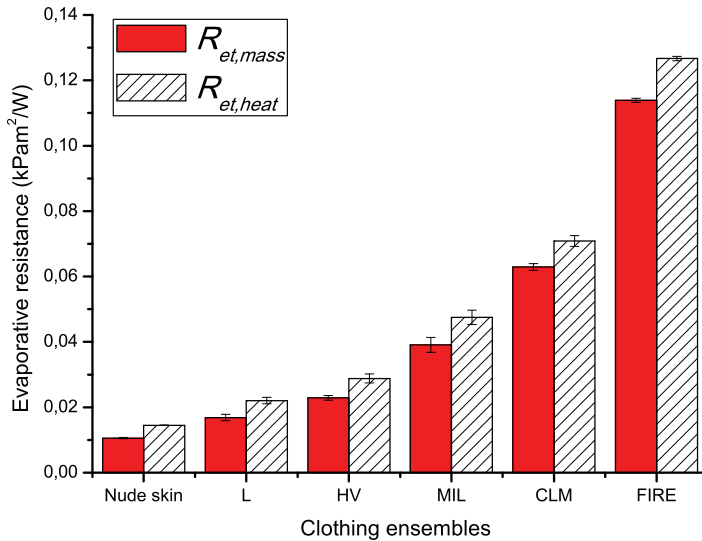


Fig. 1. The evaporative resistances of the boundary air layer and five clothing ensembles calculated by heat loss method and mass loss method at an isothermal condition ($T_{manikin} = T_a = T_r = 34.0^\circ\text{C}$).

–2.0, 0.3, and 0.6 W m^{-2} , respectively; these may be mainly due to measurement error, for example the weighing scale's drift). Therefore, the indirect method to investigate and to quantify the amount of heat taken from environment for the evaporation from the wet textile skin in this study has been successfully validated.

DISCUSSION

There were three main findings in this study. Firstly, the isothermal heat loss method overestimated the heat stress, which is in line with the results presented in a previous study (Havenith *et al.*, 2008a). Secondly, the higher thermal insulation of a clothing ensemble dressed on top of the manikin's wet textile skin, the less evaporative heat energy taken from the environment. This is mainly because the high insulation clothing prevented the wet textile skin from absorbing heat energy from the ambient environment. For instance, the firefighting clothing provides a thermal insulation of 2.58 clo, the calculated clothing evaporative resistance by heat loss method is only 11.2% greater than that based on mass loss method. On the other hand, if there was no clothing dressed on top of the pre-wetted textile skin, the difference between those two evaporative resistance values rose to 37.1%. Thirdly, Havenith *et al.* (2008b) proposed a new term 'real evaporative cooling efficiency' to describe how much latent

evaporative heat loss taken from the body when clothing is worn. It can be deduced from this study that the real evaporative cooling efficiency is higher if a higher insulation clothing ensemble was worn. However, the total amount of evaporation leaving the manikin-clothing system will be greatly impeded by the clothing. Therefore, the real evaporative cooling efficiency is not always necessarily high and how much sweat evaporation leaving the manikin-clothing system is more important.

Although there are more than 100 thermal manikins in the world, few of them can simulate sweating (Holmér, 2004). Thus, sweating thermal manikins are still rare at present. Today, the evaporative resistance is mostly determined on sweating guarded hotplates (Gibson *et al.*, 1994; Huang, 2006). Since the sweating guarded hotplate is a 'flat' apparatus, it does not take into consideration of garment features such as the human body shape and clothing microclimate. In addition, sweating guarded hotplates can only determine the static evaporative resistance of a piece of fabric. Therefore, the evaporative resistance value determined on such equipment may present a big discrepancy with that measured on sweating thermal manikins. For these reasons, sweating guarded hotplates might be used as a supplemental instrument for the determination of clothing evaporative resistance.

Generally, the selection of evaporative resistance calculation method is constrained by the manikin's

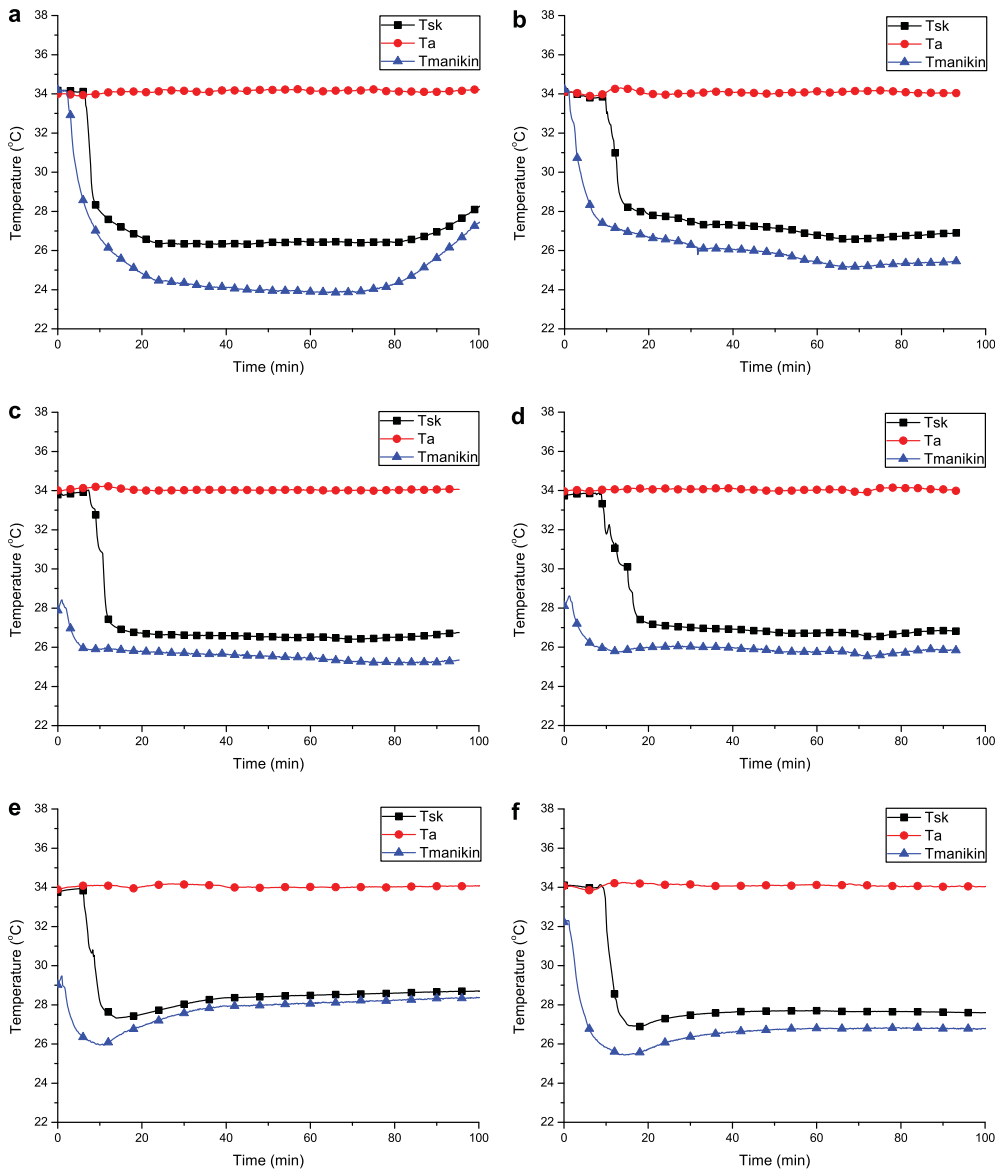


Fig. 2. The observed wet textile skin temperature, manikin surface temperature (the manikin is not heated), and air temperature. (a) nude textile skin, (b) L (c) HV, (d) MIL, (e) CLM, (f) FIRE. Note: In some experiments (e.g. c, d, e, and f), the manikin surface has an initial temperature $<34.0^{\circ}\text{C}$ due to a previous test cooled down the manikin.

sweating simulation method. Currently, sweating simulation on thermal manikins might be categorized into three types (Gao and Holmér, 2006): pre-wetted textile skin dressed on a dry heated thermal manikin, manikins equipped with a water supply system and a certain number of sweating glands, and a body of water that

hold by a piece of waterproof but permeable Gore-tex fabric. The thermal manikin Tore used in this study uses the first type of sweat simulation. It is a simplified sweating simulation but functions well (Holmér and Nilsson, 1994; Holmér, 2006). Both the heat loss method and the mass loss method can be used for

Table 2. The mass loss rate, total evaporative heat loss, observed evaporative heat loss taken from the manikin and the environment, and the ratio of observed heat from the environment and total calculated evaporative heat loss

Clothing ensemble	$dm/dt _{no,heat}$ g h ⁻¹	dm/dt g h ⁻¹	$H_{e,mass}$ W m ⁻²	$H_{e,heat}$ W m ⁻²	$H'_{e,env}$ W m ⁻²	$H_{e,env}$ W m ⁻²	$H_{e,env}/H_{e,mass}$ %
Nude skin	48.8	454.2	215.7	156.9	23.2	51.4	23.8
L	27.7	334.4	158.8	122.2	13.2	28.4	17.9
HV	21.2	292.1	138.7	112.9	10.4	22.3	16.1
MIL	13.6	207.4	98.5	85.9	6.5	14.6	14.8
CLM	8.9	135.6	64.4	57.1	4.3	7.0	10.9
FIRE	6.2	86.3	41.0	35.5	2.9	4.9	12.3

The real evaporative cooling efficiency $\eta_{real} = 1 - H_{e,env}/H_{e,mass}$, non-dimensional.

the evaporative resistance calculation. The new 'Newton' family thermal manikins are provided with the second type of sweating mechanism (Wang, 2008; Measurement Technology Northwest, 2010). For this type of sweating manikin, it is pretty difficult to adjust a suitable sweating rate for different tested garments in order to avoid water dripping. Thus, it limits the application of mass loss method. The measurements are mainly determined by the heat loss method. Sweating thermal manikins such as 'Walter' and 'Kyoto Electronics Manikin' belong to the third category (Fan and Chen, 2002; Fukazawa *et al.*, 2004). The measurements of clothing evaporative resistance using this type of sweating thermal manikins are based on the mass loss method. Therefore, the clothing evaporative resistance determined on different types of sweating thermal manikins may differ a lot. In order to make those results comparable, a correction on the real evaporative heat loss (i.e. the observed value from the sweating thermal manikin) has to be made. One possible approach to correcting the real evaporative heat loss by adding the part of heat energy taken from the environment $H_{e,env}$. An alternative method is using the real evaporative cooling efficiency to correct the real evaporative heat loss.

The main objective of thermal manikin measurements on the determination of clothing evaporative resistance is to provide a physical value related to clothing moisture transfer property. It would be meaningless to determine this parameter at non-isothermal low ambient conditions because the complicated heat and moisture transfer pathways in such a cool/cold condition could definitely introduce further errors on the evaporative resistance. On the other hand, it is the main task for human-clothing-environment models (e.g. Xu and Werner, 1997) to consider those effects such as absorption, desorption, diffusion, and condensation on clothing evaporative resistance. Therefore, we suggest using only the isothermal condition to measure clothing evaporative resistance.

This can avoid the combined effects of dry heat loss, condensation, and heat pipe on the clothing evaporative resistance (Havenith *et al.*, 2008b). The mass loss method is always the correct option for clothing evaporative resistance testing conducted in the isothermal condition. The isothermal heat loss method should not be used except if a correction was made on the real evaporative heat loss.

LIMITATIONS AND SUGGESTIONS

This study had some limitations. The test conditions selected in this study ($T_{manikin} = T_a = T_r = 34.0^\circ\text{C}$) was not a strictly isothermal condition from a physical point of view. The isothermal condition should be defined as $T_{sk} = T_a = T_r$ (i.e. $T_{manikin} > T_{sk}$). In this study, the observed pre-wetted skin temperature was lower than the manikin surface temperature due to water evaporation. That is why evaporative heat loss differences between those two calculation options have been observed. Currently, almost all sweating thermal manikins cannot control the wet skin surface temperature because there is no feedback between the wet textile fabric skin and manikin's controlling system. Perhaps, sweating thermal manikins 'Walter' (Fan and Chen, 2002) and 'Coppellius' (Meinander, 1992) are the few reported manikins that can regulate the skin surface temperature. However, it is questionable whether those manikins could regulate a relatively even distributed fabric skin surface temperature. Furthermore, selection of temperature sensors for measuring the wet textile skin temperature is a great challenge (Pušnik and Miklavec, 2009). The measured temperature value is highly dependent on the sensor size, attachment method, and number of sensors (Cheung and Sweeney, 2001). More suitable temperature sensors may emerge in the future. Finally, it is an urgent task to develop a skin-manikin feedback system in order to control the wet textile skin surface temperature.

CONCLUSIONS

In summary, the evaporative resistance based on the heat loss method produced greater values than those determined by the mass loss method. This is because part of the evaporative heat energy was taken from the environment. Thus, the heat loss method overestimated the heat stress. In order to avoid the combined effects of dry heat transfer, condensation, and the heat pipe on clothing evaporative resistance, thermal manikin measurements on the determination of clothing evaporative resistance should be performed in the isothermal condition. Furthermore, the mass loss method was suggested to be used to calculate clothing evaporative resistance. Otherwise, a correction on the real evaporative heat loss must be made for the heat loss method before application.

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Localised Boundary Air Layer and Clothing Evaporative Resistances for Individual Body Segments

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Abstract

Evaporative resistance is an important parameter to predict one's body heat strain. However, previous work has focused mainly on either total static or dynamic evaporative resistance. There is a lack of investigation of localised clothing evaporative resistance. The objective of this study was to study localised evaporative resistance using sweating thermal manikins. The individual and interaction effects of air and body movements on localised resultant evaporative resistance were examined in a strict protocol. The boundary air layer's localised evaporative resistance was investigated on nude sweating manikins at 3 different air velocity (0.18, 0.48 and 0.78 m/s) and 3 different walking speeds (0, 0.96, and 1.17 m/s). Similarly, localised clothing evaporative resistance was measured on sweating manikins at 3 different air velocities (0.13, 0.48, and 0.70 m/s) and 3 walking speeds (0, 0.96 and 1.17 m/s). Results showed that the wind speed has distinct effects on local body segment. In contrast, walking speed brought much more effect on body limbs such as thigh and forearm than on body torso such as chest and waist. In addition, the combined effect of body and air movement on localised evaporative resistance demonstrated that the walking effect has more influence on the extremities than on the torso. Therefore, localised evaporative resistance values should be provided when reporting test results in order to clearly describe clothing local moisture transfer characteristics.

Keywords: localised evaporative resistance; sweating thermal manikin; clothing ensemble; boundary air layer; reduction factor; local thermal comfort

Statement of Relevance: Mainly due to walking and air velocities, which were investigated in this study, localised evaporative resistances at different local body segments may differ a lot. In this paper, clothing localised evaporative resistance was investigated and reduction equations for localised dynamic evaporative resistance were developed. The findings are very useful for clothing interface modelling for both human local thermal comfort studies and human thermoregulatory model developments.

