Pergamon

PII: S0003-4878(99)00061-7

Ann. occup. Hyg., Vol. 43, No. 5, pp. 347–352, 1999

Printed in Great Britain.
0003–4878/99/$20.00 + 0.00

The Effects of Wind and Human Movement on the Heat and Vapour Transfer Properties of Clothing

K. C. PARSONS*§, G. HAVENITH*[1], I. HOLMÉR†, H. NILSSON† and J. MALCHAIRE‡

**Department of Human Sciences, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK; †National Institute for Working Life, Solna, Sweden; ‡Université Catholique de Louvain, Belgium*

This paper integrates the research presented in the papers in this special issue of Holmér *et al.* and Havenith *et al.* [Holmér, I., Nilsson, H., Havenith, G., Parsons, K. C. (1999) Clothing convective heat exchange: proposal for improved prediction in standards and models. Annals of Occupational Hygiene, in press; Havenith, G., Holmér, I., den Hartog, E. and Parsons, K. C. (1999) Clothing evaporative heat resistance: proposal for improved representation in standards and models. Annals of Occupational Hygiene, in press] to provide a practical suggestion for improving existing clothing models so that they can account for the effects of wind and human movement. The proposed method is presented and described in the form of a BASIC computer program. Analytical methods (for example ISO 7933) for the assessment of the thermal strain caused by human exposure to hot environments require a mathematical quantification of the thermal properties of clothing. These effects are usually considered in terms of 'dry' thermal insulation and vapour resistance. This simple 'model' of clothing can account for the insulation properties of clothing which reduce heat loss (or gain) between the body and the environment and, for example, the resistance to the transfer of evaporated sweat from the skin, which is important for cooling the body in a hot environment. When a clothed person is exposed to wind, however, and when the person is active, there is a potentially significant limitation in the simple model of clothing presented above. Heat and mass transfer can take place between the microclimate (within clothing and next to the skin surface) and the external environment. The method described in this paper 'corrects' static values of clothing properties to provide dynamic values that take account of wind and human movement. It therefore allows a more complete representation of the effects of clothing on the heat strain of workers.

Keywords: clothing; heat stress; vapour transfer

INTRODUCTION

The wearing of clothing during work in the heat will have major effects on the thermal strain of workers. If the work is hard and the clothing is heavy, then serious effects on health can occur in what may ordinarily be considered to be moderate environments. If environments are hot then the work is potentially dangerous. To predict the extent of the thermal strain on workers and whether it will be acceptable, any risk assessment must consider the influence of clothing and must therefore take a view on the thermal properties and effects of the clothing. A simple approach would be to judge the likely effects from minimally clothed/very light clothing, where the worker would be free to evaporate sweat and lose heat to the environment, to heavy and impermeable clothing which will restrict the evaporation of sweat and hence cause the body to 'heat up' rapidly in a hot environment. Where clothing is worn the heat and vapour (evaporated sweat) transfer properties of the clothing will be important. A simple estimate of these properties can be obtained from tables of different clothing garments and ensembles (for example ISO 9920 (1995)). Also of great significance however are the ventilation properties of the clothing and how the thermal properties are affected by the workers' activity and environment. If the worker

Received 6 January 1999; in final form 20 May 1999.
§Corresponding author. Tel.: +44-1509-223-023; fax: +44-1509-223-940.
[1]Formerly TNO-Human Factors Research Institute, Soesterberg, The Netherlands

moves, then depending on clothing design and type, saturated warm air will be forced through vents and the clothing layers. If there is wind then this will also affect the exchange of air between the microclimate within clothing and the outside environment. Traditional methods for the assessment of heat stress rarely take these important factors into account. Failure to do so may greatly distort any heat stress assessment and any method that provides guidance on these thermal properties will have practical value and will improve the validity of heat stress assessment methods. This paper presents a method for incorporating the effects of wind and human movement into an estimate of the thermal properties of clothing such that it can improve heat stress assessment methods.

