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TRANSIENT INTERACTION BETWEEN THE HUMAN AND THE THERMAL ENVIRONMENT

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ABSTRACT

The two-node model of human thermal regulatory response was combined with a transient model of heat and moisture flow through clothing. The combination provides a means to simulate the dynamic response of the human to the thermal environment and to evaluate the dynamic load the human imposes on the environment. The accumulation of moisture on the skin and in the clothing, the thermal capacitance of the clothing, and the interaction between the clothing and the body's thermal regulatory responses are included in the simulation. Transient responses typically last 20 to 60 minutes after changes in the environment and activity. During this period, the mix of dry and latent heat flow at the skin can differ significantly from the mix dissipated to the environment. These differences can impact the amount of sweating required and the latent load imposed on the environment.

INTRODUCTION

Standards for human comfort such as *ANSI/ASHRAE 55-1981* (ASHRAE 1981) are based on steady-state laboratory measurements of human response to various environments. It can take more than an hour for a person to approach a true steady state in many situations. For example, much of the data on which Standard 55 is based were collected after three hours of constant conditions to ensure a steady-state condition (Rohles and Nevins 1971). In real situations, people are moving about, changing their activity, changing their clothing, etc. The steady-state situation is probably the exception rather than the rule for most people, especially when one leaves the typical office environment. Transient response is even more of a concern for heat stress and cold stress. In these situations, it is often impossible for a person to endure the conditions indefinitely and some form of work-rest cycle or exposure and recovery cycle is required. Tolerance time is most certainly dependent on the transient nature of the person's response in these situations.

Engineers must also deal with the heat and moisture loads generated by occupants. In most office situations, the load due to the people—and, in particular, the transient nature of that load—is sufficiently small compared to the overall response of the building that the dynamics of the heat release from the occupants are not critical. There are many situations, however, where the occupant density is high and variable, and the transient nature of the heat release from the body can become important in these situations. Mass transportation vehicles, where large numbers of people get on simultaneously, are obvious examples. Similar concerns may also occur in theaters and auditoriums if the occupants enter all together. In these situations, the exposure and activity of the occupants prior to entering the space can impact the load they bring to the space. For example, a group of people who have been standing in a cold rain wearing winter outdoor clothing will bring a much different load to a bus than a group of people waiting in a well-conditioned airport lobby will bring to an airplane.

The transient nature of a person's response to changing conditions is dependent on the physiological responses of the body, including the thermal regulatory responses. However, the clothing a person is wearing also can have a major impact. Information is available in the literature to describe how a person is likely to react to changes in the environment. Thermal response models such as the two-node model (Gagge et al. 1971) can describe the physiological response. Some studies have been conducted that describe the subjective response of people in transients (De Dear et al. 1988). However, these studies do not provide a quantitative basis for addressing the expected response in specific applications and do not address the interaction of the transients in clothing systems with the transient responses that occur in the body. In the present work, a means to assess the transient response of people to their environments, to changes in clothing, and to changes in activity is developed. Both the impact on the body and the impact on the environment are included.

METHODOLOGY

The approach used in this work was to combine a modified version of the two-node model (Gagge et al. 1971) with a recently developed transient clothing model. The transient clothing model is described in some detail in Jones (1991). The modifications to the two-node model and the interface of the two-node and clothing models are described in this paper.

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Two-Node Model

The two-node model was chosen for simulating the human physiological response for this work because it is transient in nature and simpler than other dynamic models of human thermal physiology (Wissler 1985; Stolwijk n.d.), all of the equations are readily available in *ASHRAE Fundamentals* (ASHRAE 1989), and it provides outputs in terms of subjective responses as well as physiological variables. The basic heat balance equations for the two-node model follow.

$$dU_{sk}/dt = A_d \cdot (Q_{cr:sk} - Q_{sk}), \tag{1}$$

$$dU_{cr}/dt = A_d \cdot (M - W - Q_{cr:sk} - Q_{res}), \tag{2}$$

$$Q_{cr:sk} = (K + c_{pbl} \cdot \dot{m}_{bl}) \cdot (T_{cr} - T_{sk}), \tag{3}$$