Introduction

Clothing evaporative resistance (or moisture vapour resistance, Fan and Chen 2002) is one of the most important physical parameters for both clothing thermal comfort and prediction of body heat strain when working in hot environments (Havenith *et al.* 1990b, Chen *et al.* 2003). With the increasing air temperature, the human body becomes more and more dependent on evaporative heat loss to keep heat balance. However, the evaporative heat loss can be greatly attenuated by wearing clothing (Havenith *et al.* 1999). Clothing evaporative resistance might be determined from measurement of its fabric material on a sweating guarded hot plate, clothing test on a sweating thermal manikin, or wear trial by human subjects (Gibson *et al.* 1994, ISO11092 1993, McCullough 2001, Wang *et al.* 2009, Holmér and Elnäs 1981, Havenith *et al.* 1990b, Bernard and Matheen 1999). Although measurement of fabric material's evaporative resistance is essential, such a value is not enough to describe clothing property because it does not consider clothing design factors such as air gap and clothing pattern (Wang *et al.* 2011b). Therefore, determination of clothing evaporative resistance is more often performed on human subjects and sweating thermal manikins.

Determination of clothing evaporative resistance on human subjects has been well documented in many previous studies. Holmér and Elnäs (1981) measured clothing effective evaporative resistance on human subjects using partitioned calorimetry method. Nielsen *et al.* (1987) also performed human subject trials using the calorimetric method and found that the evaporative resistance was reduced by 39% when cycling compared to standing on a heavy garment. Lotens and Havenith (1988) tested impermeable rainwear using tracer gas method on human subjects. It was concluded that the evaporative resistance decreased by 77, 52, and 22% , respectively, when subjects were walking (1.2 m/s) under 0, 2 and 6 m/s wind speeds compared with standing at the respective wind speeds. Later Havenith *et al.* (1990b) conducted human subject measurements and determined clothing evaporative resistance using trace gas diffusion method. The effect of posture on clothing evaporative resistance was also examined in their study. They observed that the walking and wind decreased the evaporative resistance by 72-89% when compared to standing in relatively low wind. However, the tracer gas method does not consider the moisture transport mechanisms between clothing layers. Therefore, this is different from the real case. Recently, Caravello *et al.* (2005) studied the apparent total evaporative resistance of five work garments on 29 human subjects using a progressive protocol method. The measurement accuracy was highly enhanced and the standard deviations for resultant evaporative resistances ranged from 0.003 to 0.007 kPam²/W. However, human subject tests are time and money costly, and ethical issues are always involved. In addition, human trials are not reproducible due to individual differences.

Sweating thermal manikin is the most appropriate apparatus for determination of clothing evaporative resistance (Holmér *et al.* 1996, Holmér 1999, Fan and Chen 2002, Holmér 2006, Wang 2010a). However, a previous round robin study (McCullough 2001, Richards and McCullough 2005) has revealed that results are not highly repeatable and reproducible due to various reasons such as different sweating simulation methods, different test protocols, and technical dilemmas (Huang 2007, Wang *et al.* 2010b, Wang *et al.* 2011b). In order to get repeatable evaporative resistance values from a thermal manikin, Wang *et al.* (2011b) investigated the effect of temperature difference between manikin temperature and wet fabric skin temperature on evaporative resistance. It was found that the temperature difference could lead to an error of up to 35.9% on the boundary air layer's evaporative resistance. Moreover, this temperature difference could introduce an error of up to 23.7% on clothing evaporative resistance. Finally they suggested that the wet fabric skin temperature must be measured by attaching additional temperature sensors on the skin in order to reduce the potential errors made on clothing evaporative resistance. Later Wang *et al.* (2011a) examined the effect of different calculation options on clothing evaporative resistance at a so called isothermal condition ($T_{manikin}=T_a=Tr$). They concluded that the mass loss method produces a lower evaporative resistance than that by the heat loss method. The mass loss method was suggested to be used to calculate clothing evaporative resistance. Furthermore, those two calculation options could generate the same evaporative resistance value if measurements are performed in a real isothermal condition ($T_{sk}=T_a=Tr$). By strictly controlling the testing protocol and choosing reasonable calculation method, the measurement repeatability on clothing evaporative resistance could be greatly enhanced.

Almost all researches have currently focused on clothing total evaporative resistance or total resultant/dynamic evaporative resistance (Havenith *et al.* 1990b, Caravello *et al.* 2005, Wang *et al.* 2009, Wu *et al.* 2011). However, little is known on how the local evaporative resistance changes with posture, walking and/or wind. More importantly, an overall/total evaporative resistance value cannot always provide detailed characteristic information for clothing local area. On the other hand, the ability to describe clothing local effects on human skin temperature has lagged human thermoregulatory modelling (Nelson *et al.* 2005). There is a great need to study localised clothing evaporative resistance. Also, it is useful to investigate the effects of body and air movement on localised clothing evaporative resistance. Such investigations are of great importance for studies on both human local thermal comfort and thermoregulatory modelling.

The purpose of the present study was to study localised evaporative resistance of both boundary air layer and clothing ensembles. The individual and interaction effects of walking and wind on localised evaporative resistance were

extensively investigated. Furthermore, empirical equations for prediction of localised dynamic evaporative resistance were developed.

Methods

Thermal manikin

The Newton thermal manikins (MTNW, Seattle, WA) were used in this study (Wang and Lee, 2010c). This type manikin has a carbon epoxy shell with embedded heating and measuring wire sensors. The controlling system was developed using advanced CAD digital modelling to ensure manufacture repeatability. In addition, the manikin was fully jointed, providing motions at elbows, hips, knees and ankles to allow any possible body postures. The manikin uses an external constant pressure pump to control its local fluid supply to each segment. There are more than 134 sweating holes distributed uniformly over the whole body. The local body heat loss, temperature, sweat rate were acquired through either ThermDAC® software or newly developed ManikinPC²® (manikin physiology control and predictive comfort) software (ThermoAnalytics Inc., Calumet, MI).

Test protocols

The fabric skin was fully wetted with distilled water prior to dressing the manikin. An appropriate flow rate (500-2000 ml/hr/m²) for each segment was adjusted to ensure its local fabric skin was fully wet throughout the experimental period. Fourteen thermocouples (copper-constantan, data logger: Testo 177-T4, Testo AG, Germany) were attached on the right part of the wet skin surface using thread rings to record local body segment's skin temperature (Fig.1). The air temperature (Betatherm/MTNW temperature sensors), relative humidity (Vaisala humidity sensor) and air velocity (TSI air flow transducer) were monitored throughout the whole experiment. The segmental heat losses were directly obtained from the manikin program.

-----*Fig.1 near here*-----

Previous studies (Wilbik-Halgas *et al.* 2006, Bivainyte and Mikucioniene 2011) have demonstrated that there is no correlation between clothing air permeability and its water vapour permeability. On the other hand, Kaplan and Okur (2010) and Irandoukht and Irandoukht (2011) found that the fabric weight was significantly correlated with its water vapour resistance. Thus in this study, the fabric mass per unit area was used as one of the predictors for localised clothing resultant evaporative resistance. The fabric weight was determined as follows: 10×10 cm fabric specimens were conditioned in a standardized condition room (20.0±1.0 °C, RH=65±2%) for at least 24 h before measurements (ISO139 2005). The specimens were weighed on a balance

(Mettler Type AE260S, Mettler-Toledo AG, Switzerland; accuracy: 0.0001g) according to ISO3801 (1977). Test results were reported in g/m².

Calculations

The localised clothing evaporative resistance is determined by Eq. (1)

$$R_{e,i} = \frac{P_{sk,i} - P_a}{He_i} \quad \text{Eq.(1)}$$

where, $R_{e,i}$ is the localised evaporative resistance at the segment i , kPam²/W; $p_{sk,i}$ is the localised water vapour pressure on the wet fabric skin at the segment i , kPa; p_a is the water vapour pressure in the air, kPa; He_i is the localised evaporative heat loss at the segment i , W/m².

The correction/reduction factor $Corr$ for the localised resultant evaporative resistance can be expressed by Eq.(2)

$$Corr = \frac{R_{e,r,i}}{R_{e,i,ref}} \quad \text{Eq.(2)}$$

where, $R_{e,r,i}$ is the localised resultant/dynamic evaporative resistance at the segment i determined in a specific condition, kPam²/W; $R_{e,i,ref}$ is the localised static evaporative resistance of the segment i determined at reference condition, kPam²/W. In this study, the reference air velocities for the nude manikin measurements and for the clothing measurements were 0.18 and 0.13 m/s, respectively (Havenith and Nilsson 2004).

Data obtained from each test scenario were gathered in a database and analysed with multiple nonlinear regression analysis using the software XLSTAT version 2011 (Addinsoft Inc., Brooklyn, NY). The prediction parameters used for nude measurement data were air velocity and walking speed, whereas the prediction parameters for clothing experimental data were air velocity, walking speed, and fabric weight. The correction equations for localised resultant evaporative resistance of each segment were developed accordingly.

Test conditions and clothing ensembles

The experiments were performed at three different research institutes: CeNTI in Portugal, TTRI in Taiwan and INAIL in Italy. All measurements were conducted at an air temperature of 34.0 °C and the relative humidity 38.0%. The manikin surface temperature was controlled at 34.0 °C. The nude skin

measurements were performed at two research institutes: CeNTI and TTRI. Two air speeds were selected at CeNTI: 0.18 and 0.48 m/s, which were created by adjusting ventilation rate inside the climatic chamber; the only air speed of 0.78 m/s was used at TTRI, which was generated by a large fan placed in front of thermal manikin. A honeycomb was mounted in front of the fan to reduce turbulence (Nilsson 1997). The CeNTI and INAIL participated clothing experiments. The two air speeds of 0.13 and 0.48 m/s were observed at CeNTI, whereas the used air speed at INAIL was 0.70 m/s. The air ventilation systems inside the chamber at CeNTI and INAIL are very similar, i.e., air enters from front mesh wall facing to the anterior part of the thermal manikin and exits through back mesh wall. Three walking speeds were used: 0, 45 and 55 dspm (double steps per minute). The corresponding walking speeds were 0, 0.96 and 1.17 m/s, respectively. Three different patterns of light clothing ensembles were used: permeable overall, tee-shirt and knee pants, and long sleeve military jacket and military long trousers. The details of these three clothing ensembles are listed in Table 1.

-----*Table 1 near here*-----

Results

Wind effect on localised evaporative resistance (boundary air layer)

The effect of air velocity on boundary air layer's dynamic evaporative resistance at each local segment is displayed in Fig.2 (walking speed $w=0$ m/s). The linear regression curves show very good prediction ($R>0.95$). As expected, the localised evaporative resistance decreases with increasing air velocity. However, the reduction rate differs a lot among different segments. The reduction rates at the face, upper arm, hand and foot under 0.78 m/s wind were the lowest, ranging from 48.6 to 55.9%, whereas the reduction rates at the head, shoulders, back and thigh were the highest, ranging from 72.5 to 86.9%.

-----*Fig.2 near here*-----

Walking effect on localised evaporative resistance at reference air speed (boundary air layer)

The effect of walking speed on localised dynamic evaporative resistance at the reference air velocity was examined (Fig.3). The correlation factors demonstrate that predictions are good ($R>0.93$). The walking speed decreases local evaporative resistance at the extremities much more than on other segments. The reduction rate of the localised evaporative resistance at the thigh was the greatest of all 14 segments, when the manikin was walking at 1.17 m/s compared with standing (reduction of 64.8%, i.e., $0.0297 \text{ kPam}^2/\text{W}$). The reduction on localised evaporative resistances at segments such as face, head

and chest were less than 10% of that on the thigh for the same walking condition. The reduction on localised evaporative resistance at the forearm was greater than that on the upper arm. The arm swing created local turbulent air flow which led to stronger decrease of the evaporative resistances at the manikin torso (shoulders and back) than at the face.

-----Fig.3 near here-----

Interaction effect of air and body movement on localised evaporative resistance (boundary air layer)

The relationship among air speed, walking speed and the localised boundary air layer's evaporative resistance has been also examined by multiple nonlinear regressions. In order to ensure that the correction factor equals 1 for measurements made at standing posture with less than 0.18 m/s wind, a subtraction of this reference wind speed was made. The correction factors for the boundary air layer's evaporative resistance R_{ea} at each local manikin segment are plotted in Fig.4. The prediction quality is judged by the correlation factor R and the SEE (standard errors of the estimate) value.

-----Fig.4 near here-----

The correction equation for localised boundary air layer's evaporative resistance reads

$$R_{ear} = Corr \times R_{ea}$$

$$= \exp\left(a \times (v_a - 0.18) + b \times (v_a - 0.18)^2 + c \times w + d \times w^2\right) \times R_{ea}$$

where, a , b , c and d are coefficients; v_a is the wind velocity inside the climatic chamber, m/s; w is the walking speed, m/s (the maximum walking speed is 55 dspm); the validity intervals for the reduction equations are 0.18-1.0 m/s wind speed and 0-1.2 m/s walking speed.

The coefficients a , b , c and d , correlation factor R^2 and SEE values for each local segment are displayed in Table 2.

-----Table 2 near here-----

Correction equations for localised clothing evaporative resistance

For the data obtained from clothing measurements, there was no covering on the manikin's hand, face, head and foot, thus these four segments were excluded from the analysis. The relation between air velocity, walking speed, and fabric weight and correction factors for localised clothing evaporative resistance at the remaining 10 local segments, was determined by multiple non-linear regressions. The correction equation is written as

$$R_{eTr} = Corr \times R_{eT} \\ = \exp \left\{ \left(a \times (v_a - 0.13) + b \times (v_a - 0.13)^2 + c \times w + d \times w^2 \right) \times W_f^e \right\} \times R_{eT}$$

where, a , b , c , d and e are coefficients; v_a is the wind speed relative to the manikin inside the climatic chamber, m/s (range: 0.13-0.71 m/s), in this study, the observed minimum air velocity inside the climatic chamber at CeNTI was 0.13 m/s, thus this values was treated as the reference air speed; w is the walking speed, m/s, the maximum walking speed is 55 dspm; W_f is the fabric weight (range: 179-239 g/m²).

The coefficients a , b , c , d and e , correlation factor R^2 and SEE values for each local segment are displayed in Table 3.

-----Table 3 near here-----

Discussion

To the best of our knowledge, this paper is the first study to investigate both individual and interaction effects of air and body movement on localised evaporative resistance using sweating thermal manikins. The international standard ISO 9920 (2009) has published an empirical equation to estimate combined effects of air and body movement on total clothing evaporative resistance. However, this equation was deduced through an indirect approach- i_m approach, i.e., by deduction from clothing dynamic permeability index, dynamic total thermal insulation and the Lewis relation (Havenith *et al.* 2002). The reasons are probably due to little data are available on clothing evaporative resistance and such measurements are rather complex and expensive (Havenith *et al.* 1999). It should be also noted that this standard aims at providing a method to estimate clothing insulation and evaporative resistance rather than measure the values. In this study, we used a direct approach to investigate localised evaporative resistance. The results are more reliable as the accuracy of reduction equations is further improved.