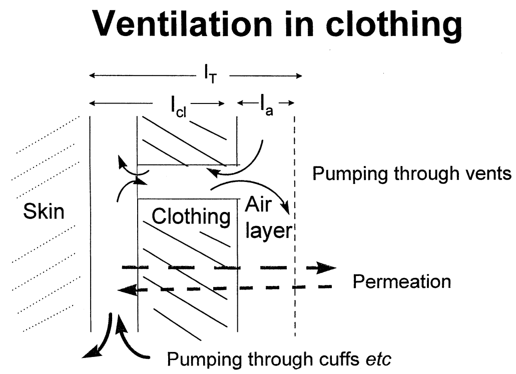

Fig. 2. Clothing model to include ventilation effects.

CLOTHING UNITS AND REDUCTION FACTORS

The prevailing method of representing clothing heat transfer is to lump convection, radiation and conduction into one term — named dry heat transfer. The total insulation (I_T) value includes all layers from the skin to the environment; clothing layers as well as the boundary air layer (I_a): see Fig. 1. (Note: where the air boundary layer is not included then this is called intrinsic clothing insulation I_{cl}.)

This simple model does not take account of air movement due to pumping through vents and cuffs (Fig. 2).

In human sciences, the unit of thermal insulation used is the Clo. One Clo of insulation equals 'normal' indoor clothing and will balance the heat produced by a resting man under normal indoor climatic conditions. One Clo equals 0.155 m^2 °C/W of thermal insulation to the whole body and assumes that any clothing is distributed across the whole body. A business suit for example would therefore have an insulation of around 1.0 Clo whereas a glove would have an insulation value of 0.05 Clo. The Clo value therefore is not a measure of material insulation but of the insulation provided to the whole person. Simple units for intrinsic vapour resistance of clothing have not been developed but a value for typical permeable clothing could be around 0.015 m^2 kPa/W (Parsons, 1993). ISO 7933 (1989) uses two clothing reduction factors to quantify heat and vapour transfer properties of clothing. These are the factors F_{cl} and F_{pcl}, respectively and are described in detail by Holmér *et al.* (1998, 1999) and Havenith *et al.* (1998, 1999). Burton and Edholm (1955) suggested that the effect of clothing could be described as a 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). So for a nude person the F_{cl} is unity and for a clothed person it is a reduction factor. The F_{pcl} reduction factor (Nishi and Gagge, 1970) is the vapour resistance of the air layer around the nude body divided by the sum of the intrinsic vapour resistance of clothing and the vapour resistance of the air layer around the clothed body: hence a reduction factor for a clothed person.

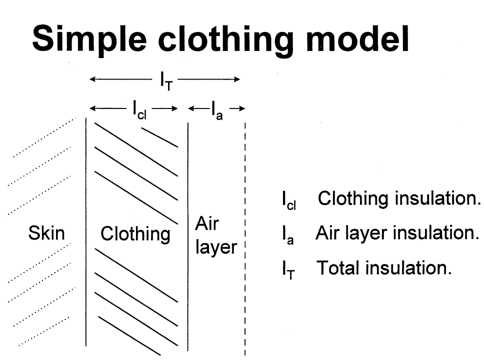

Fig. 1. Simple model of clothing insulation.

HEAT AND VAPOUR TRANSFER THROUGH CLOTHING

ISO 7933 (1989) gives the following formulae:

$$C = F_{cl}h_c(t_{sk} - t_a) \quad (1)$$

$$R = F_{cl}h_r(t_{sk} - t_r) \quad (2)$$

$$E = \frac{w(P_{sk,s} - P_a)}{R_T} \quad (3)$$

$$R_T = \frac{1}{h_e F_{plc}} \quad (4)$$

$$h_e = 16.7h_c, \quad (5)$$

where C is the heat transfer by convection, R the heat transfer by radiation, E heat transfer by evaporation, h_c the convective heat transfer coefficient, h_r the radiative heat transfer coefficient, h_e the evaporative heat transfer coefficient, t_{sk} the mean skin temperature, t_a the air temperature, t_r the mean radiant temperature, $P_{sk,s}$ the saturated vapour pressure at skin temperature, P_a partial vapour pressure in the air, and R_T is total evaporative heat resistance, w the skin wettedness.

