PREDICTION OF THERMAL PROPERTIES OF MULTI-LAYER ENSEMBLES

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INTRODUCTION

There has been, and still is great interest in improving or developing new thermal models to predict the heat and mass properties of ensembles. Multi-layers (n layers) ensemble generally impose greater air-layer resistance, $\Sigma R_{a,n}$, than does a single-layer one, $R_{a,1}$. But distribution and insulation value, R_f, (thickness) of the fabric layers as well as the physical activity may affect this relationship. *So,* an expression is needed for prediction of the thermal properties of the air layers of different ensembles during various physical activities.

METHODS

The effect on the heat resistance of adding garment layers beneath the outer layer was studied both theoretically and experimentally. The air-layer velocity, v_i, and air-gap width, d_h, govern the internal convection coefficient (1). The v_i and d_h values are affected by the type and rate of physical activity and the ensemble fit. If extra garment layers are added under the outer layer of the ensemble, the convection heat transfer will change. Experiments were performed for evaluating the convection coefficient in multi-layer ensembles. *Dry heat* transfer from the skin was measured with heat flux sensors. Loose- and tight-fitting ensembles were used. The heat flux was measured at the lower leg, thigh, lower *trunk,* mid trunk, lower arm, and upper arm. Heat flux was measured when the jacket was worn: (A) with no clothes under, (B) with a shirt and (C) with a shirt and sweater. The trousers were worn with and without long underwear. The physical activities were standing and walking on the treadmill at no external wind. The mechanisms behind the mass transfer in clothing air layers are not fully understood. But, if the mass transfer is purely convective, the heat-mass analogy should be valid for a number of climatic conditions and channel geometries. It has been assumed that $d_e = 0{,}031 / h_c$, where d_e is the water vapour resistance, is valid for laminar air flow normally occurring in internal air layers. For turbulent air flow $d_e \approx 0{,}026 / h_c$. The expression has been used for estimation of the external evaporative resistance when walking. A prediction model was based on the experimental convection coefficient results and the assumptions about the mass transfer mechanisms. The model calculates the heat and vapour resistance for each part of the body (13 parts), while standing or walking in calm air or in a wind. It also calculates the ventilation rates. The ensemble composition *starts* from the outer layer, tight- or loose-fitting, under which is added an arbitrary number of garment layers. The only material parameters needed are the fabric thickness and whether the fabric is permeable to vapour or not.

