

TRANSIENT THERMAL RESPONSE OF CLOTHING SYSTEMS

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INTRODUCTION

Clothing parameters such as thermal insulation and moisture permeability are based on steady state measurements and provide useful predictions of how the clothing will perform in applications where conditions do not change rapidly. There are also situations where the ambient environment changes or physiological responses occur with sufficient rapidity that transient effects become important. Examples of these situations include: going from a dry space to a humid space, exposure to a hot environment, and the onset of sweating. The heat exchange between the body and the environment may be affected significantly by the dynamic response of the clothing system in these instances. In cases where only short tolerance times are possible, such as the exposure to extreme heat or cold, the transient response of the clothing may dominate. The objective of this study was to develop a computer model which could simulate a variety of clothing system and predict how they respond under rapidly changing conditions.

METHOD

In previous work, it was shown that computer models could be developed that can accurately predict both dry and evaporative heat flow through clothing systems [2]. These models divide the body into a number of segments such that each segment represents a well defined part of the body (e.g., head, chest, upper arm, etc.). The segments are divided into subsegments such that each subsegment is uniformly clothed. The subsegments are modeled as cylinders with the clothing treated as concentric cylinders. Each fabric layer is described in terms of thickness of the fabric, thickness of the trapped air layer, thermal resistance, and moisture permeability. Equations for radial heat and moisture flow are solved for each subsegment. Data bases describing the clothing geometry were developed to use with the models. Manikin measurements were used to validate the accuracy of the model predictions.

The same approach was used to model transient response. In addition, there are two main transient effects that must be modeled: the changes in fabric temperature, and sorption and desorption of moisture by the fabric. These effects can be described in finite difference form by

$$\frac{dQ_s(R)_i}{dt} \tau Q_s(R)_i \text{ th} = \frac{P(T,R)_{i-1} + P(T,R)_{i+1} - 2P(T,R)_i}{R_{ef}} \times \frac{\text{tf}}{\text{th}}$$

$$\frac{dT_i}{dt} \tau c_p \text{ th} = \frac{T_{i-1} + T_{i+1} - 2T_i}{R_f} \times \frac{\text{tf}}{\text{th}} + \frac{dR_i}{dt} \tau \text{ th} Q_s(R)_i$$

where R is the local regain, T is the local temperature, P is the equilibrium vapor pressure at the local temperature and regain values, Q_s is the heat of sorption for the fabric, c_p is the heat capacity of the fabric, τ is the fabric density, R_{ef} is the evaporative resistance of the fabric, R_f is the dry resistance of the fabric, tf is the thickness of the fabric, th is the thickness of the layer, and i is the finite difference index. For thick clothing layers, such as in outdoor winter clothing, each fabric layer is divided into a number of sub-layers for the finite difference solution. For thin fabrics, such as typical indoor clothing fabrics, one layer of clothing can be treated as one layer in the finite difference solution. In addition to the parameters needed for the steady state model, the density, heat capacity, moisture regain, and heat of sorption are required for each fabric. Moisture regain for a

given fabric is a function of relative humidity; and the heat of sorption is a function of moisture regain. This information is represented in the model in the form of look-up tables.

To validate the model, data were collected for a number of clothing ensembles on a manikin subjected to humidity transients. Data collected at the Technical University of Denmark (TUD) for a wool ensemble were also used.

RESULTS

The model predictions agree well with the measured responses on the manikin. A sample result is shown in the figure. Although agreement between the model and data is not as close as in the previous steady state studies, the comparison is surprisingly good considering the complexity of the sorption process and the coupling between the heat and mass transfer in the transient case. In fact, the agreement between the model and the manikin data is comparable to the agreement between our data and the TUD data for the ensemble that was evaluated at both laboratories. It should be noted that the computational time for the model is not trivial. Typically about ten minutes of computing time on a modern PC are required for each minute of simulated time.

CONCLUSIONS

A computer model was developed which can simulate the transient response of clothing systems and predict the effect of this response on heat flow from the body. For the conditions tested, the model proved to agree with laboratory data indicating that the model does correctly describe the key transient processes in clothing system. Computational requirements are such that each condition to be simulated should be selected carefully.

REFERENCES

1. De Dear, R. J., et al., Impact of Air Humidity on Thermal Comfort During Step-Changes, Final Report ASHRAE 503RP, Technical University of Denmark, 1988.
2. McCullough, E. A., Jones, B. W., and Tamura, T., A data base for determining the evaporative resistance of clothing. ASHRAE Trans., 95, 1989.