Belghazi *et al.* (2005) studied the effect of air velocity on whole body and regional evaporative heat transfer coefficients in neonates using a thermal mannequin. Since their baby manikin has a supine posture, was placed in an incubator and exposed to various turbulent air speeds, it is very difficult to compare our data with their results. On the other hand, the evaporative heat transfer coefficient h_e is inversely related to the evaporative resistance and the Lewis relation suggests $h_e/h_c=16.5$ Kelvin per kilopascal (h_c is the convective heat transfer coefficient, Parsons 1988). In our study, we found that the smaller the diameter of a local segment (such as the hand, forearm, calf and foot), the smaller the localised evaporative resistance, i.e., the higher the localised evaporative heat transfer coefficient and the greater the evaporative capacity. The results are consistent with Belghazi *et al.*'s findings (2005). The intersegment differences between upper limbs and the torso ranged from 75-100%. Belghazi *et al.* (2005) observed the differences were 30% on their baby manikin. One possible reason for those differences could be that their baby manikin has a relatively small surface area compared with our adult manikins.

De Dear *et al.* (1997) investigated the convective and radiative heat transfer coefficients for individual human body segments using a 16-segment articulated thermal manikin. They observed that the hands, feet and peripheral limbs had higher convective heat transfer coefficients than the central torso region. It can be deduced from Lewis relation that the evaporative heat transfer coefficients at those extremities also had greater values than those at the central torso. Therefore, the evaporative resistances at those segments such as hands, feet, and limbs were smaller than those at the torso such as back, shoulders, waist, and chest. The results presented in this study show good agreement with their observations.

Moreover, the air inside the climatic chamber comes from the front mesh wall and flows toward the anterior region of the thermal manikin. Theoretically, the localised convective heat transfer coefficients at the anterior body segments are much greater than those at the posterior body segments. The localised evaporative heat transfer coefficients are also greater at the front than those at the back. Therefore, the localised evaporative resistances at the front local segments are smaller than those at the back. Our results (boundary air layer's evaporative resistances) determined at the reference condition ($v_a=0.18$ m/s, $w=0$ m/s) are in good agreement with this theoretical analysis. The localised evaporative resistances at the chest, stomach, and waist are 0.0240, 0.0212 and 0.0213 kPam²/W, respectively. In contrast, localised evaporative resistances at the shoulders and the back are 0.0486 and 0.0404 kPam²/W respectively, which are 168-229 % greater than those observed at the anterior local body segments.

Furthermore, clothing thermal insulation is equal to the inverse of total dry heat transfer coefficient. It consists of two parts: convective heat transfer

coefficient and radiative heat transfer coefficient, whereas the evaporative resistance is inversely related to evaporative heat transfer coefficient. Thus it is anticipated that reduction in the evaporative resistance at the same wind and body movement condition will be greater than that in thermal insulation. The localised boundary air layer's evaporative resistance decreased by 57.2-88.1% at an air velocity of 0.78 m/s and a walking speed of 1.17 m/s compared with those measured at the reference condition (standing with an air velocity of 0.18 m/s). Those values compare well with the data from Havenith *et al.*'s study (1990b). The previous reported reductions (Nielsen *et al.* 1985, Gaspar *et al.* 2006, Havenith *et al.* 1990a, Holmér *et al.* 1992, Holmér and Nilsson 1995) on clothing thermal insulation determined at similar conditions are much smaller than our observed reduction values on the evaporative resistance.

The present study also demonstrated that body movement has greater influence on the extremities such as forearm, hand, thigh, calf and foot than on the torso. At high wind speeds, the body movement has very little effect on the localised evaporative resistance. At higher walking speeds, the wind effect has smaller effect than at lower walking speed. This trend becomes even more obvious at the body extremities such as hands, feet, thigh, and arms. These findings fit very well with the results concluded by Havenith *et al.* (1990b).

Finally, the moisture transfer became more complex when clothing ensembles were dressed on the sweating manikin. The clothing ventilation resulting from posture, body movement, wind, air gap and apertures of clothing (open/close) can greatly influence the localised evaporative resistance. The observed reductions at the limbs such as upper arm, forearm, thigh and calf were greater than these generated by the empirical equation given in the ISO 9920 (2009) standard. On the other hand, reductions at some local body segments, such as chest and shoulders, were smaller than those produced by this equation. Consequently, the empirical equation (i.e., Eq.38) presented in the ISO9920 standard should not be used when estimating localised clothing evaporative resistance. The empirical equations presented in this study provide a good choice for estimating localised clothing evaporative resistance.

Limitations and suggestions

In this study, all measurements were performed at low air velocities (<1.0 m/s), representing typical indoor condition. The outdoor air velocity is often greater than 1.0 m/s at most of working places. Thus further experiments under higher air velocity are needed in order to expand the result database. In addition, we only tested three sets of one-layer light clothing ensembles. More experiments with multi-layer thermal protective clothing are required in order to extend the equation applicability. Second, the heat loss method was only used for calculation of localised evaporation resistance. In order to apply the mass loss method (ASTM 2010; Wang *et al.* 2011b) for calculation, one

possible solution could be that using instruments such as EPI evaporimeter (Pinnagoda *et al.* 1990) and perspiration meter (SKD-2000, Nishizawa Electric Meters Manufacturing Co., Japan) to determine local mass loss rate from the wet fabric skin. Third, the effect of wind direction on localised resultant evaporative resistance was not investigated. The wind direction can greatly influence local body heat loss, and thus localised evaporative resistance at different segment might vary. Finally, the manikins were fixed on a frame and this differs from the real human walking case. Therefore, the results obtained from the head, face and torso may slightly differ from those obtained in real cases.

Conclusions

Clothing local moisture transfer property should be quantified by localised evaporative resistance rather than by a total/overall evaporative resistance of the whole clothing ensemble. The localised dynamic evaporative resistance resulting from combined air and body movement varies a lot, which mainly depends on local body shape, position and local ventilation characteristics. Finally, local clothing evaporative resistance is of great importance for both human local body thermal comfort study and human-clothing-environment modelling.

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Tables

Table 1 The characteristics of clothing ensembles.

Clothing ensemble code	Garment component	Fabric thickness mm	Weight g/m ²
PERM	Permeable overall (hydrophobic layer laminated with inner PTFE membrane)	0.89	205.3
SR	Tee-shirt (100% polyester)	0.72	230.7
	Riverside knee pants (65% polyester, 35% cotton)	0.40	239.7
MIL	Military jacket and trousers (50% cotton, 50% polyamide)	0.38	179.2

Note: The fabric thickness was determined on a thickness tester according to ISO5084 (1996), the pressure was 10.2 g/cm² and the diameter of pressure foot was 50.8 mm.

Table 2 Coefficients, correlation factor and the *SEE* values of the reduction equations (localised boundary air layer's evaporative resistance).

Segment	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>R</i> ²	<i>SEE</i>
Face	-2.256	1.572	-0.072	0.009	0.983	0.026
Head	-2.472	0.661	-0.085	-0.051	0.989	0.030
Chest	-0.368	-2.587	-0.238	0.150	0.984	0.032
Shoulders	-2.388	0.560	-0.503	0.168	0.969	0.047
Stomach	-0.232	-2.433	0.011	-0.116	0.988	0.026
Back	-0.309	-3.327	-0.314	-0.128	0.993	0.022
Upper arm	0.462	-2.979	-0.331	0.188	0.935	0.060
Forearm	-1.663	-0.420	-1.288	0.242	0.949	0.067
Hand	0.075	-1.928	-1.240	0.190	0.988	0.032
Waist	-0.757	-0.364	-0.091	-0.044	0.913	0.034
Hip	-1.490	0.588	-0.185	-0.007	0.972	0.027
Thigh	0.075	-5.039	-0.731	-0.042	0.985	0.037
Calf	-0.041	-3.427	-1.372	0.176	0.994	0.021
Foot	-0.544	-0.748	-1.026	0.375	0.935	0.061

Table 3 Coefficients, correlation factors and the *SEE* values of the reduction equations (localised clothing evaporative resistance).

Segment	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>R</i> ²	<i>SEE</i>
Chest	-0.013	-0.050	-0.003	-0.003	0.686	0.960	0.037
Shoulders	-1.469	-1.468	-0.488	-0.167	-0.066	0.976	0.029
Stomach	-17.970	-31.213	-32.990	24.598	-0.423	0.948	0.054
Back	-2.376	0.410	-2.356	1.560	0.037	0.947	0.051
Upper arm	0.025	-0.592	-0.440	0.320	0.341	0.892	0.073
Forearm	-0.320	0.350	-0.041	-0.023	0.412	0.949	0.043
Waist	-6.574	-21.618	-10.284	5.484	-0.353	0.909	0.069
Hip	-0.810	-3.425	-3.446	2.475	0.032	0.969	0.042
Thigh	0.035	-0.333	-0.226	0.137	0.464	0.966	0.046
Calf	-0.069	-0.350	-0.369	0.147	0.230	0.952	0.050

Figures

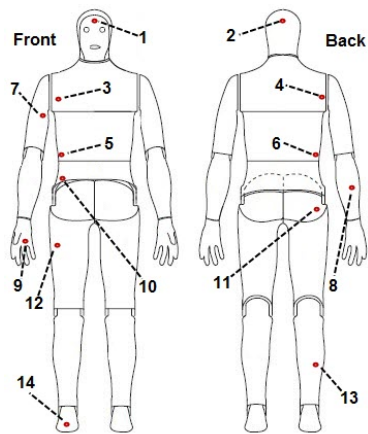


Fig.1 Location of temperature sensors on saturated wet fabric skin: 1-face, 2-head, 3-chest, 4-shoulders, 5-stomach, 6-back, 7-right upper arm, 8-right forearm, 9-right hand, 10-waist, 11-right hip, 12-right thigh, 13-right calf, 14-right foot.

Fig.2

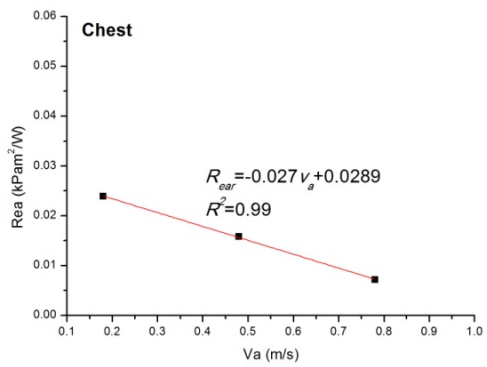
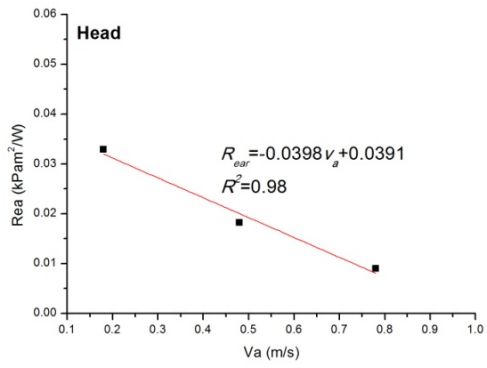
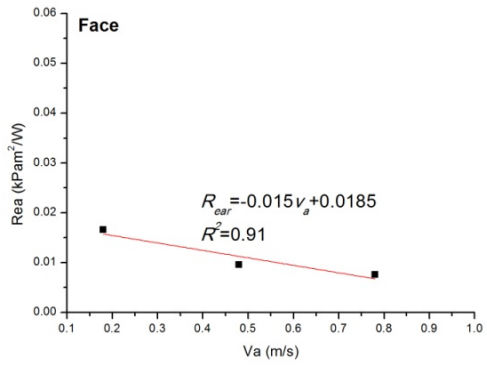


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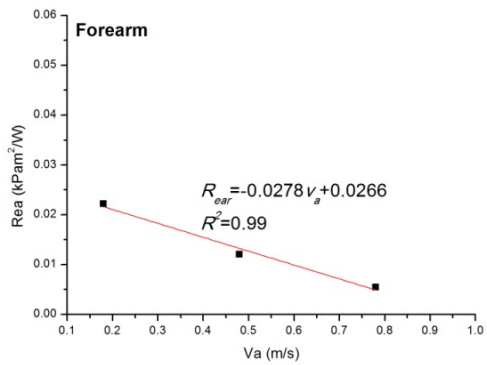
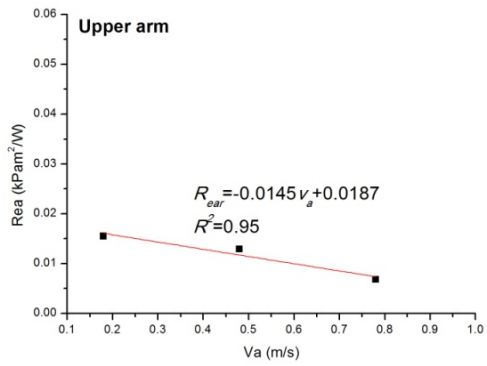
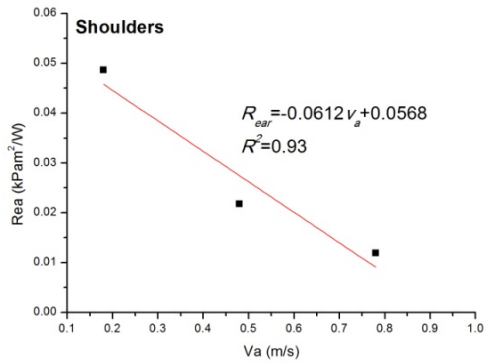


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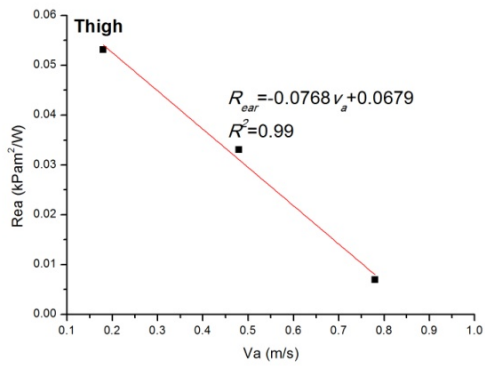
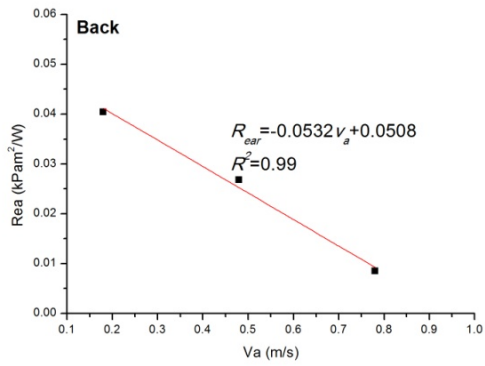
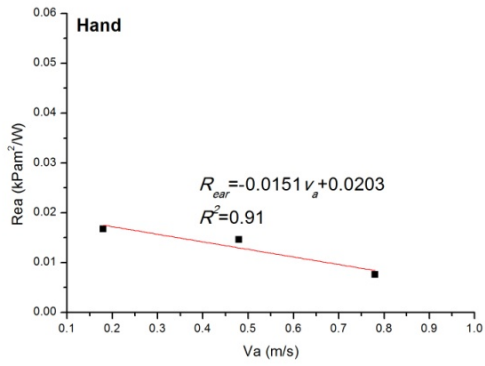
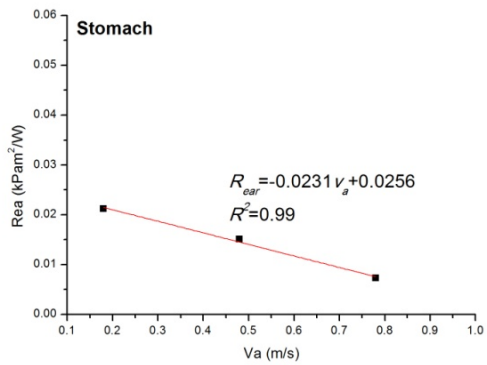
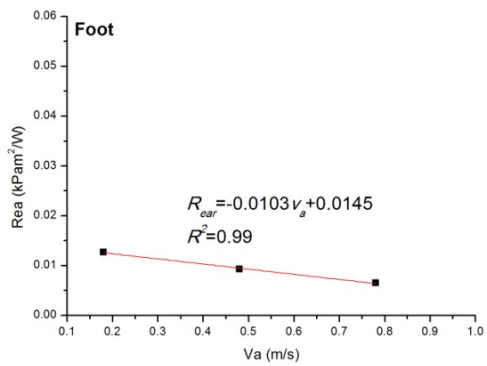
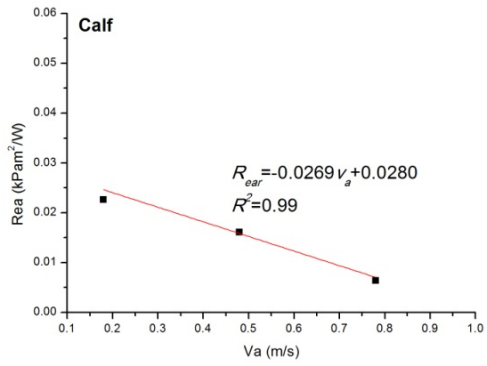