where

U_{sk} = internal energy of the skin node, J (Btu),
U_{cr} = internal energy of the core node, J (Btu),
$Q_{cr:sk}$ = flow of heat from the core to the skin node, W/m^2 (Btu/h·ft^2),
Q_{sk} = total heat flow from the skin surface, W/m^2 (Btu/h·ft^2),
Q_{res} = total heat loss due to respiration, W/m^2 (Btu/h·ft^2),
M = metabolic heat generation, W/m^2 (Btu/h·ft^2),
W = physical work done by the body, W/m^2 (Btu/h·ft^2),
K = thermal conductance between the core and the skin nodes, W/m^2·°C (Btu/h·ft^2·°F),
c_{pbl} = specific heat of the blood, J/g·°C (Btu/lbm·°F),
$\dot{m}_{bl}$ = circulation of blood between the core and the skin, g/s·m^2 (lbm/h·ft^2),
T_{sk} = temperature of the skin node, °C (°F),
T_{cr} = temperature of the core node, °C (°F),
A_d = body surface area, m^2 (ft^2).

The metabolic heat M and the work performed W are inputs to the model. The heat loss from the skin Q_{sk} is determined by the environmental conditions and the clothing worn. This heat flow is determined in conjunction with the clothing model and will be discussed later.

Body mass is allowed to shift between the core and skin nodes in later versions of the model (Gagge et al. 1986). This shift is described by the variable α, the fraction of the total body mass in the skin node. The value of α depends on the blood flow according to

$$\alpha = 0.0418 + 0.745/(3600 \cdot \dot{m}_{bl} + 0.585).$$

Shifting mass from one node to the other also results in a shift of internal energy from one node to the other. This energy transfer is not reflected in any published version of the two-node model. With slow transients, the effect of the energy transfer due to mass shift is small compared to other heat flows. The present work is concerned with rapid transients as well as slow transients, and thus the energy transfer associated with the mass transfer must be included. The energy transferred with this mass shift is calculated by

$$\dot{U}_{cr:sk} = \begin{cases} -(U_{sk}/\alpha) \cdot (d\alpha/dt) & d\alpha/dt \le 0 \\ [U_{cr}/(1-\alpha)] \cdot (d\alpha/dt) & d\alpha/dt \ge 0 \end{cases} \tag{4}$$

where

$\dot{U}_{cr:sk}$ = the transfer of energy from the core to the skin node, W (Btu/h).

Equations 1 and 2 now must be rewritten to reflect this term:

$$dU_{sk}/dt = A_d \cdot (Q_{cr:sk} - Q_{sk}) + \dot{U}_{cr:sk}, \tag{1'}$$

$$dU_{cr}/dt = A_d \cdot (M - W - Q_{cr:sk} - Q_{res}) - \dot{U}_{cr:sk}. \tag{2'}$$

The skin blood flow is determined by the thermal regulatory signals from the body. Empirical relationships are given in chapter 8 of *ASHRAE Fundamentals* (ASHRAE 1989) relating $\dot{m}_{bl}$ to the skin temperature and the core temperature. As these relationships are rather complicated, they will be represented here simply by

$$\dot{m}_{bl} = f(T_{sk}, T_{cr}). \tag{5}$$

Previously published versions of the two-node model have assumed that the above action occurs instantaneously. This instantaneous action also means that α changes instantaneously and that the associated energy transfer also occurs instantaneously, resulting in differential equations that are difficult to solve. This problem was resolved by omitting the assumption of instantaneous action. Rather, Equation 5 was considered a steady-state expression with the actual thermal regulatory response lagging behind the response indicated by this equation. This effect is achieved by rewriting Equation 5 as

$$\dot{m}_{bl'} = f(T_{sk}, T_{cr}) \tag{5'}$$

where

$\dot{m}_{bl}'$ = the indicated blood flow, g/s·m^2 (lbm/h·ft^2).

The actual blood flow, $\dot{m}_{bl}$, then follows this indicated blood flow with a first-order delay:

$$dm_{bl}/dt = (\dot{m}_{bl}' - \dot{m}_{bl})/b \tag{6}$$

where

b = the time constant for the delay, s.

The two-node model also includes thermal regulatory functions to determine sweat generation and shivering.

These expressions are described in *ASHRAE Fundamentals* and will not be restated here.