PROPOSED CLOTHING MODEL

The background to the approach is presented in Havenith *et al.* (1999); Holmér *et al.* (1999) in this special issue. 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 insulation values which can be used to assess likely thermal strain. The model requires values for: absolute wind speed in the environment (v_a); metabolic rate of the person (M); intrinsic clothing insulation (I_{cl}); the static vapour permeability index for clothing (i_m); and walking speed and direction. From these it calculates dynamic values of clothing properties that can be used to provide more realistic assessments of human responses to hot environments. An annotated version of sections of a BASIC (Turbo Basic, Borland, 1987) computer program describes the model as follows.

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. When the activity is unidirectional walking then the angle between the walking and the wind is taken into account (walking into wind, angle = 0°, wind behind, angle = 180° etc.). If walking is omnidirectional with respect to the wind then walking speed or absolute air velocity are taken as relative air velocity, whichever is greater.

That is:

```
IF 'Stationary or undefined speed
Walksp = 0.0052*(Metn–58): IF Walksp > 0.7 THEN Walksp = 0.7
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. It 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 °C/W. The total clothing insulation is the intrinsic clothing insulation plus the insulation of the air layer ($I_{ast} = 1/HCR_{st}$ — assumed to be a value of 1/9, and corrected for the increase in available surface area for heat exchange caused by clothing (f_{cl})).

That is:

$$I_{clst} = \text{Clo} \times 0.155$$
$$f_{cl} = 1 + 0.3 \times \text{Clo}$$
$$\text{HCR}_{st} = 9$$
$$I_{ast} = 1/\text{HCR}_{st}$$
$$I_{totst} = I_{clst} + I_{ast}/f_{cl}$$

Correction to static insulation for wind and walking

The correction to static clothing insulation for wind and walking is based upon a regression equation providing the best fit of a database of measurements over a wide range of wind speeds, walking speeds, and clothing types. Where the ranges are exceeded the corrections are given limiting values. It should be remembered that the correction due to walking takes account of only the effects of the movement (for example; pumping effects) and not those of the relative air velocity that would be caused in a walking person. That aspect is considered elsewhere. Because light clothing below 0.6 Clo were not included in the database a simple interpolation is taken for corrections between 0.6 and 0 Clo (i.e. nude). The correction to the air layer is taken for nude data.

That is:

```
Vaux = Var: IF Var > 3.5 THEN Vaux = 3.5
Waux = Walksp: IF Walksp > 1.5 THEN Waux = 1.5
CORRclothed = 1.044*EXP((0.066*Vaux –0.398)*Vaux + (0.094*Waux –0.378)*Waux)
IF CORRclothed > 1 THEN CORRclothed = 1
CORRia = EXP((0.047*Var–0.472)*Var + (0.117*Walksp–0.342)*Walksp)
IF CORRia > 1 THEN CORRia = 1
IF clo ≲ 0.6 THEN
CORRtot = (0.6–clo)*CORRia + clo*CORRclothed/0.6
```

```
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 in heat transfer calculations instead of the static values to provide an improved model of heat transfer.

That is:

```
Itotdyn = Itotst*CORRtot
Iadyn = CORRia*IAst
Icldyn = Itotdyn–Iadyn/fcl
```

Dynamic vapour resistance

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

That is:

```
Lewis = 16.7
reduct = 1–CORRtot
CORRe = (1 + (1.3 + 2.6*reduct)*reduct)
imdyn = imst*CORRe: IF imdyn > 0.9 THEN
imdyn = 0.9
Rtdyn = Itotdyn/imdyn/Lewis
```

A full listing of the computer program is provided in Appendix A. An example of the use of the model is provided below.

PRACTICAL EXAMPLE

Consider the case of workers wearing boiler suits and conducting light work outside where the air velocity is 1 m/s. The intrinsic clothing insulation is estimated at 0.8 Clo and a normal static vapour permeability index would be $i_m = 0.38$. For light work, metabolic heat production is estimated at 100 W/m^2. The subject is not walking with a defined speed. The screen output from the computer program (Appendix A) is provided below.