RESULTS and DISCUSSION

When donning the garment layers, the gaps between the various fabric layers are hardly the same from one occasion to the next. The influence of different air gap widths on the total intrinsic air-layer insulation value was simulated theoretically by distributing the various fabric layers randomly. The multi-air-layer insulation value, $\Sigma R_{a,n}$, increases with increasing air gap width. The $R_{a,1} / \Sigma R_{a,n}$ ratio is roughly 0,75, 0,65 and 0,60 for ensembles with two, three and four equidistant air-layers, when the fit of the outer layer ranges from loose to very tight. When the material layers are distributed randomly, the ratios increase slightly. Generally, the total intrinsic air-layer insulation value is raised about 40% by adding to the outer layer various combinations of material thickness and number of air layers, equidistant or randomly distributed. This prediction assumes a standing position and relatively thin fabric layers. However, walking appears to have little effect on the standing values for $R_{a,1} / \Sigma R_{a,n}$. The human experiments showed that the $\Sigma R_{a,n}$ value was affected by both the number of air layers and the insulation value (thickness) of the fabric layers. The results also suggest that these variables had the greatest effect when walking. Furthermore, n and R_f seemed to affect $R_{a,n}$ differently depending on the degree of compression and part of the body. A correlation was done between the single-air-layer insulation value (outer layer), $R_{a,1}$, the number of intrinsic air layers, n, the insulation value of each intrinsic fabric layer, R_f, and the multi-air-layer insulation value (each layer), $R_{a,n}$. The equation obtained was $R_{a,n} = R_{a,1} / n^x - R_f \cdot (1 - 1/n^x)$ where the exponent x depended on the walking speed. Each fabric layer was assumed to have the same insulation value, which was obtained by averaging. The equation was found to describe rather well the effect of n and R_f on the multi-layer $R_{a,n}$ value at the various parts of the body. Each new air layer had an insulation value that was the single-layer value reduced by a factor n^x, if very thin fabric layers are assumed. As the exponent x is less than unity, the sum of all the air-gap insulation values will always be greater than the value of the original single layer. If the thickness of the materials is significant, the air insulance is reduced. The reduction is not equivalent to the complete removal of an air layer, since R_f is multiplied by $(1 - 1 / n^x)$. This factor include the effect of folds. The influence on the $R_{a,n}$ value was greatest when adding the first fabric layer. With several material layers, most of the folds are eliminated. Another effect included in (1 - 1 / n") is the f_{cl} factor, which also reduces the fabric insulation value. The correlation equation can also be expressed as $\Sigma(R_{a,n} + R_f) = \Sigma[(R_{a,1} + R_f) / n^x]$. The left-hand side of the equation is the Same as the ensemble intrinsic insulation value, $R_{cl,E}$. The expression $\Sigma(R_{a,1} + R_f)$ is n times the intrinsic insulation value of the outer garment, $R_{cl,G}$. If the fit and fabric insulation value of each garment layer, which together constitute the whole ensemble, is similar to that of the outer layer $R_{cl,E} = n^{-x} \cdot \Sigma R_{cl,G}$ is obtained. For a two-&-layer ensemble, $x = 0{,}49$, $R_{cl,E} \approx 0{,}7 \cdot \Sigma R_{cl,G}$ is obtained when standing. This is the same expression suggested by several researchers (e.g. **2, 3**). The prediction model produced standing results which correlated well with those presented in the literature, (e.g. **4**). The mean difference between the measured and predicted total clothing heat resistance, R_t for a number of ensembles was -0,002 m^2K/W, with a standard deviation, s.d., of **0,018** m^2K/W. The R_{cl} values gave a mean difference of **0,001** m^2K/W and s.d. of **0,020** m^2K/W. The coefficients of variation, c.v., were thus about **8%** of the mean R_t value and about **13%** of the R_{cl} value. The s.d. of the differences of the total vapour resistance, $d_{e,t}$, was **2,1** mm and the mean difference was **1,9** mm. For $d_{e,cl}$, the corresponding values were **2,1** mm and **1,1** mm. The predictions thus underestimated the measured values by roughly **10%**. The c.v. for the permeable ensembles was about 15% of the mean water vapour resistance. The model was also validated by comparing it with R_t and R_{cl}-results obtained during walking (5). The mean difference for R_t was **-0,002** m^2K/W and the standard deviation of the differences was 0,010 m^2K/W. The corresponding R_{cl} results were -0,001 and **0,009** m^2K/W. The model thus seems to predict the total and intrinsic resistance values fairly well. The model requires no information on the radii for each garment layer. Hence, no measurements are needed on the subject or manikin.

CONCLUSIONS

The multi air-layer insulation value was affected by both the number of air layers and the thickness of the material layers. The insulation value of the single-layer ensemble was about **70%** of the multi -layer value when thin fabric layers were added beneath the outer layer. This relation was fairly constant for various numbers of air layers and walking velocities, which indicates that the intrinsic insulation value of an arbitrarily composed ensemble can be predicted quite easily. A simulation model has been constructed which only demands information on the tit, tight (default) or loose, the fabric thickness and vapour permeability (permeable or impermeable) of each material layer. The output from the model is: the heat resistance, vapour resistance and f_{cl} at each sub-part (foot, thigh etc.); the heat resistance, vapour resistance, f_{cl} and ventilation rate at each part (leg, trunk, arm and head); and the same variables calculated for the whole body. The results can be computed for combinations of walking and wind speeds. The model requires no measurements on clothed subjects or manikins.

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