A PROPOSED METHOD FOR QUANTIFYING THE EFFECTS OF WIND *AND* HUMAN MOVEMENT ON THE THERMAL AND VAPOR TRANSFER PROPERTIES OF CLOTHING

K.C. Parsons[1], *G.* Havenith[1,2], I. Holmér[3], H. Nilsson[3] and J. Malchaire[4]

[1]Department of Human Sciences, Loughborough University, UK
[2]Formerly, TNO-Human Factors Research Institute, Soesterberg, NL
[3]National Institute for Working Life, Solna, Sweden
[4]Universite Catholique de Louvain, Belgium

❧

INTRODUCTION

This paper provides a preliminary proposal to improve models of the thermal properties of clothing by taking the effects of wind and human movement into account. The improvements can have a significant impact on the estimated heat transfer properties of clothing and are of practical importance. Methods for the assessment of the thermal strain caused by exposure to hot, moderate and cold environments require a mathematical quantification of the thermal properties of clothing. These are usually considered in terms of "dry" thermal insulation and vapor resistance (1). This simple model of clothing can account for the insulation properties, which reduce heat loss (or gain) between the body and the environment and the resistance to the transfer of evaporated sweat from the skin, which is important for cooling the body in a hot environment. However, when a clothed person is either exposed to wind or is active, potentially there is a significant limitation in the simple model of clothing. Heat and mass transfer can take place between the microclimate (i.e., within clothing and next to the skin surface) and the external environment. This paper integrates the research presented in the papers of Havenith et al. (2) and Holmér et al. (3) in this volume.

CLOTHING UNITS AND REDUCTION FACTORS

The earliest, and still preferred, method of handling clothing heat transfer is to combine convection, radiation and conduction into one term, the *dry* heat transfer coefficient (1). The insulation value includes all layers from the skin to the environment: clothing layers as well as the boundary air layer. Burton also introduced a new unit for clothing insulation—the clo unit. One clo of insulation equals 0.155 $m^{-2} \cdot °C \cdot W^{-1}$ and is the "normal" indoor clothing that will maintain heat balance in a resting man under normal indoor climatic conditions. Simple units for the intrinsic vapor resistance of clothing have not been developed, but a typical value for permeable clothing would be around 0.015 $m^{-2} \cdot kPa \cdot W^{-1}$(6). The International Standards Organization **(ISO)** 7933 (4) uses two clothing reduction factors to quantify the heat and vapor transfer properties of clothing. These are F_{cl} and F_{pcl}, respectively, and are described in detail by Holmer et al. (3) and Havenith et al. (2). Burton suggested that the effect of clothing could be described **as** the reduction factor, F_{cl}, compared to "nude" conditions. The F_{cl} is

the insulation of the air layer around the nude body (boundary layer or resistance of the environment) divided by the sum of the intrinsic insulation of clothing plus the insulation of the air layer around the clothed body (total clothing insulation). Thus, for a nude person the F_{cl} is unity, and for a clothed person it is a reduction factor. The F_{pcl} reduction factor *(5)* is the vapor resistance of the air layer around the nude body divided by the **sum** of the intrinsic vapor resistance of clothing and the vapor resistance of the air layer around the clothed body. Hence, this is a reduction factor for a clothed person.

HEAT *AND* **VAPOR TRANSFER THROUGH CLOTHING**

ISO 7933 (1989) provides the following formulas for clothing properties:

$$C = F_{cl} \circ h_c (t_{sk} - t_a) \quad (1)$$
$$R = F_{cl} \circ h_r (t_{sk} - t_r) \quad (2)$$
$$E = w (P_{sk,s} - P_a)/RT \quad (3)$$
$$RT = 1/h_e \circ F_{pcl} \quad (4)$$
$$h_e = 16.7 \circ h_c \quad \textbf{(5)} \quad \text{where,}$$

C = heat transfer by t_{sk} = mean skin temperature

R = heat transfer by radiation t_a = air temperature

E = heat transfer by evaporation t_r = mean radiant temperature

h_c = convective heat transfer coefficient   w = skin wettedness

h_r = radiative heat transfer coefficient P_a = partial vapor pressure in the air

h_e = evaporative heat transfer coefficient

$P_{sk,s}$ = saturated vapor pressure at skin temperature

PROPOSED CLOTHING MODEL

Data from stationary and moving human subjects and manikins were used to derive a general correction to "static" insulation values, based upon empirical analysis. The resulting "corrections" provide dynamic values that can be used to assess likely thermal strain. The model requires values for t, t_r, v_a (absolute wind speed in the environment), Pa and M (metabolic rate of the person). An annotated version of parts of a **BASIC** computer program describes the model.

