A COMPREHENSIVE CLOTHING ENSEMBLE HEAT AND VAPOUR TRANSFER MODEL

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INTRODUCTION

Relative to the sophisticated models that have been developed for the prediction of the human physiological response to thermal stimuli (1) the description of the heat transfer through clothing has so far been primitive. The classical description of clothing is with fixed heat and vapour resistances (2), representing the average for the whole skin area. For static, indoor conditions this might be sufficient (3), but for actual work conditions this description shows a number of deficiencies that might cause large errors:

- clothing insulation changes dramaticly with motion and wind, due to ventilation (4)
- changes in insulation follow a different mechanism than changes in vapour resistance (4)
- the effective insulation of unevenly distributed clothing depends on the environmental condition
- during condensation or absorption heat transport deviates from that by independent *dry* and wet heat
- the effect of heat radiation is difficult to account for correctly

Given these sources of error it seems that a better balance in accuracy would be obtained by combining an enhanced clothing model with a less complex physiological model. In this paper such an enhanced clothing model is described. The challenge was to make the model compatible with the wide variety in clothing ensembles and realistic physical conditions, and yet simple enough to require few input data. The approach was to base the model on physical transport processes and to include only those that have an appreciable effect on the result.

METHODS

The model is the compilation of the important features of four different models dealing with heat and vapour transport by the following mechanisms: ventilation, caused by motion and wind (5), heat radiation (unpubl), condensation (unpubl), and vapour absorption (unpubl). The four models have in common that the outer clothing layer is distinguished from all other layers, which are considered as a single layer, called underclothing (Fig. 1). This is justified by the argument that the outermost layer is in many conditions the focus of the above listed processes. Between the outer layer and underclothing, air is trapped that may be exchanged with environmental air by ventilation. The clothing is covered with an adjacent air layer. Both clothing layers have vapour absorption capacity, depending on the type of fibre used. The vapour resistance of the outer layer is one of the determinants of condensation and so is the reflection coefficient of the outer material for radiant heat absorption.

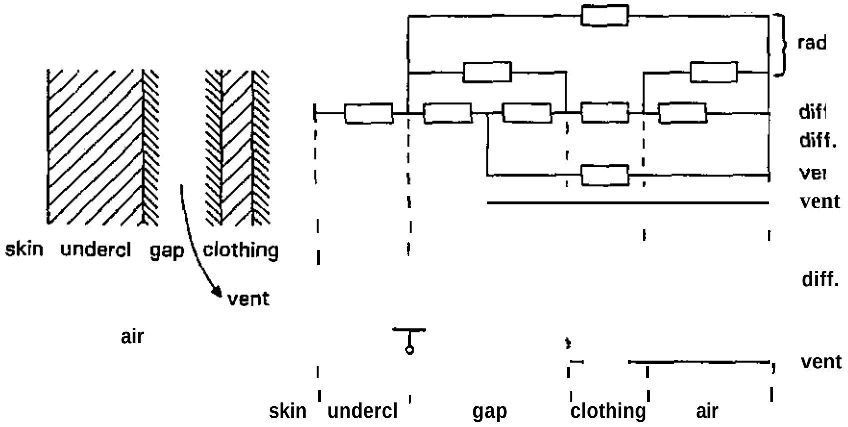

Fig. 1. Model describing the pathways for heat transport (right, top) and vapour transport (right, bottom) in a two-layer clothing system (left); rad = radiation, diff = diffusion, vent = ventilation.

The effects of motion and wind on the adjacent air layer and on ventilation of the trapped air are described by a single parameter called effective wind speed (4), integrating natural convection, wind, displacement and motility, whereas the properties of the clothing layers are hardly affected by motion and wind.

The model has been implemented in a computer program that calculates the dynamic response to changes in clothing or boundary conditions (CLODYN). The model calculates all surface temperatures, water vapour concentrations and flows, keeping track of the moisture accumulation. This is done for bare and clothed skin, irradiated as well as in the shade. For simulation purposes it has been coupled to a 5-node thermoregulatory model, using the controller of Gagge et al. (6). This program (THDYN) allows one to calculate physiological responses to clothing, work, and environment.

The model has been used to simulate 3 previously performed experiments on condensation (9 conditions), 4 on heat radiation (24 conditions), 1 on absorption (4 conditions) and 2 on ventilation (72 conditions), and a couple of experiments described in the literature. The clothing varied from a light work ensemble to heavy fire fighters and chemical protective clothing; the work rates varied from rest to 250 W/m^2, environmental temperatures ranged from 0 to 31°C, radiation from 0 to 800 W/m^2, and wind speeds covered natural convection to 3 m/s.

RESULTS

The root mean square difference between model and experiments is 15 W/m^2 in total heat transport and 2°C in various clothing surface temperatures. These errors are similar in magnitude to results from experimentation with subjects and there is thus no proof of systematic deviation of the model.

The most relevant clothing parameters in the model are the insulation and vapour absorption of underclothing, insulation, vapour absorption, heat radiation reflection, and vapour resistance of the outer layer, and the ventilation. Radiant transmission of heat and the air permeability of the outer layer and its fit may be important under special conditions.

In contrast to the classical clothing description, the observed and predicted intrinsic insulations ranged over a factor of 3 during condensation, depending on the environmental temperature and work rate. Even more extreme effects were found during the transient phase of vapour absorption and during exposure to heat radiation.

Some of the experimentally observed physiological phenomena during vapour absorption in clothing emerge from the clothing heat transfer, rather than from physiological source. These are predicted by the THDYN model. Using the classical clothing description, disregarding absorption, these phenomena are not found.

CONCLUSIONS

The features included in the two-layer clothing model are sufficient to describe heat transfer through clothing ensembles for a wide range of conditions. The accuracy compares to that of the experimental methods for verification.

The model explains the widely varying insulation of identical clothing observed in various environments. It also explains some physiological phenomena during absorption.

It is felt that the current more complex clothing model, combined with a simple physiological model gives better results for neutral to warm work conditions than a complex physiological model, combined with the classical clothing description.

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