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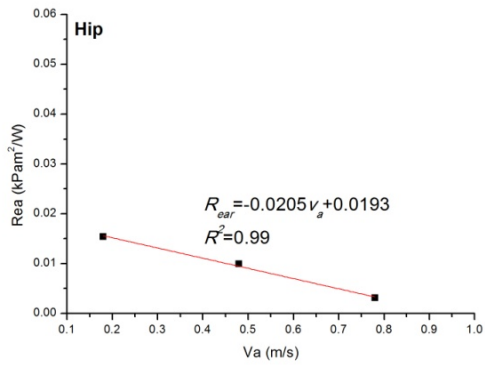
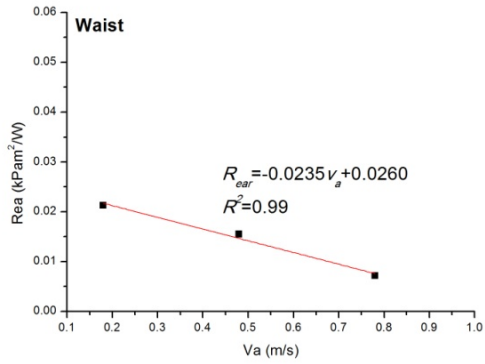


Fig.2 Effect of air speed on localised boundary air layer's evaporative resistance.

Fig.3

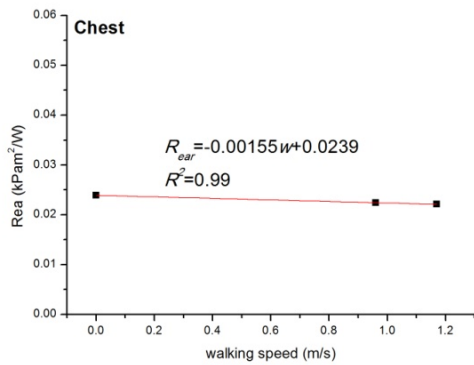
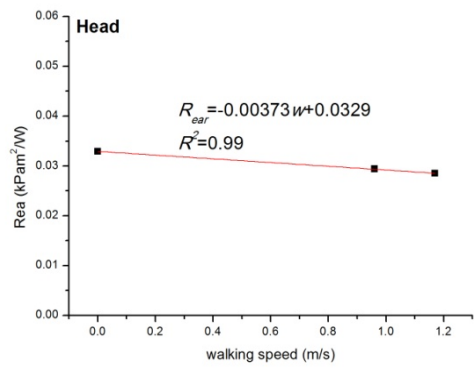
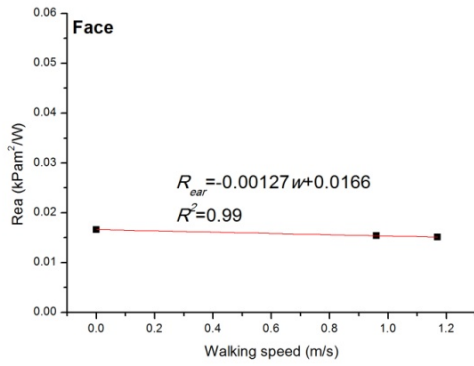


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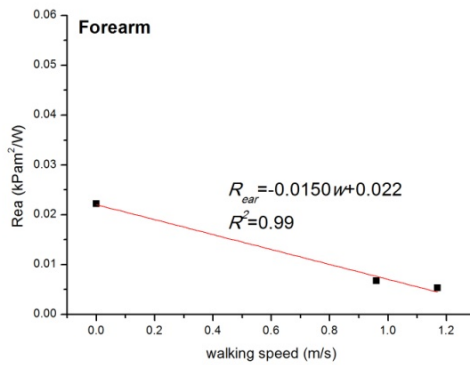
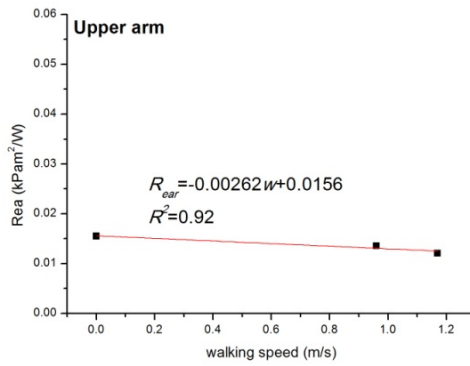
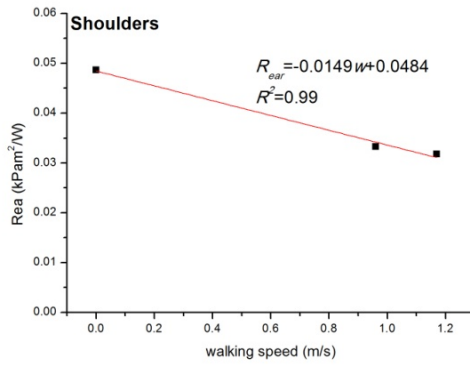


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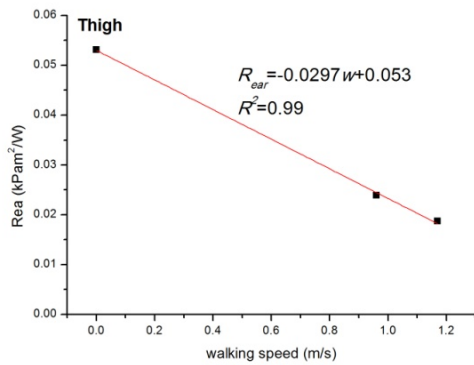
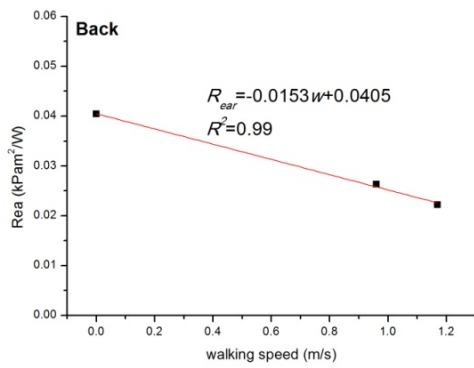
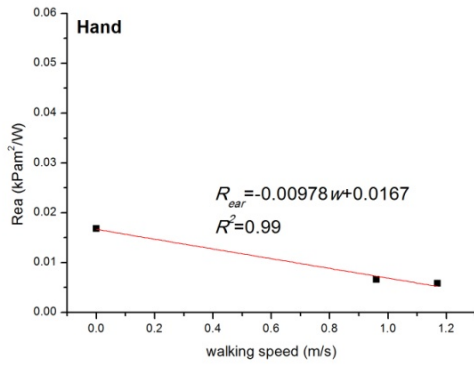
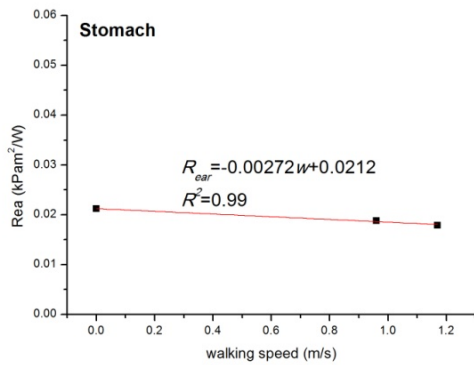
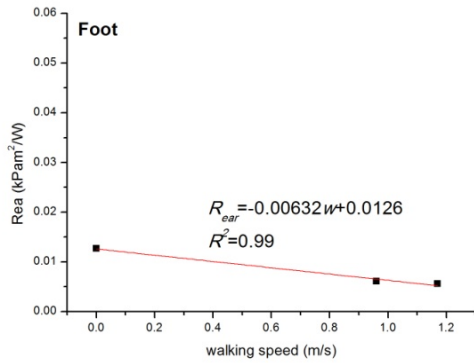
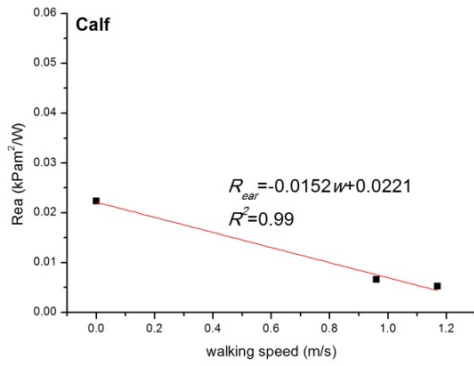


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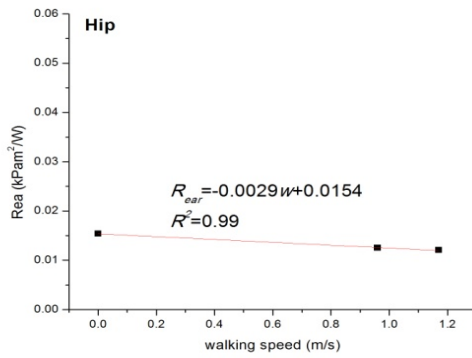
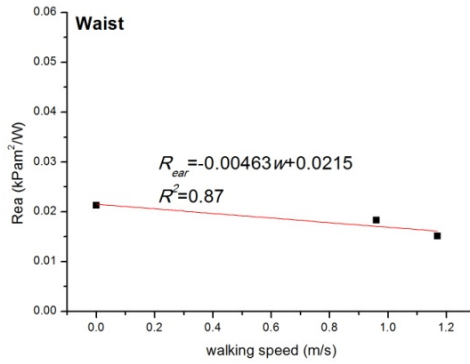


Fig.3 Effect of walking speed on localised boundary air layer's evaporative resistance at reference air speed (0.18 m/s).

Fig.4

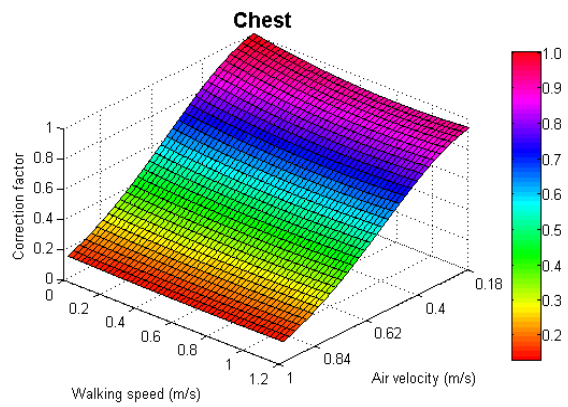
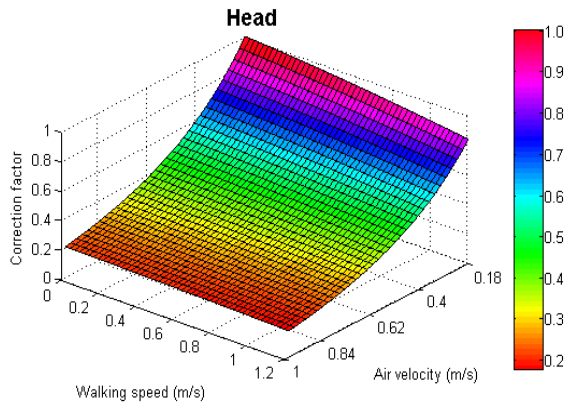
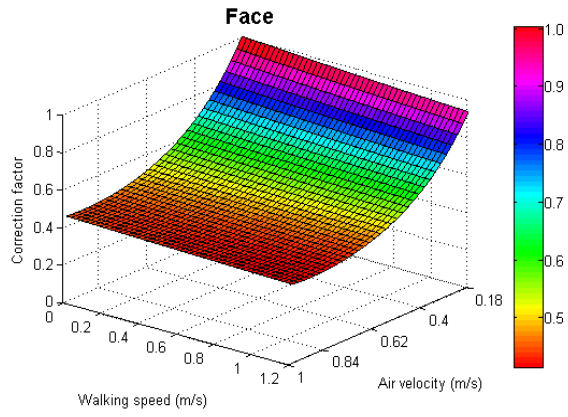


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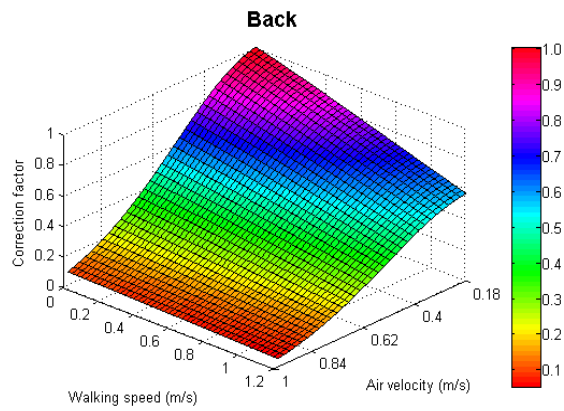
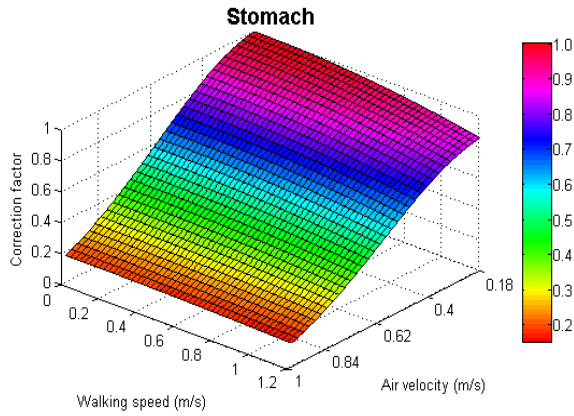
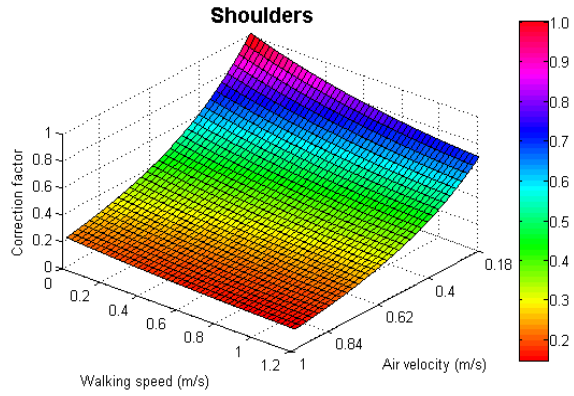


