CONVECTIVE HEAT LOSS THROUGH CLOTHING

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INTRODUCTION

Convection and evaporation comprise the most significant ways of heat exchange between the human body and the environment. Both convection and evaporation are sensitive to air motion and, consequently, are modified by worker movements, external wind and their interaction. However, it seems that most of the methods for calculation of convective and evaporative heat losses in use do not accurately account for such dynamic effects, leading to errors in the heat balance calculations and, eventually, inaccurate risk assessments. Criticism of the ISO 7933 method has been raised on these grounds. Within the Biomed 2 research project "Assessment of the risk of heat disorders encountered during work in hot conditions (Heat Stress)," the problem has been analyzed and the result is presented in three papers.

This first paper analyzes convective heat exchange through clothing and proposes ways of improving the consideration of dynamic effects.

Bodv Surface Convection

Convective heat loss at the surface of the human body has been studied for many years . The presently used formulas in international standards are

It is observed that convective heat loss by equation 1 is 42 % higher than 2 and 3 at an air velocity of 1 m/s. Yet equations 2 and 3 give values in the upper range of a large number of reported formulas .

$h_c = 12.1 \cdot v^{05}$		(3)	ISO 7730	(1)
$h_c = 3.5 + 3.2 \cdot v_{ar}$	for $v_{ar} \leq 1 m \cdot s^{-1}$	(6)	ISO 9233	(2)
$h_c = 8.7 \cdot v_{ar}^{0.6}$	for $v_{ar} > I m \cdot s^{-1}$	(6)	ISO 9233	(3)

In general, most of the studies only dealt with the effect of external wind on stationary subjects. The concept of net or relative air velocity was introduced to account also for the effects on convective heat exchange by body movements. This factor is described below.

Clothinp Heat Transfer

The effect of clothing on *dry* heat exchange is defined and determined by the insulation value (I). Burton proposed

$$I = \frac{At}{DRY} \qquad (4)$$

where I is the insulation value in $m^{-2} \cdot °C \cdot W^{-1}$, At is the temperature gradient between the skin and the environment and DRY is the combined convection, radiation and conduction heat transfer in Wm-2. The insulation value, so defined, includes all layers fiom the skin to the environment, clothing layers, as well as, the boundary air layer.

The success of this approach was linked to the fact that methods for actual measurements of I were readily available. The first thermal manikins were developed at this time and allowed quick, reliable and accurate measurements. The manikins, however, did not move, and measurements were taken in still-wind conditions. The insulation values so obtained

- did not account for wind effects and
- did not account for pumping effects due to wearer motion.

Burton provided a solution to the first problem by introducing a correction of the I-value for different wind speeds . However, the second problem was left unsolved. Goldman, et al. addressed it in several studies and provided a series of correction equations to wind and body motion. The approach was the same as Burton's I value (obtained with the static thermal manikin) and was corrected for the effective (relative) air velocity. Each equation was specific for an ensemble and was empirically derived from wear trials.

Fanger **(3)** defined clothing *dry* heat exchange as a two-step process—from skin to clothing surface and fiom clothing surface to the environment. This requires separate equations for clothing heat exchange:

- body surface heat exchange handled by normal convection formula,
- clothing surface area to be defined and calculated and
- an equation for heat transfer from skin to clothing surface.

In **ISO 7730,** no correction **is** made for dynamic clothing effects, whereas the external heat loss (clothing surface) depends on both wind and body movements. In the most common interpretation of ISO **7730,** this means that the clothing requirement (insulation value) becomes increasingly underestimated when relative air velocity increases.

