COMPRESSION OF CLOTHING AIR LAYERS AND THE EFFECT ON CONVECTION COEFFICIENT

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INTRODUCTION

Bodily movements induce an internal forced *air* flow in clothing air layers. The speed of this flow is affected by the type of activity performed and the fit of the ensemble. Deformation of the garment causes folds to develop, which reduce the enclosed air volume, V_0, and force the air to move. The air volume displaced, V_d, inside the ensemble also causes an exchange of air with the environment. In clothing air layers the convection coefficient, h„ has been found relate to the internal air speed, v_i , and gap width, d, according to $(v_i / d)^{1/3}$ (1). But as this relation does not account for different compression at various parts of the body a more general expression is needed.

METHODS

Mathematical simulation was performed to estimate the influence of different degrees of compression and radius of the body part on the v_i value. The effects of compression, air gap width and internal air speed on the h_c value were investigated on a physical model, a fabric-covered cylinder. The *air* flow rate between the textile layer and the cylinder surface was governed by a piston pump, whose pump frequency and stroke volume could be adjusted. The effect of constant *air* gap width was studied with a stretched fabric layer where the air gap was open at both ends. The effect of alternating gap width was investigated with the air gap closed at one end and the fabric loosely draped. The effect of air gap width on the convection coefficient was also investigated on a clothed subject. Loose- and tight-fitting ensembles (jacket and trousers) were worn while the subject walked on a treadmill at various speeds. The convection heat flux and the internal air speed were measured at the various parts of the body.