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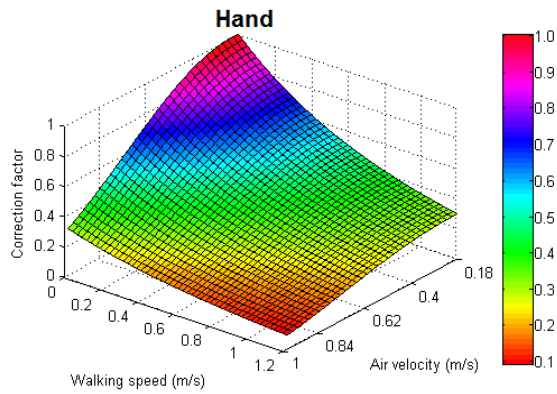
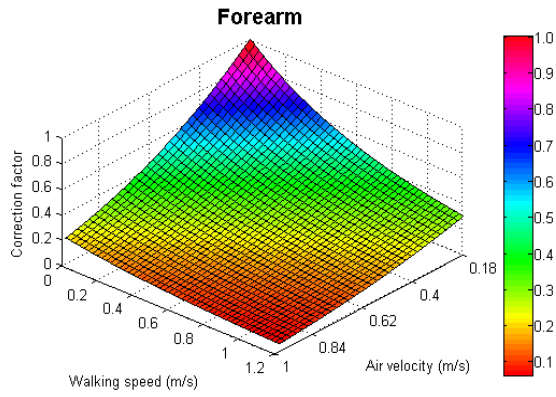
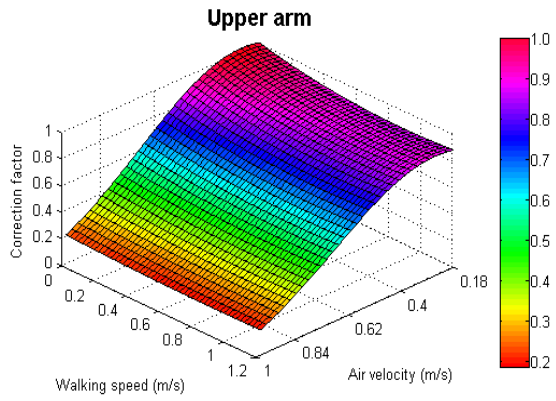
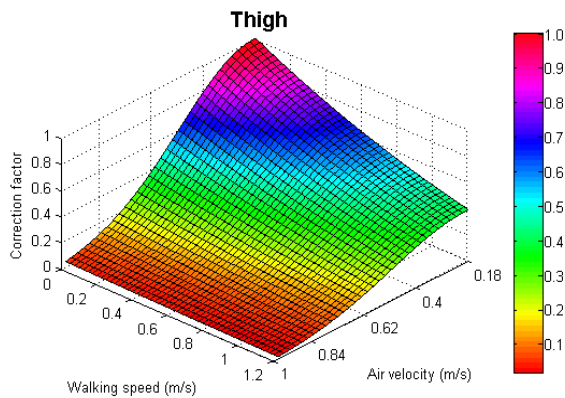
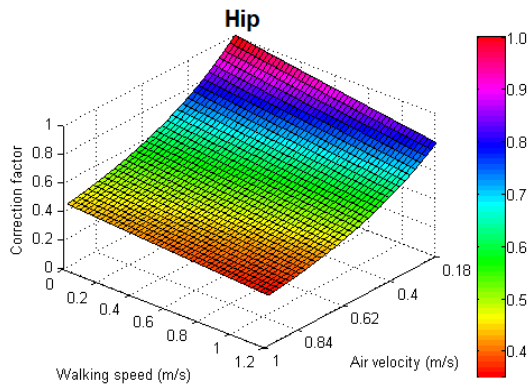
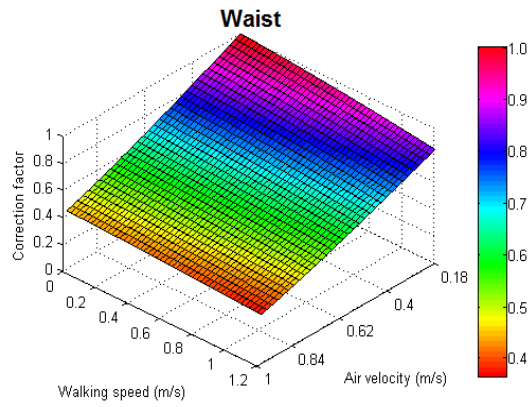


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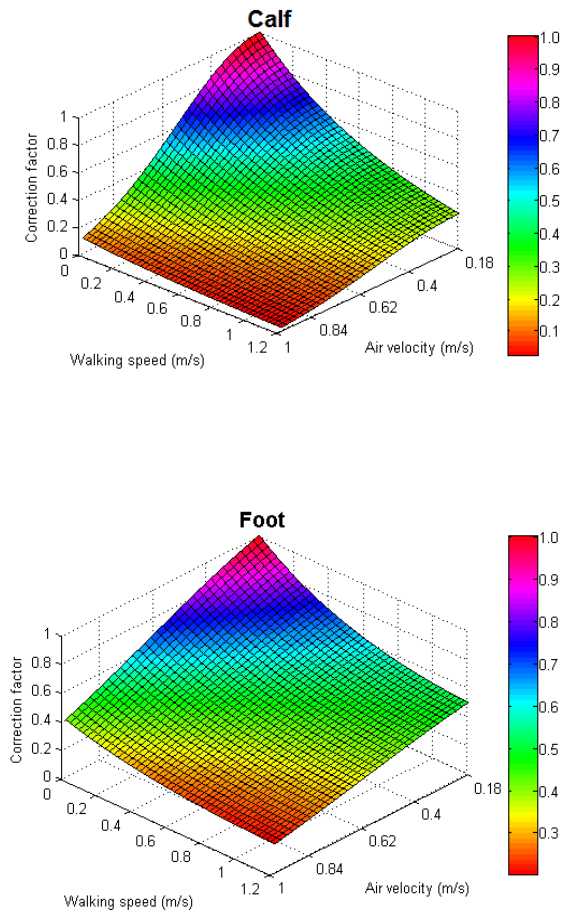


Fig.4 Correction/reduction factor of R_{ea} for each local manikin body segment at different air speeds ($0 < v_a < 1.0$ m/s) and walking speeds ($0 < w < 1.2$ m/s).

Can the PHS model (ISO7933) predict reasonable thermophysiological responses while wearing protective clothing in hot environments?

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Abstract

In this paper, the prediction accuracy of the PHS (predicted heat strain) model on human physiological responses while wearing protective clothing ensembles was examined. Six human subjects (aged 29 ± 3 years) underwent three experimental trials in three different protective garments (clothing thermal insulation I_{cl} ranges from 0.63 to 2.01 clo) in two hot environments (40°C , relative humidities: 30% and 45%). The observed and predicted mean skin temperature, core body temperature and sweat rate were presented and statistically compared. A significant difference was found in the metabolic rate between FIRE (firefighting clothing) and HV (high visibility clothing) or MIL (military clothing) ($p < 0.001$). Also, the development of heart rate demonstrated the significant effects of the exposure time and clothing ensembles. In addition, the predicted evaporation rate during HV, MIL and FIRE was much lower than the experimental values. Hence, the current PHS model is not applicable for protective clothing with intrinsic thermal insulations above 1.0 clo. The results showed that the PHS model generated unreliable predictions on body core temperature when human subjects wore thick protective clothing such as firefighting clothing ($I_{cl} > 1.0$ clo). The predicted mean skin temperatures in three clothing ensembles HV, MIL and FIRE were also outside the expected limits. Thus, there is a need for further extension for the clothing insulation validation range of the PHS model. It is recommended that the PHS model should be amended and validated by

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individual algorithms, physical or physiological parameters, and further subject studies.

Keywords: PHS model, heat stress, thermoregulatory modeling, protective clothing, hot environment

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Over the past few decades, heat wave shocks and high rates of heat-related morbidity and mortality have become major urgent public health concerns (Semenza *et al* 1999, Weisskopf *et al* 2002, Kovats and Ebi 2006). Although progress has been made scientifically in understanding human thermophysiological responses to various hot environments, it is still a great challenge to predict heat strain accurately for most of the existing human thermoregulation models (Havenith 2001, Sanders 2003). On the other hand, there have been more than 60 heat stress indices developed over the last century to characterize the heat strain introduced by hot environments. However, no heat stress index has achieved widespread acceptance in the field (Brake and Bates 2002).

The predicted heat strain (PHS) model was developed as a part of the EU BIOMED II (Biomedicine and Health) program and later adopted by ISO7933 (Malchaire *et al* 2001). It was aimed at predicting human physiological responses (i.e. predict core temperature and temperature increase over time) in hot environments for occupational groups (especially for standard subjects) (ISO7933 (ISO 2004)). The PHS model calculates heat exchange between the human body and environment, so it can be defined as a rational model (Brake and Bates 2002, Bethea and Parsons 2002). This model was derived from a previous heat stress index 'required sweat rate' SW_{req} (ISO7243 (ISO 1989), ISO7933 (ISO 1989)). One major criticism of this index was that it was only validated for clothing intrinsic thermal insulation $I_{cl} < 0.6$ clo (1 clo = $0.155 \text{ } ^\circ\text{C m}^2 \text{ W}^{-1}$). The PHS model has been validated by data obtained from 672 experiments in 8 European thermal physiology laboratories and 237 field experiments. The clothing intrinsic thermal insulations (mean \pm SD) used in laboratory studies were 0.38 ± 0.34 clo and 0.77 ± 0.18 clo for field studies (Malchaire *et al* 2002). The validation range on clothing intrinsic thermal insulation was extended to $I_{cl} < 1.0$ clo (Malchaire 2006). NIOSH (1986) stated that the thermal insulation values of the most of personal protective equipment (PPE) worn in industry were above 2 clo. Obviously, workers who are required to wear PPE in hot conditions have a much greater chance of suffering from heat stress than those wearing clothing with a thermal insulation value below 1.0 clo. For these reasons, a rational model such as the PHS model is required to supervise occupational workers to reduce physiological strains. Since the PHS model was only applicable for $I_{cl} < 1.0$ clo, there is a need to further extend its validation range on clothing insulation in order to include most of the PPE.

The main aim of this study was to check the prediction reliability of the PHS model on human physiological responses while wearing protective clothing. Three protective clothing ensembles with an intrinsic thermal insulation range of 0.63–2.01 clo were selected for human trials under two hot environmental conditions. The observed and predicted skin temperature, core body temperature (i.e. rectal temperature), evaporation rate and sweat rate while wearing those protective clothing ensembles were presented and statistically compared. Finally, some suggestions on modification of the PHS model were discussed.

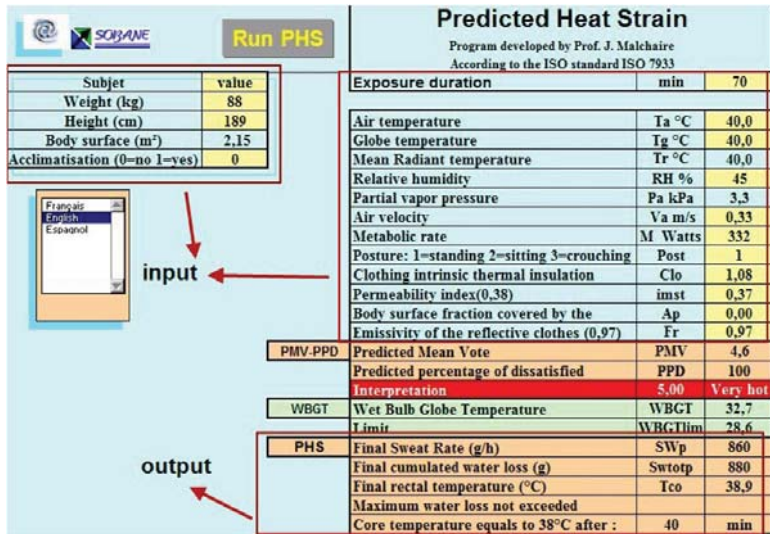


Figure 1. A schematic diagram of the PHS model.

2. Methods

2.1. PHS model

Figure 1 shows a schematic diagram of the PHS model program (Malchaire 2009). The PHS model predicts the sweat rate, cumulated water loss, rectal temperature, and skin temperature curves as a function of the exposure time based on 13 input parameters: subject's weight, subject's height, acclimatization state of the subject, air temperature, globe temperature, relative humidity, air velocity, metabolic rate, posture, clothing intrinsic thermal insulation, permeability index, body surface fraction covered by reflective, and the emissivity of the reflective clothes. The clothing thermal insulation, emissivity of the reflective clothes, permeability index and the metabolic rate used in this model were usually taken from the reference tables specified in annexes C and D in ISO7933 (ISO 2004).

2.2. Subjects

Six male subjects voluntarily participated in the study. All participants were habitually active and in good health. The subjects were informed about the nature of the experiment and signed an informed consent before the participation. The study procedures followed the Helsinki Declaration. The subjects had the following characteristics (mean \pm SD): age = 29 ± 3 years; body weight = 80 ± 8 kg; height = 178 ± 5 cm; body surface area = 1.98 ± 0.12 m²; body mass index = 25.2 ± 2.2 kg m⁻². The subjects were informed that they should neither smoke nor consume caffeine/alcohol 24 h before the experiment. They should also not carry out high intensive physical activities at least 1 h before the experiment. Each subject came to the lab and performed the exposures during the same period of the day with the intervals of at least 1 day between two experiments.

Table 1. Details of the clothing ensembles.

Code	Clothing ensemble components	Total thermal insulation (clo)	Intrinsic thermal insulation (clo)	Evaporative resistance (kPa m ² W ⁻¹)	Permeability index (nd)
HV	Short sleeve t-shirt, briefs, long trousers with 3M reflective materials, socks, sports shoes	1.20	0.63	0.0257	0.44
MIL	Polyamide/cotton jacket, long trousers, short sleeve net t-shirt, briefs, socks, sports shoes	1.65	1.08	0.0421	0.37
FIRE	RB90 firefighting clothes, underwear, t-shirt, briefs, socks, sports shoes	2.58	2.01	0.1224	0.20

HV: high visibility clothing; MIL: military clothing; FIRE: firefighting clothing; nd: nondimensional.

2.3. Experimental garments

Three protective clothing ensembles mainly worn by road construction workers, military during warm season and firefighters were selected for this study. In order to enhance the input accuracy on clothing physical properties for the PHS model, thermal insulation and evaporative resistance were measured using a thermal manikin 'Tore' (Holmér and Nilsson 1995). The tests followed two standards, i.e. ISO15831 (ISO 2004) and ASTM F2370 (ASTM 2010). The manikin surface temperature was controlled at 34 °C. All dry tests were performed at an air temperature of 20 °C and relative humidity of 45%. For wet tests to determine clothing evaporative resistance, a pre-wetted cotton fabric skin (fabric mass per unit area: 228 g m⁻²) was dressed on top of the dry heated thermal manikin. All wet tests were conducted under an isothermal condition, where the ambient temperature was set to 34 °C and the relative humidity was 38%. The partial water vapour pressure inside the climatic chamber was 2 kPa accordingly. The air velocity in the chamber for both dry and wet tests was controlled at 0.33 ± 0.05 m s⁻¹. The description and characteristics of all clothing ensembles are drawn in table 1.