CLOTHING CORRELATION FOR WIND AND HUMAN MOVEMENT

ABSOLUTE AIR VELOCITY (WIND SPEED) M/S	=	1
METABOLIC RATE W/M^2	=	100
INTRINSIC CLOTHING INSULATION (CLO)	=	0.8
STATIC VAPOUR PERMEABILITY INDEX (I_M)	=	0.38
Is the subject walking with a defined speed? (1 = YES: 0 = NO)	=	0
CALCULATED WALKING SPEED FOR PUMPING M/S	=	0.22
CALCULATED RELATIVE AIR VELOCITY M/S	=	1.00
INTRINSIC CLOTH INSUL, STATIC CONDITION (CLO)	=	0.8
INTRINSIC CLOTH INSUL, WIND AND WALKING (CLO)	=	0.63
STATIC VAPOUR PERMEABILITY INDEX (I_M)	=	0.38
I_M CORRECTED FOR WIND AND WALKING	=	0.63

The walking speed of pumping is calculated as the relative air velocity due to movement based upon metabolic rate. The relative air velocity is the absolute air velocity. It can be seen that the intrinsic clothing insulation is reduced from 0.8 to 0.63 Clo due to the effects of wind and human movement. It can also be seen that the permeability index is raised from $i_m = 0.38$ to $i_m = 0.63$. This has significant implications for the clothed workers in hot environments. The effective decreased clothing insulation and increased vapour permeability will allow greater heat transfer by convection and evaporation. In many conditions this will allow workers to work for longer than previously supposed as wind and human movement have increased the potential for cooling by evaporation of sweat through clothing.

DISCUSSION AND CONCLUSION

The empirical research using human subjects and thermal manikins has provided a proposed method to account for wind and human movement and the thermal properties of clothing. It is expected that this will improve the validity of heat stress assessment methods. In a hot environment where there is still capacity for the body to lose heat to the environment, then the proposed correction to static vapour and heat transfer properties may have significant effects. Greater heat loss will be predicted which will predict greater allowable work times before the conditions become unacceptable. This may allow an improvement to the method proposed in ISO 7933 which has been thought to be overprotective. However, the results must be used with caution in the first instance as there are a number of interactive components in an analytical method, such as that in ISO 7933, and a full validation will be required.

Acknowledgements—The work was supported by the BIOMED II Programme, European Commission.

REFERENCES

Burton, A. C. and Edholm, O. G. (1955) *Man in a Cold Environment*, p. 273. Edward Arnold, London.

Havenith, G., Holmér, I., den Hartog, E. and Parsons, K. C. (1998) Representation of the effects of movement and wind on clothing vapour resistance in ISO standards. In *Environmental Ergonomics*. ICEE, San Diego.

Havenith, G., Holmér, I., den Hartog, E. and Parsons, K. C. (1999) Clothing evaporative heat resistance: proposal for improved representation in standards and models. *Annals of Occupational Hygiene* **43**, 339–346.

Holmér, I., Nilsson, H., Havenith, G. and Parsons, K. C. (1998) Convective heat loss through clothing. In *Environmental Ergonomics*. ICEE, San Diego.

Holmér, I., Nilsson, H., Havenith, G. and Parsons, K. C. (1999) Clothing convective heat exchange: proposal for improved prediction in standards and models. *Annals of Occupational Hygiene* **43**, 329–337.

ISO 7933 (1989) *Hot Environments: Analytical Determination and Interpretation of Thermal Stress using Calculation of Required Sweat Rate*. ISO, Geneva.

ISO 9920 (1995) *Ergonomics of the Thermal Environment: Estimation of the Thermal Insulation and Evaporative Resistance of a Clothing Ensemble*. ISO, Geneva.

Nishi, Y. and Gagge, A. P. (1970) Moisture permeation of clothing: a factor governing thermal equilibrium and comfort. *ASHRAE Transactions* **76**(1), 137–145.

Parsons, K. C. (1993) *Human Thermal Environments*. Taylor and Francis, London.