RESULTS and DISCUSSION

The simulation model showed that roughly the Same *air* speeds can be expected in the tight- and the loose-fitting ensembles if the relative compression, V_d/V_0, is the same. But if V_d is the same in the two ensembles v_i will be greater in the tight-fitting one. In both cases the radius of the part of the body should have little effect. This indicates that the induced internal air speed should depend on e.g. garment design and type of activity. The cylinder measurements showed that the relation between the internal air velocity and the convection coefficient at the cylinder surface was similar for different air gap widths and V_d/V_0 ratios when the fabric was stretched. The internal air speed was the most important factor for the h_c value where $h, = 21,4 \cdot v_i^{0,5}$. This suggests that the air flow characteristics in a wide channel, >1 cm., with roughly constant gap width *can* be compared with forced laminar flow at an external, flat surface. This condition is probably valid in e.g. skirts during walking. When the fabric covering the cylinder was loose and the air layer width changed at the pace of the pump stroke, the convection coefficient was governed by the internal air velocity, initial gap width and compression. One common pattern was that the lowest h_c value was obtained for the lowest compression when v_i was kept constant. Another was that a smaller initial gap width resulted in a greater h_c value. Both factors affected the distance between the fabric and cylinder surface. This condition probably occurs in ordinary single- and multi-layer ensembles. The results indicated that the convection was similar to developing laminar air flow, i.e. an air flow where the temperature and velocity profiles have not yet become developed. The experimental data correlated best with $h_c = 4,1 \cdot [v_i / (l \cdot d_k)\ ]^{0,35}]$ where l (entry Iength) is a distance related to the development of the profiles and d_k is the average gap width during the compression and expansion cycle. For the clothed subject the equation correlating the whole-body h_c and v_i values when wearing the loose-fitting ensemble was $h_c = 14,5 \cdot v_i^{0,34}$. The corresponding equation for the tight-fitting ensemble was $h_c = 17,0 \cdot v_i^{0,27}$. The internal air speeds at the various parts of the body were similar in the tight- and loose-fitting ensembles. According to the simulation model this indicates that the relative compression was comparable in the two ensembles. But the corresponding convection coefficients differed considerably, except at the trunk where the compression is fairly small during low and medium walking speeds. So the air gap distance and compression seemed to affect the convection coefficient during physical activities. This suggests that the induced convection in clothing air layers with alternating gap widths can be characterized as forced, laminar, developing air flow. To use the related h, expression the mean air gap width (d_k) and entry length (I) at the various parts of the body must be estimated. These are normally not known. Different measures of the air gap width d (calculated from the body part and clothing circumferences), the effective gap width d_{th} (calculated from the internal convection heat flux in concentric cylinders and in the clothing air layers when standing still) or unit gap width $d0$, were applied to the h, equation. The results showed that for the loose-fitting ensemble d_{th} was best although it was only slightly better than using no information on the distances, $d0$. These results from the human measurements are in coincidence with the results when the cylinder was covered with the stretched fabric. Then the wide channel h_c values were practically independent of the gap width. The tighter the garment and the fewer the folds, the closer will the d_{th} value approach the d value. For the tight-fitting ensemble the correlation for d was also better than for d_{th} or d^0. But if a common method is needed for measuring the gap widths in ensembles of different fit the best choice is to use the d_{th} value. The entry length, *1*, should be associated with a distance related to the compression of the air layer. If the V_d/V_0 value is large and the temperature and velocity profiles are far from developed, the corresponding entry length should be small. This will introduce great methodological difficulties as neither of these variables are normally known. However, as d_k depends on V_d and V_o a compression factor k could be introduced. For the cylinder covered with the loose fabric, the k factor ranged from about 2,4 to 0,5 when V_d/V_0 ranged from 0,34 (minor compression) to 1 (maximum compression). From the h, correlation equation and the measured h_c, v_i and d_{th} values the local and whole-body k factors could be calculated for different walking speeds. At the various body parts k ranged from 0,95 to 7,4 for the tight-fitting ensemble, and from 1,4 to 8,7 for the loose-fitting ensemble. The whole-body k factor was lower for the tight-fitting ensemble (2,1) than for the loose-fitting one (2,8). These factors correspond to a reduction in the enclosed volume of about 40% and 30% respectively. This is what one might expect if one assumes that the most pronounced compression occurs with the most tight-fitting ensemble. The regional volume reduction ranged from 10% (upper arm, loose fit) to 65% (thigh, tight fit). The simulation model suggested that fork = 1,5 and a cylinder length of 0,25 m the internal air speed should be 0,22-0,34 m/s when the walking speed was 0,9-1,9 m/s. For a cylinder length of 0,40 m the air speed should increase to 0,35–0,55 m/s. The lengths of the lower leg, thigh, trunk, lower arm and upper arm fall in the range of 0,25–0,40 m. So the measured internal air speed should be found in the range of about 0,2–0,6 m/s. But since the compression varied between 10% and 65%, values slightly lower than 0,2 m/s and higher than 0,6 m/s *can* be expected. Most of the measured v_i values were found between 0,1 and 0,6 m/s, with the maximum at just above 0,7 m/s. The internal air speed at the upper arm where the compression was small was, as expected, lower than at the longer thigh where the garment was more compressed.

CONCLUSIONS

The cylinder measurements showed that the internal convection coefficient was affected mainly by the *air* layer speed, and was practically unaffected by the size of the air gap or the stroke volume when the air gap was wide and constant. The convection coefficient coincided very well with that predicted for laminar flow in wide channels. When the air gap changed, both the size of the air gap and the stroke volume/enclosed volume affected the h, value. The convection coefficient was then very similar to undeveloped, laminar *air* flow at an entry length. This type of air flow was similar to that in the air layers of the ensembles tested during walking. The internal air speed induced in the tight-fitting ensemble was similar to that in the loose-fitting one. But because of the influence of the air gap width and the compression, the corresponding h, values were greatest in the tight-fitting ensemble. Increased walking speed reduced the air gap widths. The reduction depended on the part of the body. For the whole body, the estimated compression was about 30% and 40% for the loose-fitting and tight-fitting ensembles respectively. For the individual body parts, the compression ranged from 10% (upper arm, loose fitting) to *65%* (thigh, tight fitting).

REFERENCES

Danielsson, U. 1992, Convection in clothing air layers, *Proceedings of the Fifth International Conference on Environmental Ergonomics,* 70-71.