2.4. Test procedure

During preparation, all clothing, equipment (i.e. face mask, chest strap belt and pulse watch etc) and the subject (nude and with all clothing and equipment) were weighed on a weighing scale (KC240, Mettler-Toledo Inc., Zurich, Switzerland, accuracy: ±2 g). After the preparation, the subjects entered into a controlled climatic chamber and were asked to walk on a treadmill (ExerciseTM X Track Elite, Sweden) at a speed of 4.5 km h⁻¹. The subjects were weighed again after 30 min of walking. The heart rate, rectal (T_{re}) and skin (T_{sk}) temperatures were recorded continuously over the whole test period. The termination of walking and exposure was based on one of the following three criteria: (i) subjects felt the conditions were intolerable and were unable to continue, (ii) the rectal temperature T_{re} reached 38.5 °C or (iii) the time limit of 70 min reached, even if none of the above two criteria had been met.

After 70 min of walking, the subjects were weighed again immediately. Afterwards, they were allowed to take off equipment and clothing ensembles. Each piece of the clothing was quickly weighed separately as the subject removed it. Right after the subjects were undressed and the measuring equipment was removed, the subjects were weighed just wearing briefs and the rectal sensor. The sweat rate was calculated from the subject nude weight loss over time. The total evaporation rate was calculated by subtracting the post-exercise body weight from the pre-exercise body weight. The evaporation rate for the last 40 min exposure was also calculated.

2.5. Physiological measurements

The rectal temperature sensor (YSI-401 Yellow Springs Instrument, Measurement Specialties Inc., USA, accuracy ± 0.1 °C) was inserted by the subjects at a depth of 10 cm above the anal sphincter. Skin temperature sensors (NTC-resistant temperature matched thermistors ACC-001, Rhopoint Components Ltd, UK, accuracy ± 0.2 °C, time constant 10 s) were taped on the left side of the body at four sites, i.e. chest, upper arm, thigh and calf. The mean skin temperature was calculated according to Ramanathan's formula (Ramanathan 1964):

$$T_{sk} = 0.3T_{sk_chest} + 0.3T_{sk_upperarm} + 0.2T_{sk_thigh} + 0.2T_{sk_calf}.$$

The rectal and skin temperatures were recorded via a LabVIEW® program (National Instruments Corp., USA) at an interval of 15 s from the point when the subject started walking on the treadmill. In order to get more reliable values on the metabolic rate, the input data used in the PHS model were obtained from oxygen consumption measurements rather than from the reference table (i.e. Annex C in ISO7933). The oxygen uptake was measured with a MetaMax I instrument (Cortex Biophysik GmbH, Germany) for 5 min after 10 min of walking. The heart rate was recorded by a Polar heart rate monitor and a chest strap (Sport Tester, Polar Electro Oy, Finland) during the whole test period.

2.6. Test conditions

All human subject trials were performed at 40.0 °C. Two levels of water vapour pressure in the climatic chamber were selected: 2.0 and 3.0 kPa, when combined with the ambient temperature, resulted in relative humidities of 27% and 41%, respectively. The observed relative humidities in the chamber were 30% and 45%, respectively. Thus, the real partial water vapour pressures in the chamber were 2.2 and 3.3 kPa, respectively. For clothing ensembles HV and FIRE, the trials were conducted at 2.2 kPa. The tests on clothing ensemble MIL were performed at 3.3 kPa. The air velocity was maintained at 0.33 ± 0.05 m s⁻¹ for all exposures.

2.7. Statistical analysis

Data are presented as mean \pm standard deviation (SD). The root mean square deviation (RMSD) was used to check the prediction accuracy on the mean skin temperature and rectal temperature. The RMSD is a frequently used measure of differences between the values predicted by a model and the values actually observed from the phenomenon being modelled or estimated (O'Brien *et al* 1998, Castellani *et al* 2007). The best prediction value is that which gives the minimal RMSD value. Generally, if $RMSD < SD$, the predicted values from PHS model coincide with the observed data from human trials (Bogerd *et al* 2010). Thus, it could be considered that the PHS model predicted acceptable data. On the other hand, the PHS model would generate unacceptable values if $RMSD > SD$. The differences in metabolic rates,

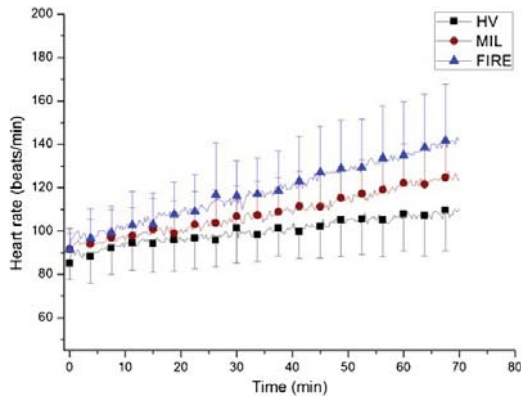


Figure 2. The development of heart rate during HV, MIL and FIRE at 40.0 °C.

sweat rates and evaporation rates in three protective garments were analysed using multi-factor ANOVA (analysis of variance) followed by a multi-comparison *post hoc* test (LSD test). The level of significance was set at $p < 0.05$.

3. Results and discussion

All subjects successfully completed the trials. One subject terminated the exposure after 63 min during FIRE due to the rectal temperature reached 38.5 °C. The heart rate demonstrated the significant effects of the exposure time and clothing ensemble. The increase in mean heart rate during FIRE was significantly higher than in clothing HV or MIL (figure 2). On the other hand, heart rate rose significantly over the exposure time for all three protective clothing ensembles, ending at 110, 124 and 142 bpm (beats per minute) during HV, MIL, and FIRE, respectively.

The observed sweat rate was considerably higher during FIRE than HV (figure 3). The subjects were significantly dehydrated during FIRE ($p < 0.01$), with a mean body weight loss of 0.96 kg, which accounted for about 1.2% of their total body weight. The predicted sweat rate obtained from the PHS model during HV was significantly higher than the experimental data ($p < 0.05$). The predicted values for clothing MIL and FIRE fall within the observed range. The mean evaporation rates for all three clothing ensembles were almost the same. However, the calculated evaporation rates from the last 40 min data showed significant differences between the mean evaporation rates based on 70 min data. This was probably due to the fact that the first 30 min were the sweating development period (Libert *et al* 1983). In addition, the predicted evaporation rate during HV, MIL and FIRE was much lower than the experimental values.

The predicted and observed skin and rectal temperature curves while wearing three protective clothing ensembles HV, MIL and FIRE over time are plotted in figure 4. In the graphs, the prediction curves on body core temperature (T_{re-p}) for clothing ensembles HV and MIL followed the observed curves relatively closely. The initial rate of rise was slightly greater than in the observed curves due to the different initial starting points. However, the predictions on body core temperature during clothing FIRE showed a much greater rise than

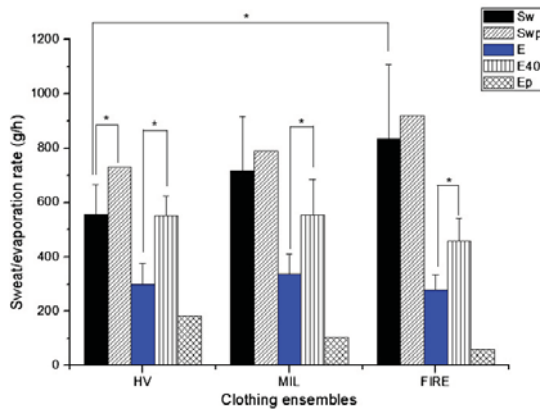


Figure 3. The mean sweat rate Sw , the predicted sweat rate Swp , the mean evaporation rate E , the predicted evaporation rate Ep and the evaporation rate $E40$ calculated from the last 40 min exposure during HV, MIL and FIRE at 40.0 °C. * $p < 0.05$.

Table 2. The calculated RMSD values of the PHS model and the mean SD of experimental data.

	HV	MIL	FIRE
RMSD (T_{sk})	1.21	1.01	0.92
SD	0.38	0.38	0.45
RMSD (T_{re})	0.10	0.37	1.05
SD	0.26	0.36	0.28

the experimental curve. The predicted ending point of the rectal temperature after 63 min exposure was 1.8 °C greater than the observed value. For all predicted skin temperature curves, a much shallower rise in curves during the first 30 min was observed compared to the measured values. The predicted values stayed continuously lower than the observed temperature curves that, however, kept rising.

For a given environmental condition and activity intensity, greater clothing thermal insulation resulted in more body heat strain. Hence, the heat strain parameters such as heart rate, skin temperature and rectal temperature were more pronounced. Also, the metabolic rate was usually higher due to heavier clothing equipment. The mean \pm SD metabolic rates for HV and MIL were 165 ± 6 and 167 ± 7 W m⁻², respectively. The weight of clothing ensemble FIRE was 6.7 kg, which was about three times heavier than clothing HV or MIL. It was also more stiff than the other two ensembles. The mean \pm SD metabolic rate for FIRE was 190 ± 7 W m⁻². Thus, there was a significant difference between FIRE and HV or MIL ($p < 0.001$). This finding is in accordance with the results reported by Dorman and Havenith (2008).

The pre-exercise starting skin temperature and rectal temperature in the PHS model are 34.1 and 36.8 °C, respectively. However, these values are different from our study because subjects had different physical activities before the test. The weather condition on the exposure day may also contribute to this difference (all trials were performed during the wintertime). In order to eliminate the effect of the initial temperature differences on the statistical result, data used for the statistical analysis excluded the first 10 min data, i.e. total 60 min data were

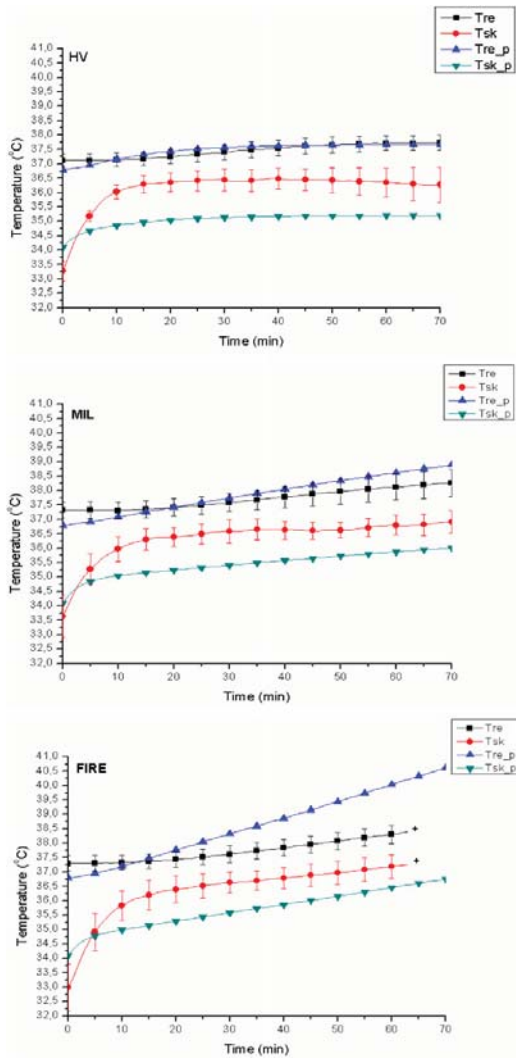


Figure 4. Predicted and observed skin and rectal temperatures plotted as a function of the exposure time for three protective clothing ensembles: HV, MIL and FIRE. T_{re} , mean observed rectal temperature; T_{sk} , mean observed skin temperature; T_{re-p} , predicted rectal temperature; T_{sk-p} , predicted skin temperature. *One subjected stopped the exposure as the core temperature reached 38.5 °C.

used for the analysis. Table 2 shows the RMSD values of the PHS model and the standard deviation of the experimental data.

The predictions from any model are more than two time greater than the mean SD of the observed data which indicates that the model predictions fall outside of the 95% of an average population (Cadarette *et al* 1999). For the skin temperature, the RMSD was 2.0 to 3.2 times greater than the subject average mean standard deviation. Therefore, the predicted skin temperature values from the current PHS model were not reliable. One possible reason could be related to that the skin temperature prediction equation in the PHS program source code has the poorest and lowest correlation when a clothed subject exercises at a humidity level above 2 kPa (Mehnert *et al* 2000). For the rectal temperature, the RMSD values of clothing ensembles HV and MIL were within 1 SD of the observed data. Thus, the PHS model predicted acceptable rectal temperature values for these two clothing ensembles. However, for such a high insulating clothing ensemble as FIRE, the RMSD was 3.75 times greater than the subject average mean standard deviation. As expected, the prediction on rectal temperature for high insulation clothing ensemble FIRE would not function.

Despite being an international standard (ISO7933 (ISO 2004)), the PHS model has been shown to be unable to cover all common heat stress scenarios at work places. Also, the implementation requires input data that may not always be available. The PHS model calculates the human body heat exchange/balance based on environmental parameters, human personal factors and clothing. However, some questionable modifications have been made based on the previous index SW_{req} , modification of respiratory heat loss, distribution of body heat storage, and averaging the skin temperature and sweat rate exponentially. In addition, the validation data on both rectal temperature and sweat rate have revealed a large proportion of variation. The reasons have not yet explained. One possible reason could be that the estimation of human heat balance was based on a thermometry approach (Jay and Kenny 2010).

Furthermore, the PHS model uses estimated clothing insulation and permeability index from the referenced database (ISO9920 (ISO 2007)) as the input data, which may not be that accurate (Gavhed *et al* 2000). The most reliable way is to measure the clothing thermal insulation on a dry heated thermal manikin (Holmér 2004) and evaporative resistance on a sweating guarded hotplate (ISO11092 (ISO 1993)) or a sweating thermal manikin (McCullough 2005, Havenith *et al* 2008, Wang *et al* 2009). The permeability index can be calculated from these two parameters accordingly. Although the PHS model considered the effects of walking and wind on clothing insulation and permeability index, the calculation of permeability index requires clothing evaporative resistance. One suggestion to simplify the calculation on the permeability index is to use an empirical equation to directly calculate the dynamic evaporative resistance (Havenith *et al* 1999, Huang 2007, ISO9920 (ISO 2007)).

The mean skin temperature is one of the most important factors in those studies about the heat exchange between the human body and surrounding environments (Berger and Grivel 1989). However, the mean skin temperature prediction equation used in the PHS model was developed from a pure statistical way (Mehnert *et al* 2000). The effect of clothing (especially PPE) on the skin temperature was not considered. It should be noted that protective clothing might play two distinct roles: it slows the surrounding heat transferring to the human body if the skin temperature is lower than air temperature; on the other hand, it prevents the body heat transferring to the environment when the skin temperature is higher than the air temperature. Therefore, the empirical equation on mean skin temperature in the PHS model requires further modification.

