THE TRANSIENT EFFECTS OF CLOTHING ON HEAT EXCHANGES BETWEEN SKIN AND ENVIRONMENT

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INTRODUCTION

The traditional clothing parameters such as heat and vapor resistance are static and therefore not always sufficient to describe the processes of heat and mass transfer from skin through clothing to the environment (1,2,3). With changing environmental conditions, moisture absorption/desorption and condensation/evaporation in clothing play an important role and affect the transfer processes. In this study a mathematical model which describes thermal responses of the clothing system to the skin and the environment was developed. Furthermore, the clothing model was further incorporated into a six cylinder thermoregulation model to obtain a man-clothing model which can be used to investigate the effects of clothing on heat exchanges between skin and environment.

METHODS

Fig.1 shows heat and mass (moisture) transfer from the skin through the clothing layer to the environment. These two flows interact due to absorption/desorption and condensation/evaporation. By considering changes in heat storage and mass in the clothing, together with the heat and mass flow into and out of the clothing, the heat and mass balance equations can be obtained (4). They are not independent but interrelated by the differential heat of sorption and the mass change rate. The differential heat of sorption and the moisture content for a given fabric may be approximately expressed as a function of the vapor pressure and temperature (1,5).

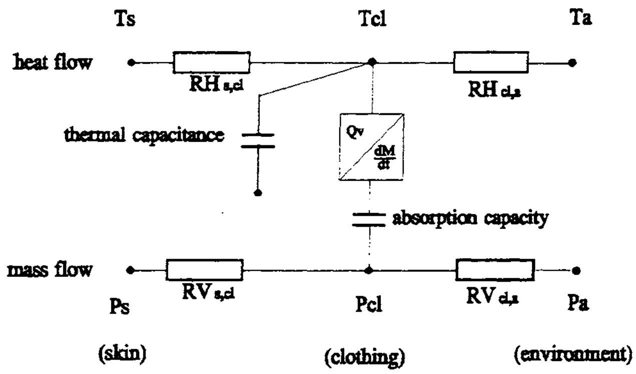

Fig.1 heat and mass transfer from skin through clothing to environment
T: temperature, P: vapor pressure, RH: heat resistance, RV: vapor resistance
Qv: differential heat of sorption, dM/dt: mass change rate
s: skin, cl: clothing, a: environment

The thermal and vapor resistances are required to solve the heat and mass equations. $RH_{s,cl}/RV_{s,cl}$ can be determined by adding the resistance due to the air layer between the skin and the clothing and half of the resistance due to the clothing, both of which may be estimated from their thickness (1,6). $RH_{cl,a}/RV_{cl,a}$ may be calculated as the sum of half of the resistance due to clothing and the resistance of the outer air layer.
The equations can be solved by finite difference methods when the clothing properties thickness, regain, density and heat capacity are given and appropriate initial values are assigned.
The man-clothing model is obtained by incorporating the clothing model into a six cylinder thermoregulation model (7), which simulates human temperature regulation. The six cylinders are head, trunk, arms, hands, legs and feet, each of which may be uniformly clothed or unclothed. It is necessary to use such a model to consider the inhomogeneous coverage over the body surface, as the body is usually not uniformly covered (8). The skin exchanges heat and mass with clothing if the corresponding region is clothed, or directly with the environment if not clothed.

RESULTS

Experiments were carried out to validate the man-clothing model. In the experiments the subjects wore cotton clothing with a density of 0.195 kg/m^2 and were exposed to a change of environment from 28°C to 45°C (rel. humidity RH40%) and vice versa. The simulated core and mean skin temperatures agree well with the experimental results. This indicates that the calculations of the man-clothing model are realistic. As the clothing ensemble is thin and light, it affects thermoregulation only slightly.

Calculations from the man-clothing model demonstrate the impact of humidity transients on thermoregulatoin in clothed humans. The subject wearing a 1 clo woolen or polyester ensemble was at rest in the first environment with 20%RH and then moved to the second environment with 80%RH, while the environmental temperature was the same (23.3°C). The simulation is shown in Fig.2. The response while wearing wool is obviously greater than wearing polyester. The difference should be due to heat of sorption in clothing, as wool is much more hygroscopic than polyester. As seen by these results, the dynamic effects of clothing are not negligible in many circumstances. It is also important to determine initial values reasonably, especially the relative humidity or vapor pressure in clothing, which greatly affects the prediction, since the absorption/desorption process is dependent on its initial conditions. The simulation is also very similar to the experimental results, which were obtained by DeDear (9) with the same conditions as used here.

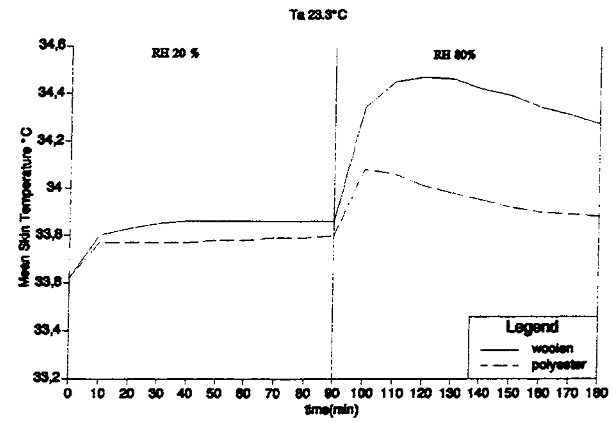

Fig.2 Mean skin temperature during humidity (RH) step-changes while wearing woolen or polyster clothing

CONCLUSIONS

It is necessary to describe clothing with both static and dynamic thermal properties. The man-clothing model can be applied to simulate the effects of different clothing ensembles, for example different fabric and inhomogeneous coverage etc. The range of application of the thermoregulation models is enhanced greatly, although further improvements of the clothing model and validations of the man-clothing model may still be necessary.

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