The relative air velocity is defined as the resulting (net) effect **of** wind and body movements relative to the skin surface of the body. The commonly used expression for this in ISO-standards is

(with **M,** metabolic rate in $W \cdot m^{-2}$) (5)

A third approach taken to describe clothing heat transfer was also introduced by Burton. He suggested that the effect **of** clothing could be described as a reduction factor compared to "nude" conditions. This approach was further developed by Nishi and Gagge. The efficiency factor could be easily defined by where I,, is

$$F_{cl} = \frac{1}{I_{cl} \cdot (h_c + h_r) + 1/f_{cl}} = \frac{1}{I_{cl}/I_a + 1/f_{cl}} = \frac{I_a}{I_{cl} + I_a/f_{cl}} = \frac{I_a}{I_{tot}} \quad (6)$$

the basic clothing insulation value in $m^{-2} °C \cdot W$, hcl is the clothing conductance and f_{cl} is the clothing area factor. It is clear fiom this equation that F_{cl} will pick up changes to both I, and I_{tot} as a result of increased air velocities. The clothing area factor is determined by

$$f_{cl} = 1 + 1.97 * I_{cl} \qquad \text{(with } I_{cl} \text{ in } m^{2}\cdot{}^{\circ}C\cdot W^{-1}) \qquad (7)$$

Insulation Corrections

Havenith, et al. suggested sets of equations for correcting a static, standing insulation value (I_{st}) for the effect of posture, walking speed (w) and wind **(v).** The corrected value (I_{corr}) used in the determination of *dry* heat loss **was** determined by

$$\frac{I_{corr}}{I_{st}} = \frac{100-(12.3+12.5\cdot I_{st})\cdot w}{94.9+29.7 . ?1;} \qquad (8)$$

Nilsson and Holmér recently published a similar formula, derived fiom measurements with a moving manikin. The study comprised measurements of 9 ensembles (0 to **3** layers, Itot 0.7 to **4.6** clo). The equation incorporates in one expression the effects of walking and wind speed. The absolute error (mean value) **of** this formula in predicting the dynamic effect on one particular ensemble **was** less than 0.05 0.04 clo. The greatest difference was observed for nude conditions and for the 3-layer ensembles.

$$\frac{I_{corr}}{I_{st}} = e^{(-0.025-0.335\cdot v-0.214\cdot w)} \qquad (9)$$

Figure 1 shows the combined effect of wind and walking speed for the insulation range (0.7 to **3.5** clo), walking speed (0 to 1.2 $m\cdot s^{-1}$) and wind speed (0.2 to 1.0 $m\cdot s^{-1}$).

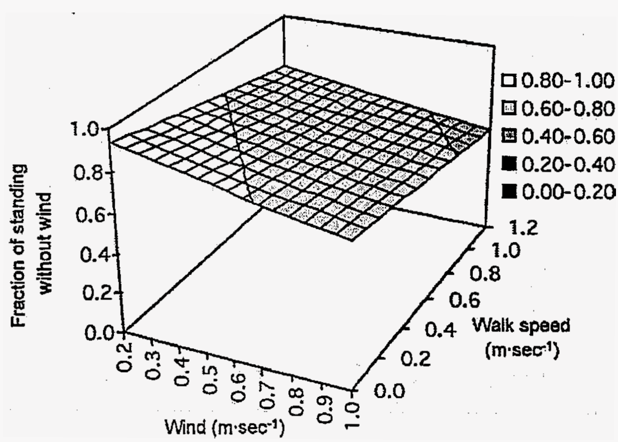

Figure 1. Fractional change in total insulation as function of wind and "walk speed" **(8).**

The two data sets were merged except for two winter ensembles and equations **10** and **11** were derived and proposed for inclusion in the revised **ISO 7933.**

$$\frac{I_{corr}}{I_{st}} = e^{(0.126-0.899 \cdot v+0.246 \cdot v^2 -0.313 \cdot w+0.097 \cdot w^2)} \qquad \text{undressed} \quad \mathbf{(10)}$$

$$\frac{I_{corr}}{I_{st}} = e^{(0.043-0..398 \cdot v+0.066 \cdot v^2 -0.378 \cdot w+0.094 \cdot w^2)} \qquad \text{dressed} \quad (11)$$

CONCLUSIONS

Available information on dynamic effects on clothing heat transfer indicates significant effects of wind and walking. Present methods in ISO **7730** and **ISO 7933** do not account for this in an accurate way. It is suggested that the dynamic effects are handled by two new equations that correct **the** static total insulation value (as provided by ISO **9920)** for given values of wind and walking speed.

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