Finally, it is clear that the PHS model is based on the heat balance equation. The metabolic rate is one of the critical inputs that determine whether or not body heat storage will occur. In our study, although the input on metabolic rate was accurately measured using the

cardiopulmonary instrument, the PHS model still generates errors on predicted physiological responses. On the other hand, people always use the estimated metabolic rate as an input for the PHS model in field studies. The estimation may have a quite low accuracy, which could generate even larger errors on the prediction. Moreover, some previous studies showed that estimation of the metabolic rate could introduce an error up to 60% (NIOSH 1986, ISO8996 (ISO 2004), Bethea and Parsons 2002). In order to improve the model prediction, the data from the reference table in ISO7933 must be used with care. More accurate methods are described in ISO9920 (ISO 2007).

4. Conclusions

The PHS model generated the body core temperature predictions that lie outside reasonable limits when the subjects wore thick protective clothing such as firefighting clothing. This could be due to the fact that the PHS model was developed and validated based on occupational clothing with a thermal insulation value below 1.0 clo. The prediction on the mean skin temperature in three tested clothing ensembles also exceeded the set expectations (Pušnik and Miklavc 2009). That might be related to a poor correlation of the skin temperature empirical equation in the program source code with the test conditions specified in this study, e.g., higher partial vapour pressure in the air than 2 kPa. Thus, the PHS model has to be improved in order to achieve widespread acceptance for most common work situations involving heat stress. It may also need simplification in order to implement the method more widely by health and safety personnel at work sites who may not have required level of expertise. Moreover, errors on input parameters should be avoided in order to enhance the model prediction accuracy. It is therefore recommended that the PHS model should be amended and validated by individual algorithms, physical or physiological parameters, and further subject studies.

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Effects of Various Protective Garments and Thermal Environments on Heat Strain of Unacclimated Men: the PHS Model (ISO7933) revisited

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Abstract

Five protective garments (L, HV, MIL, CLM and FIRE) were assessed on eight unacclimated male subjects at two WBGT temperatures: 19.0 and 24.5 °C. The thermophysiological responses and subjective sensations including thermal sensation, humidity sensation and Borg's RPE were reported. Moreover, the PHS model (ISO7933) was used to predict thermophysiological responses for each test scenario. It was found that there were significant differences between FIRE and other clothing on thermal sensation ($p<0.05$). Significant differences were detected on humidity sensation between FIRE and L, HV and MIL ($p<0.001$). The RPE in FIRE is significant different compared to L and HV ($p<0.05$). At 19.0 °C WBGT, the post-exercise skin temperatures increased by 0.59 and 1.29 °C in MIL and CLM. In contrast, skin temperatures in L, HV, MIL, CLM and FIRE at WBGT=24.5 °C increased by 1.7, 2.1, 2.1, 2.8 and 3.3 °C, respectively, core temperatures increased by 0.32, 0.33, 0.39, 0.48 and 0.82 °C, respectively. The PHS model presented good performance on the predicted mean skin temperature in MIL and CLM at both two moderate warm environments. However, the prediction on the skin temperature in light clothing at the high humidity environment was weak. For thick protective clothing, the prediction on rectal temperature showed highly conservative value. It is thus concluded that the present PHS model is inapplicable for high insulating clothing and measurements performed in humid environments. Further work is needed to revise the PHS model in order to enhance its applicability.

Keywords: heat stress, heat strain, PHS model, thermophysiological response, protective clothing

Introduction

People who are doing open air mining, power line constructing, military training, and firefighting jobs are frequently exposed to severe heat stress, which may deteriorate the productivity or even threaten the body survival (Allnutt and Allan, 1973; Epstein *et al.*, 1980). Heat strain arises from different physical activities, clothing ensembles and thermal environments, which results in a rise in both body core and skin temperatures (Shibolet *et al.*, 1976). The physical activity contributes to the total heat stress of the work by generating metabolic heat in the human body in proportion to the work intensity. The heat and moisture transfer characteristics of clothing worn affect the amount of heat stress by changing the dry and evaporative heat exchange rates between the body surface and the working environment (Holmér, 2006). In addition, thermal environmental factors such as the air temperature, air velocity, water vapor pressure and radiation also contribute to the total heat stress (Epstein and Moran, 2006; Johnson, 1946; Millard and Withey, 1998).

Many attempts have been made to assess or predict the corresponding physiological heat strain and to combine various heat stress parameters into a single index, such as the WBGT (wet-bulb globe temperature) index (ISO-7243, 1994) and the DI (discomfort index) index (Jáuregui and Soto, 1967). The US Army Research Institute of Environmental Medicine (USARIEM) developed a Heat Strain Model (Cadarette *et al.*, 1999). This empirical model predicts core temperature, maximum work times, sustainable work/rest cycles, water requirements and heat casualties. Second, many rational models have been developed for predicting body heat strain during the past 60 years, such as the heat strain index (HSI), the index of thermal stress (ITS) and the required sweat rate (ISO 7933) index. Third, more advanced human thermoregulatory models have also been developed. Such models are rather complicated and most of them were derived from a previous fundamental work made by Stolwijk and Hardy (Stolwijk and Hardy, 1977). For example, the LUT 25-node model, the Werner's model and the Tanabe's model (Parsons, 2003; Werner, 1989; Tanabe *et al.*, 2002).

Recently, a rational model "Predicted Heat strain (PHS) model" (Malchaire *et al.*, 2001) was derived from an in-depth revision of the previous Required Sweat Rate model (ISO-7933, 1989; Malchaire *et al.*, 2000) and new algorithms were created based on scientific literature concerning, convection, evaporative heat transfer, rectal and skin temperatures. This rational model was later adopted by ISO 7933 (2004) and was used as a tool to predict human thermo-physiological responses of a

standard person exposed in hot environments. More detailed information about the present PHS model can be found in papers authored by Malchaire *et al.* and also, the international standard ISO 7933 (ISO-7933, 2004; Malchaire, 2006; Malchaire *et al.*, 2001).

In a previous paper, we demonstrated that the PHS model presented unreasonable physiological data for subjects wore high insulating protective clothing in hot environments (Wang *et al.*, 2011). In order to further check the applicability and prediction accuracy of the PHS model, we examined the human physiological responses of eight unacclimatized men in five protective clothing ensembles under two moderate warm environments. The PHS model was applied to check the prediction accuracy on subject's physiological responses such as the rectal temperature and mean skin temperature for each test scenario. Comparisons between observed and predicted data on the rectal temperature and mean skin temperature were also performed. The applicability of the present PHS model was finally addressed.

Methods

Subjects

Eight unacclimated male volunteers with no history of heat illness participated in the study. The mean \pm SD age was 27 \pm 3 (range 24-34), height was 1.76 \pm 0.06 m (range 1.65-1.89), weight was 77.0 \pm 10.2 kg (range 60-92), body surface area was 1.94 \pm 0.15 m² (range 1.66-2.15) and the body mass index (BMI) was 24.6 \pm 2.2 kg/m² (range 22.0-26.1). They were informed that they should not smoke and consume alcohol, coffee or tea two hours before the trial. They should not do high intensive physical activities at least one hour before the experiment either. Each subject performed testing during the same time of a day with an interval of at least 48h between trials in order to minimise the circadian variation of the measured variables.

All subjects were informed of the purpose, procedure and potential risks of the trials. They provided written consents prior to participation. The study protocol followed the Helsinki Declaration.

Clothing ensembles

Five vocational clothing ensembles were selected in the study. The characteristics of all five clothing ensembles are described in Table 1.

Table 1 Details of clothing ensembles.

Code	Garment components	I_T clo	I_{cl} clo	R_e Pa m ² /W	i_m nd
L	short sleeve tee-shirt, briefs, short pants, socks, sports shoes	1.05	0.48	19.8	0.49
HV	short sleeve tee-shirt, briefs, long trousers with reflective materials, socks, shoes	1.20	0.63	25.7	0.43
MIL	jacket, long trousers, short sleeve net tee-shirt, briefs, socks, sports shoes	1.65	1.08	42.1	0.36
CLM	polyamide overall laminated with Gore-tex membrane, short sleeve tee-shirt, briefs, socks, sports shoes	1.68	1.11	74.5	0.21
FIRE	RB90 firefighting clothes, underwear, short sleeve tee-shirt, briefs, socks, sports shoes	2.58	2.01	122.4	0.20

L: light clothing; HV: high vision clothing; MIL: military clothing; CLM: climber overall; FIRE: firefighting clothing. I_{cl} , clothing intrinsic thermal insulation; i_m , clothing permeability index; nd, nondimensional.

Test procedures

All clothing, equipment and subjects were weighed on a weighing scale (Mettler-Toledo Inc., Switzerland, precision: ± 2 g) during preparation. After the preparation, the subject came into a climatic chamber, and walked on a motorized treadmill (Exercise™ X Track Elite, Sweden) at 4.5 km/h (i.e., 1.25 m/s). In order to get a steady-state sweat production rate, the subjects were weighed again after 30 min of walking (Wang *et al.*, 2011). The heart rate, the rectal (T_{re}) and skin (T_{sk}) temperatures were recorded throughout the exposure. Test sessions were terminated when one of the following three criteria was reached: (i) subjects felt the conditions were intolerable and were unable to continue, (ii) the rectal temperature T_{re} reached 38.5 °C or (iii) subjects walked 70 min on the treadmill.

The subject was weighed again immediately after the exposure. Afterwards, they took off equipment and garments. Each garment was quickly weighed separately after the subject removed it. Right after the subjects were undressed and the measuring equipment was removed, the subject was weighed just wearing briefs and the rectal sensor.

Measurements and Calculations

The rectal sensor (YSI-401 Yellow Springs Instrument, Measurement Specialties Inc., USA, accuracy ± 0.1 °C) was inserted by the subject at a depth of approximately 10 cm beyond the anal sphincter. Four thermocouples (NTC-resistant temperature matched thermistors ACC-001,

Rhopoint Components Ltd, UK, accuracy ± 0.2 °C, time constant 10s) were taped (surgical waterproof tape, 3M, USA) on the left side of the human body at four sites, i.e., chest, upper arm, thigh and calf. The mean skin temperature was calculated using the Ramanathan 4-point weighting system (Ramanathan, 1964) of 0.3 chest, 0.3 upper arm, 0.2 thigh and 0.2 calf. The rectal and skin temperatures were recorded via a LabVIEW program (National Instruments Corp., USA) with an interval of 15s when the subject started walking on the treadmill. The oxygen uptake was measured with a MetaMax I instrument (Cortex Biophysik GmbH, Germany) for 5 min after 10 min of walking. A heart rate monitor (Sport Tester, Polar Electro Oy, Finland) was worn throughout the exposure.

Subjective ratings

Subjective ratings of the perceived physical exertion, based on Borg RPE Scale (Borg, 1982), 9-point whole-body thermal sensation (-4= very cold to 4= very hot) (EN-10551, 2001) and 4-point skin humidity sensation (0= neutral, 1=slightly wet, 2=wet, 3= very wet) were recorded every 10 min during the whole exposure.

Test Conditions

Two thermal environmental conditions were chosen, 20 °C, RH=86 % (WBGT=19.0 °C) and 30 °C, RH=47 % (WBGT=24.5 °C). At WBGT=19.0 °C, the subjects performed three trials in clothing ensembles HV, MIL, and CLM. At WBGT=24.5 °C, they conducted totally five trials with all five clothing ensembles. The air velocity inside the climatic chamber was controlled at 0.33 ± 0.05 m/s.

Statistical analysis

Means and SD (standard deviation) during the whole exposure period were reported for dependent variables. Using a SPSS 16.0 (SPSS Inc., Chicago, IL, USA) program, the repeated measures ANOVA was used to determine whether there were significant differences on the metabolism, heart rate, subjective sensations, sweat rate and the evaporative rate for different clothing and thermal environments. The statistical significance was set at $p < 0.05$.

Results

All subjects successfully completed each exercise at eight different test scenarios. The measured and calculated parameters are presented in the following four sections.

Metabolism and heart rate

The mean metabolic rate and heart rate of all eight subjects were displayed in Table 3. The mean heart rate was about 100 bpm (beats per minute) for all test conditions and no significant difference was observed among those clothing ensembles ($p>0.1$). Similarly, the two thermal temperatures have no significant effect on the heart rate either ($p>0.1$). The metabolic rates during walking in clothing ensembles L, HV, MIL and CLM were around 165 W/m^2 . In contrast, the metabolic rate in clothing FIRE was significantly higher than other four clothing ensembles ($p<0.001$). Additionally, the testing temperature has no significant effect on the subject's metabolic rate ($p>0.1$).

Table 3 The metabolic rate and heart rate for all eight test scenarios (mean \pm SD)

Clothing ensemble	WBGT °C	Metabolism W/m^2	Heart rate bpm
HV	19.0	169 \pm 13	95 \pm 14
MIL	19.0	163 \pm 7	92 \pm 15
CLM	19.0	167 \pm 11	99 \pm 15
L	24.5	163 \pm 7	96 \pm 14
HV	24.5	164 \pm 12	98 \pm 13
MIL	24.5	165 \pm 11	94 \pm 11
CLM	24.5	175 \pm 14	108 \pm 19
FIRE	24.5	190 \pm 6*	107 \pm 17

* $p<0.001$.

Subjective sensations

All subjects had very similar pre-exercise subjective sensations. The post-exercise subjective sensations of all eight subjects were presented in Table 4. The clothing ensemble has significant effects on the three subjective sensations ($p<0.05$). In contrast, the temperature has significant effects on the thermal and skin humidity sensations, but not on the RPE. Significant differences were detected between the clothing FIRE and other four clothing ensembles on the thermal sensation ($p<0.05$). Similarly, the skin humidity sensation in clothing FIRE has significant differences with

clothing L, HV and MIL ($p<0.001$). Furthermore, the RPE in clothing FIRE has significant differences with clothing L and HV ($p<0.05$). However, no significant differences were registered between clothing FIRE and MIL on the humidity sensation and RPE ($p>0.1$).

Table 4 The subjective thermal sensations at the end of the exposures (mean±SD)

Clothing ensemble	WBGT °C	Thermal sensation	Skin humidity sensation	RPE
HV	19.0	0.94±0.86	1.25±0.46	11.6±2.1
MIL	19.0	1.13±0.64	1.13±0.35	11.5±1.6
CLM	19.0	2.06±0.56	2.06±0.18	12.2±1.7
L	24.5	2.32±0.96	1.81±0.53	11.4±2.2
HV	24.5	2.13±0.69	1.75±0.46	12.1±2.4
MIL	24.5	2.38±0.79	2.13±0.52	12.3±2.2
CLM	24.5	3.00±0.60	2.50±0.27	13.1±1.4
MIL	24.5	3.63±0.79*	2.69±0.46*	14.1±2.1

* $p < 0.05$.