Calculation **of** the relative air **speed** between the body and the environment

The heat transfer from the body will depend upon the relative air movement between the body and the environment, not the absolute air speed. The model considers three cases. When the body is stationary or moving at an undefined speed, the relative air velocity is taken as the absolute air velocity, but the effects of movement (equivalent to walking) are related to the difference between active metabolic rate and that seated at rest (58 W·m⁻²). **This** is limited to an equivalent of a walking speed of **0.7 m·s⁻¹**. When the activity is unidirectional walking, then the angle between walking and the wind is taken into account (e.g., walking into

wind, angle = 0; wind behind, angle = 180). If walking is omni-directional with respect to the wind, then walking speed or absolute air velocity are taken as relative air velocity, whichever is greater. The following is in the program:

```
IF 'Stationary or undefined speed
Walksp = .0052*(Metn - 58):  IF Walksp > .7 THEN Walksp = .7
Var = Va
ELSE
IF ' unidirectional walking
THETAR = (3.14159/180)*THETA
Var = ABS(Va - Walksp*COS(THETAR))
ELSE ' Omnidirectional walking
IF Va<Walksp THEN Var = Walksp ELSE Var = Va
ENDIF
```

Clothing insulation values under static conditions

This part of the model calculates the total clothing insulation for static conditions from the intrinsic clothing insulation values. This is necessary as the correction for wind and human movement was determined using values of total clothing insulation. The intrinsic static clothing insulation is first converted from clo units to $m^{-2} \cdot K \cdot W^{-1}$. The total clothing insulation is the intrinsic clothing insulation plus the insulation of the air layer (I_{ast} = $1/HCR_{st}$; this value is assumed to be 1/9 and is corrected for the increase in available surface area for heat exchange caused by clothing [fcl]). Following is the program example:

```
Iclst = Clo * 0.155
fcl = 1 + 0.3 * Clo
HCRst = 9
Iast = 1/HCRst
Itotst = Iclst + Iast/fcl
```

Correction to static insulation for wind and walking

This is based upon a regression equation providing the best fit from a database of measurements over a wide range of wind speeds, walking speeds and clothing types. Where the ranges are exceeded, limiting values are provided for the corrections. It should be remembered that the correction due to walking takes into account only the effects of the movement (e.g., pumping effects) and not those of the relative air velocity that would result from a walking person, which is considered elsewhere. Because light clothing below 0.6 clo was not included in the database, a simple interpolation is taken for corrections between 0.6 clo and 0 clo (nude). The correction for the air layer is for nude data. For example:

```
Vaux = Var: IF Var >3.5 THEN Vaux = 3.5
Waux = Walksp: IF Walksp >1.5 THEN Waux = 1.5
CORRclothed = 1.044*EXP((.066*Vaux-.398)*Vaux+(.094*Waux-.378) *Waux)
IF CORRclothed>1 THEN CORRclothed = 1
```

CORRia $= $ **EXP((.047*Var-.472)*Var+(.117*Walksp-.342)*Walksp)**
IF CORRia>1 **THEN** CORRia=1
IF Clo **<=.6 THEN** CORRtot $=$ **((.6-clo)*CORRia+clo*CORRclothed/.6**
ELSE
CORRtot $=$ CORRclothed
ENDIF

Dynamic clothing insulation

The correction factors calculated above are used to correct the static insulation values to dynamic insulation values. These are used instead of the static values to provide an improved model of heat transfer. For example:

Itotdyn $=$ Itotst * CORRtot
Iadyn $=$ CORRia * IAst
Icldyn $=$ Itotdyn - Iadyn/fcl

Dynamic vapor resistance

This part of the computer program uses the Lewis relation and the correction to total clothing insulation to provide a dynamic vapor resistance value. It uses the Woodcock vapor permeation index (im). Values of im in static conditions can be found from tables and would be required as an input to the model. The dynamic im is a corrected, static im and leads to the calculation of a dynamic RT value. This is then used in the calculation of evaporative heat transfer as described above. For example:

Lewis $=$ **16.7**
reduct $=$ **1 -** CORRtot
CORRe $=$ (1+[1.3+2.6*reduct]*reduct)
imdyn $=$ imst*CORRe: IF imdyn>.9 **THEN** imdyn $=$**.9**
Rtdyn $=$ Itotdyn/imdyn/Lewis

SUMMARY

Empirical research using thermal **manikins** and human subjects has led to improvements in the representation of the thermal and vapor resistance properties **of** clothing. The proposals have practical significance and will affect estimations of the thermal strain caused by hot environments.

REFERENCES

1. **Burton, A.C.** and Edholm, O.G. 1955, *Man in a cold environment.* (London: Edward Arnold), **273.**
2. Havenith, **G.,** Holmér, I., den Hartog, **E.** and **Parsons,** K.C. **1999,** Representation of the effects of movement and wind **on** clothing vapor resistance in ISO standards, in **J.A.** Hodgdon, J.H. Heaney and **M.J. Buono** (eds.), *Environmental Ergonomics VIII,* (San Diego, **CA: ICEE), 305-310.**

3. Holmér, I., Nilsson, H., Havenith, G. and Parsons, K.C. **1999,** Convective heat loss through clothing, in J.A. Hodgdon, J.H. Heaney and M.J. Buono (eds.), *Environmental Ergonomics VIII,* (San Diego, CA: ICEE), **293-296.**

4. ISO **7933. 1989,** Hot environments: Analytical determination and interpretation of thermal stress using calculation of required sweat rate. (Geneva: International Standards Organization).

5. Nishi, **Y.** and Gagge, A.P. **1970,** Moisture permeation of clothing—a factor governing thermal equilibrium and comfort, *ASHRAE Transactions,* **76, 137-145.**

6. Parsons, **K.C. 1993,** *Human Thermal Environments.* (London: Taylor & Francis).

ACKNOWLEDGEMENTS