APPENDIX

Proposed clothing model to take account of wind and human movement

The background to the approach is presented in Holmér *et al.* (1999); Havenith *et al.* (1999) in this special issue of the journal. 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 insulation values which can be used to assess likely thermal strain. An example of the use of the model is provided in the text of the paper.

```
CLS
PRINT "CLOTHING CORRECTION FOR WIND AND HUMAN MOVEMENT"
PRINT
INPUT "ABSOLUTE AIR VELOCITY (WIND SPEED) m/s = ",VA
INPUT "METABOLIC RATE W/m2 = ",M
INPUT "INTRINSIC CLOTHING INSULATION (CLO) = ",ICL
INPUT "STATIC VAPOUR PERMEABILITY INDEX (im) = ",IMST
REM Calculation of the relative air speed between the body and the environment.
REM DETERMINE RELATIVE WIND SPEED AND WALKING SPEED
INPUT "Is the subject walking with a defined speed?(1=YES,0=NO)",KK
IF KK=0 THEN GOTO 300
INPUT "WALKING SPEED = ",Walksp
INPUT "IS THE WALKING MAINLY IN ONE DIRECTION? (1=YES,0=NO)",LL
IF LL=0 THEN GOTO 200
PRINT "Give the angle (in degrees) between walking direction"
PRINT "and wind direction (with wind in the back = 0 deg,"
INPUT "face into the wind = 180 deg, wind from the side = 90 deg= ",THETA
THETAR = (3.14159/180) * THETA
REM RELATIVE AIR SPEED VAR
VAR = ABS(VA - Walksp*COS(THETAR)) : GOTO 100
200 REM OMNI-DIRECTIONAL WALKING
IF (VA >= Walksp) THEN VAR = VA
IF (VA < Walksp) THEN VAR = Walksp
GOTO 100
300 REM STATIONARY OR UNDEFINED SPEED
Walksp = 0.0052*(M-58)
IF Walksp > 0.7 THEN Walksp = 0.7
VAR = VA
100 PRINT "________________________________________________
PRINT "CALCULATED WALKING SPEED FOR PUMPING M/S = ", USING "###.##";Walksp
PRINT "CALCULATED RELATIVE AIR VELOCITY M/S     = ", USING "###.##";VAR
INPUT "________________________________________________",NNN
REM STATIC CLOTHING INSULATION
REM DRY HEAT TRANSFER COEFFICIENT HST INCLUDED HC AND HR
REM FOR STATIC CONDITIONS. STATIC AIR LAYER IS 1/HST ASSUMED TO BE
REM AROUND 0.7 CLO.
HST = 9
IAST = (1/HST)/0.155
ICLST = ICL
FCL = 1 + 0.3*ICLST
ITST = ICLST + IAST/FCL
REM ITC - CORRECTION TO TOTAL INSULATION FOR WIND AND WALKING DEPENDS
REM  UPON CLOTHING LEVEL
```

```
WIND = VAR
WALK = Walksp
IF WIND > 3.5 THEN WIND = 3.5 : IF WALK > 1.5 THEN WALK = 1.5
ITC=EXP(0.043-0.398*WIND+0.066*WIND^2-0.378*WALK+0.094*WALK^2)
IF WIND > 2.0 THEN WIND = 2.0 : IF WALK > 1.2 THEN WALK = 1.2
ITNC=EXP(0.126-0.899*WIND+0.246*WIND^2-0.313*WALK+0.097*WALK^2)
IF ICL <= 0.6 THEN ITC = ((0.6 - ICL)/0.6)*ITNC + (ICL/0.6)*ITC
IF ITC > 1.0 THEN ITC = 1.0
IF ITNC > 1.0 THEN ITNC = 1.0
REM
REM DYNAMIC CLOTHING INSULATION VALUES
ITDYN = ITST*ITC
IADYN = ITNC*IAST
ICLDYN= ITDYN - IADYN/FCL
PRINT
PRINT "INTRINSIC CLOTH INSUL, STATIC CONDITIONS (CLO) =", USING "###.##";ICLST
PRINT "INTRINSIC CLOTH INSUL, WIND AND WALKING   (CLO)=", USING
"###.##";ICLDYN
REM CORRECTION TO EVAPORATIVE HEAT TRANSFER PROPERTIES OF CLOTHING
REM FOR WIND AND WALKING. L is Lewis relation=16.7K/KPa
L = 16.7
REM CORRECT IMST FOR WIND AND WALKING TO GET IMDYN
ITRED = 1 - ITC
IMC    = (1.0+1.3*ITRED+2.6*ITRED^2)
PRINT : PRINT "STATIC VAPOUR PERMEABILITY INDEX im  = ", USING "###.##";IMST
IMDYN  = IMST * IMC
IF IMDYN > 0.9 THEN IMDYN = 0.9
PRINT "im corrected for wind and walking  =",USING "###.##";IMDYN
INPUT,MMM
CLS
END
```