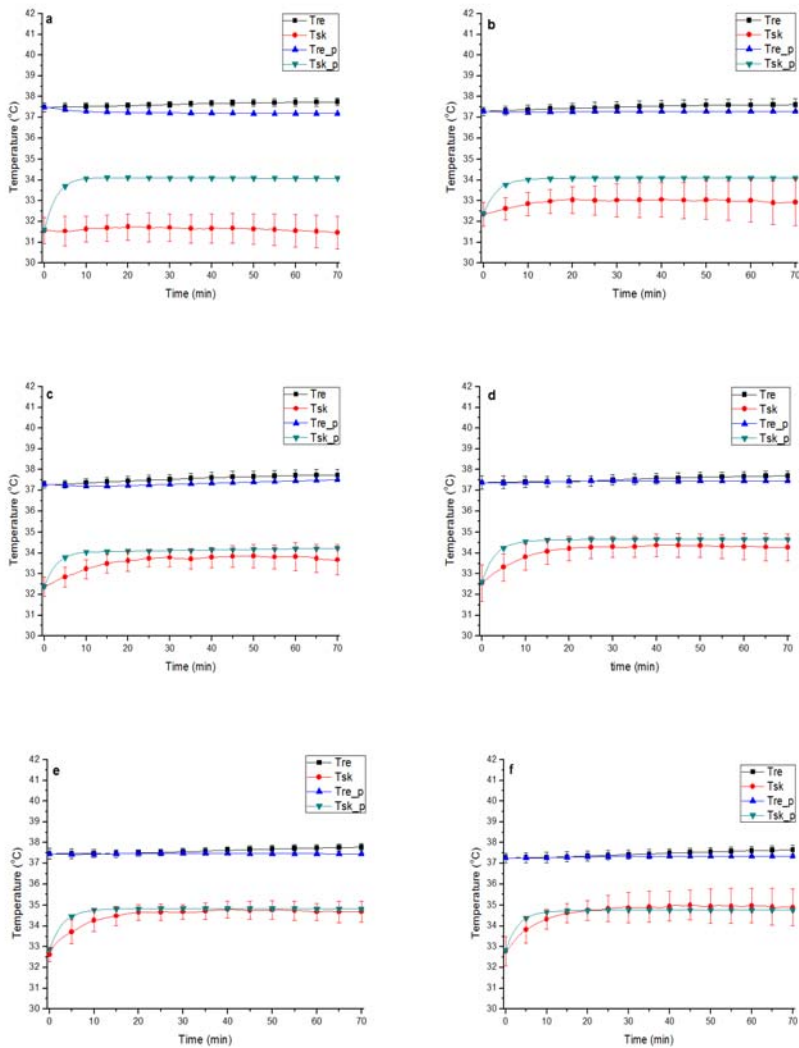
Comparison of predicted and observed skin and rectal temperatures

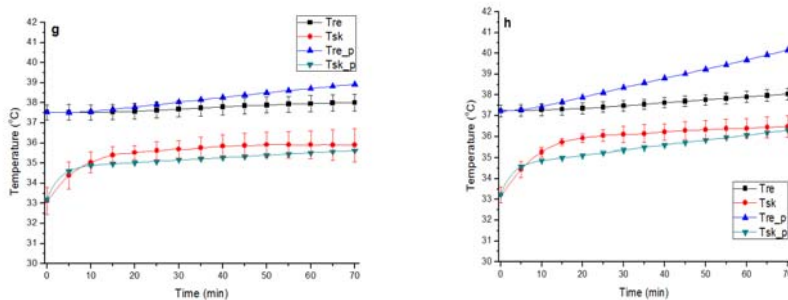
The observed rectal and skin temperatures for all eight test scenarios were illustrated in Figures 1a-h. At an environment temperature of 19.0 °C WBGT, the mean skin temperatures in clothing MIL and CLM were stable during the last 40-minute exposure, which increased by 0.57 and 1.29 °C compared with their initial points. However, the mean skin temperature in clothing HV decreased slightly by 0.1 °C. After 70 min exposure, the rectal temperature in clothing ensembles L, HV, and MIL increased by 0.26, 0.33 and 0.45 °C, respectively.

For clothing ensembles L, HV and MIL at WBGT=24.5 °C, the observed skin temperature was also stable during the last 40 min exposure. However, the mean skin temperatures in clothing CLM and FIRE continuously increased with the testing time. The mean skin temperatures in clothing ensembles L, HV, MIL, CLM, and FIRE increased by 1.7, 2.1, 2.1, 2.8 and 3.3 °C, respectively. In contrast, the rectal temperatures in clothing ensembles L, HV, MIL, CLM and FIRE increased by 0.32, 0.33, 0.39, 0.48 and 0.82 °C, respectively.

A PHS model program (Wang *et al.*, 2011) was applied to predict the skin and rectal temperatures for all testing scenarios. Compared with the original

source code presented in the international standard ISO 7933(ISO-7933, 2004), the only modification was made on the initial points of rectal and skin temperatures. The initial skin and rectal temperatures in this PHS program were set the same as our observed values for each test condition. The predicted temperature curves for all test conditions were also plotted in Figs 1a-h.





Figs 1a-h Predicted and observed mean skin and rectal temperatures for all five clothing ensembles at 19.0 and 24.5 °C WBGT. a) HV at WBGT=19.0 °C; b) clothing MIL at WBGT=19.0 °C; c) CLM at WBGT=19.0 °C; d) L at WBGT=24.5 °C; e) HV at WBGT=24.5 °C; f) MIL at WBGT=24.5 °C; g) CLM at WBGT=24.5 °C; h) FIRE at WBGT=24.5 °C; T_{re} , mean rectal temperature; T_{sk} , mean skin temperature; T_{re_p} , predicted rectal temperature; T_{sk_p} , predicted mean skin temperature.

The PHS model demonstrated good performance on predicted skin temperature in clothing MIL and CLM at both warm and hot environments. However, there was a large discrepancy between the predicted and observed skin temperatures in light clothing such as clothing HV at a high humidity environment, i.e., WBGT=19.0 °C. The predicted skin temperature curve showed an initial rate of rise much greater than the experimental data at the first 10 min, and then adopted a relatively constant temperature plateau. The predicted skin temperature after 70 min exposure was 2.01 °C greater than the experimental data. On the other hand, the predicted rectal temperature curves in clothing MIL and CLM at the warm humid environment followed closely the observed curves. However, for clothing HV at WBGT=19.0 °C, the post-exercise rectal temperature was 0.56 °C lower than the observed temperature. Moreover, the predicted curves on the rectal temperature at WBGT=24.5 °C in clothing L, HV and MIL also showed good performance. However, as shown in Figure 1g, the predicted rectal temperature curves in clothing CLM rose above the observed curve after about 45 min. Similarly, the predicted rectal temperature curve stayed above the still rising experimental curve after 15 min. Finally, the predicted rectal temperatures in clothing CLM and FIRE at WBGT=24.5 °C were 0.92 and 2.12 °C greater than the observed data.

Sweat and evaporation rates

The sweat production rate (g/h) was calculated from the nude body weight differences between pre- and post-exercise. Similarly, the evaporation rate was calculated from the weight differences of the human/clothing system before and after the trial. The sweat and evaporation rates at 19.0 and 24.5 °C WBGT were plotted in Figures 2a and 2b. The evaporation rate based on the last 40-min data was also presented. The clothing ensemble and testing temperatures have significant effect on the sweat rate ($p_1 < 0.01$, $p_2 < 0.01$). Similarly, the testing temperature also has a significant effect on evaporation rate ($p < 0.01$). However, the clothing ensemble has no significant effect on the evaporation rate ($p_1 > 0.5$, $p_2 > 0.5$). The predicted sweat rates in clothing MIL, CLM and FIRE at both two moderate warm environments were significantly greater than the observed values ($p < 0.05$). Also, the predicted evaporation rates were significantly underestimated for all test scenarios except clothing L and HV at WBGT=19.0 °C ($p < 0.05$). However, the predicted sweat rates in clothing L and HV were in close agreement with experimental data.

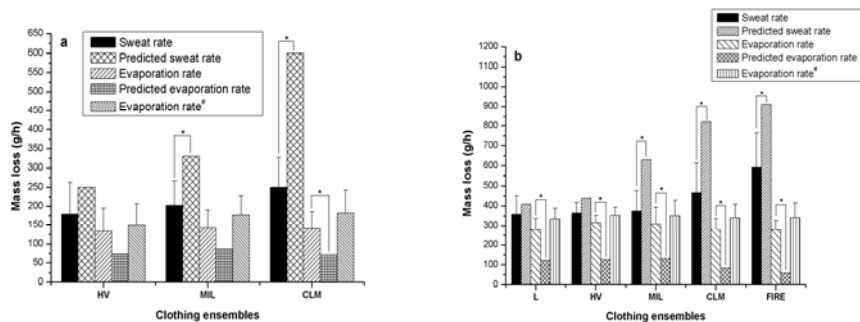


Figure 2 The observed and predicted sweat rate and evaporation rate. a) WBGT=19.0 °C; b) WBGT=24.5 °C; [#] based on the last 40 min data; * $p < 0.05$.

Discussion

The clothing thermal properties and environmental conditions such as thermal insulation, evaporative resistance, and air temperature play an important role in determining the human body heat balance. Most vocational clothing ensembles are made to protect the human body against various heat and chemical hazards, however, they may generate serious ergonomic problems (Havenith and Heus, 2004; Coca *et al.*, 2010). The main problem is the added load on the body in terms of weight, but reduced in the mobility might also be a problem because of the garment bulkiness,

stiffness and fit (Holmér, 2006). In our study, the clothing ensemble FIRE (total weight: 6.45 kg) was almost 4 times heavier than clothing L, and twice than clothing CLM. The metabolic rate and RPE value of all subjects in clothing FIRE at WBGT=24.5 °C increased about 10 % (metabolism: 15 W/m²; RPE: 1.6), which made it significantly different with other 4 clothing ensembles. This finding reconfirmed the conclusions described in previous studies (Holmér, 1995; Dorman, 2007).

Yamauchi and Morooka (Yamauchi and Morooka, 2002) studied the effect clothing humidity on the humidity sensation on human subjects. They concluded that the clothing humidity related more to the comfort feeling than the thermal sensation. Furthermore, they found that there was a higher positive correlation between humidity sensation and clothing humidity. Moreover, there were significant correlations between humid sensation and some physiological responses such as the heart rate, the oral temperature, and the mean skin temperature. Fan and Tsang (Fan and Tsang, 2008) investigated the effect of clothing thermal properties on the thermal comfort sensation during active sports. They observed that the thermal comfort sensations during active sports were strongly related to the evaporative resistance and moisture accumulation within clothing. In our study, the permeability index of all five clothing ensembles ranged from 0.20 to 0.49. The evaporative resistance of all clothing ensembles ranged from 19.8 to 122.4 Pa·m²/W. The clothing ensembles CLM and FIRE can be classified as impermeable clothing accordingly (the permeability index of typical outdoor 1-2 layer clothing was around 0.38 (Havenith *et al.*, 1999; Holmér, 2006). Such impermeable clothing ensembles could significantly influence the humidity sensation, comfort sensation and thermal sensation of the subjects.

The sweat accumulation inside clothing ensembles HV, MIL, and CLM after 70 min under the warm environment were 53, 70 and 127 g, respectively (expressed as the percentage of produced sweat: 25.1, 29.6, and 43.6 %). Similarly, for all clothing ensembles at 24.5 °C WBGT, the sweat accumulations were 92, 56, 78, 216 and 364 g (expressed as the percentage of produced sweat: 22.1, 13.5, 17.9, 39.8, and 52.7 %), respectively. No differences in sweat accumulation were registered in clothing ensembles L, HV and MIL at those two thermal environments. However, there was a much higher percentage of sweat accumulation inside clothing ensembles CLM and FIRE. The high sweat accumulation was directly corresponded to the humidity and comfort sensations of the subjects.

At a moderate warm environmental condition such as 19.0 °C WBGT, the mean skin temperatures of the subjects in clothing ensembles HV, MIL and CLM were relatively stable during the last 40-min walking, fluctuating within 0.1 °C. With only a short sleeve tee-shirt covered the upper body in clothing HV, the thermocouple attached on the left upper arm located close to the sleeve opening, which caused the mean skin temperature was much lower than other clothing at the same test environment. Furthermore, the rectal temperature increased slightly throughout the exposure in all three clothing ensembles, the increase became slow at the end of the experiments, however. For impermeable clothing ensembles CLM and FIRE at WBGT=24.5 °C, the mean skin and rectal temperatures increased continuously with the time. In this situation, the physiological heat strain could not be compensated enough by the sweat evaporation, convective and radiative heat losses.

Furthermore, Sakoi et al. (Sakoi *et al.*, 2006) reported the characteristics of the Required Sweat Rate index and pointed out that the multiple regression formula used for skin temperature prediction cannot reflect all heat transfer characteristics. Although some important modifications based on this index were made afterwards for the present PHS model, our recent study (Wang *et al.*, 2011) has clearly demonstrated that the present PHS model is inapplicable for heavy protective clothing and those tests conducted in very humid environmental conditions. The current PHS model generated relatively conservative data on the duration limited exposure (Smolander *et al.*, 1991) and thus, the worker's productivity is highly reduced. In this study, the prediction curve in clothing HV at WBGT=19.0 °C and clothing CLM and FIRE at WBGT=24.5 °C reconfirmed those findings. In order to maximize the worker's productivity but keep them safe, it is necessary to revise the current PHS model and extend its applicability. Some empirical equations such as the mean skin calculation equation (Mairiaux *et al.*, 1987; Mehnert, 2000) in the PHS model might be replaced by improved equations. Additionally, further human subject studies might be needed to modify the current PHS model to enhance the prediction accuracy.

Conclusions

In summary, we assessed five protective clothing ensembles on eight unacclimatized male subject tests at two WBGT levels: 19.0 and 24.5 °C. Comparisons were also made between the experimental data and the predicted values by the current version PHS model. Some important findings are summarized as below:

1. The study reconfirmed that the thick and high insulating protective clothing such as firefighting clothing could increase around 10 % of the total metabolic rate compared with light clothing.
2. There were significant differences between the clothing FIRE and other four clothing ensembles on the thermal sensation ($p<0.05$). Significant differences were registered on humidity sensation between clothing FIRE and clothing ensembles L, HV and MIL ($p<0.001$). The RPE value in clothing FIRE has significant differences with those in clothing L and HV ($p<0.05$). However, no significant differences were observed between clothing FIRE and MIL on the humidity sensation and RPE ($p>0.1$). Moreover, there was a significant difference in sweat rate between clothing FIRE and other 4 clothing ensembles. The predicted sweat rate and evaporation rate in clothing MIL, CLM and FIRE were significantly different with the experimental values.
3. At 19.0 °C WBGT, the post-exercise mean skin temperature increased by 0.59 and 1.29 °C in clothing MIL and CLM. Similarly, the rectal temperatures in clothing HV, MIL and CLM increased 0.26, 0.33 and 0.45 °C, respectively. In contrast, the rectal temperatures in clothing L, HV, MIL, CLM and FIRE at WBGT=24.5 °C, increased by 0.32, 0.33, 0.39, 0.48 and 0.82 °C, respectively. The skin temperatures in clothing L, HV, MIL, CLM and FIRE increased by 1.7, 2.1, 2.1, 2.8 and 3.3 °C, respectively.
4. The PHS model presented good performance on the predicted mean skin temperature in clothing MIL and CLM at both two moderate warm environments. However, there was a large discrepancy between the predicted and observed skin temperatures in light clothing such as clothing HV at a high humidity environment (WBGT=19.0 °C). For high insulating clothing ensembles such as clothing CLM and FIRE, the predicted data on rectal temperature showed highly conservative values. Furthermore, the PHS model demonstrated a weak ability in predicting mean skin temperature for subjects wore light clothing in a high humidity environment, e.g., the clothing L at WBGT=19.0 °C. It is thus concluded that the present PHS model is inapplicable for high insulating protective clothing and measurements performed in humid environments. Finally, further work at higher work intensity is needed to revise the PHS model in order to enhance its applicability.

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Conflict of interest

The authors declare that they have no conflict of interest.

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