The two-node model is one-dimensional in nature; that is, it treats the skin temperature, sweating, clothing, and heat loss as being uniform over the entire surface of the body. This uniformity may be reasonable for sweating, as that is controlled primarily by the central thermal regulatory system, but the other variables most certainly do vary over the body surface. The clothing model has the ability to reflect this non-uniformity. It is desirable to have the same capability in the physiological model. To meet this need, a "segmented two-node model" was developed. The concept behind the segmented model is shown in Figure 1. The core continues to be a single node; however, the skin node is divided into an arbitrary number of segments. Each segment constitutes a specified fraction of the total surface area f_i, where the subscript refers to the "ith" segment. Using this notation, equations 1′, 2′, 3, and 4 can be rewritten as

$$dU_{sk,i}/dt = A_d \cdot f_i \cdot (Q_{crsk,i} - Q_{sk,i}) + \dot{U}_{crsk,i}, \qquad (1'')$$

$$dU_{cr}/dt = A_d \cdot (M - W - Q_{res}) + \Sigma [A_d \cdot f_i \cdot (-Q_{crsk,i}) - \dot{U}_{crsk,i}], \qquad (2'')$$

$$Q_{crsk,i} = (K + c_{pbl} \cdot m_{bl}) \cdot (T_{cr} - T_{sk,i}), \qquad (3')$$

$$\dot{U}_{crsk,i} = \begin{cases} -[U_{sk,i}/\alpha] \cdot f_i \cdot (d\alpha/dt) & d\alpha/dt \le 0 \\ [U_{cr}/(1-\alpha)] \cdot f_i \cdot (d\alpha/dt) & d\alpha/dt \ge 0 \end{cases} \qquad (4')$$

The skin temperature for thermal regulatory purposes is replaced with the mean skin temperature $\bar{T}_{sk}$ where

$$\bar{T}_{sk} = \Sigma f_i \cdot T_{sk,i}. \qquad (7)$$

Skin Moisture

The published versions of the two-node model use the skin wettedness concept to describe the evaporative behavior of the skin. When reduced to mathematical terms, part of the skin is considered completely covered with sweat and part of the skin is considered dry. A minimum skin wettedness of 0.06 is used to account for the moisture diffusion through the skin even when active sweating is not occurring. The skin wettedness concept does not work well when combined with the transient clothing model. Moisture sorption and desorption and condensation or evaporation within the fabric depend on the local vapor pressure. These processes are very nonlinear with respect to vapor pressure. With the skin wettedness concept, the fabric over the saturated areas becomes saturated with moisture, while those over the dry regions gain no moisture. Even when no sweating occurs,

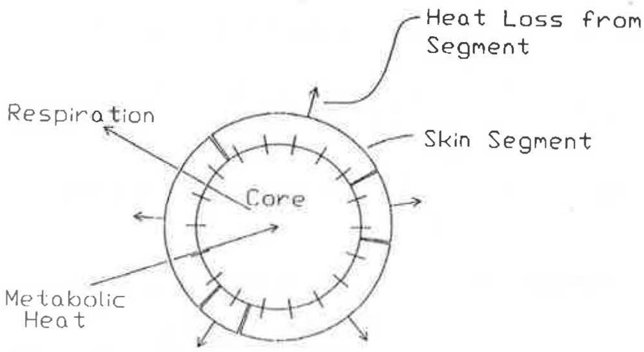

Figure 1 *Segmented model.*

6% of the clothing could be saturated with sweat. This phenomenon, of course, does not occur in reality. Over a uniformly clothed region of the body, the clothing sees a more or less uniform vapor pressure in a given layer. There may be large differences from one region of the body to another, due to differences in clothing permeability or environmental conditions, but not within a relatively small segment.

For these reasons, it was decided to abandon the skin wettedness concept. Instead, the vapor pressure at the skin is calculated by making a mass balance at the skin surface. The moisture permeability of the skin is also included as described by Fanger (1970). The basic concept is shown in Figure 2. Balancing the moisture at the skin gives the following relationship:

$$\frac{P_{sat} - P_{sk,i}}{R_{esk}} + m_{rsw} \cdot h_{fg} = \frac{P_{sk,i} - P_{ea,i}}{R_{ea,i}} \qquad (8)$$

where

m_{rsw} = regulatory sweating, g/s·m² (lbm/h·ft²),

R_{esk} = evaporative resistance of the skin, m²·kPa/W (ft²·psi·h/Btu),

$R_{ea,i}$ = evaporative resistance between the skin and the first fabric layer or the ambient environment if the layer is uncovered, m²·kPa/W (ft²·psi·h/Btu),

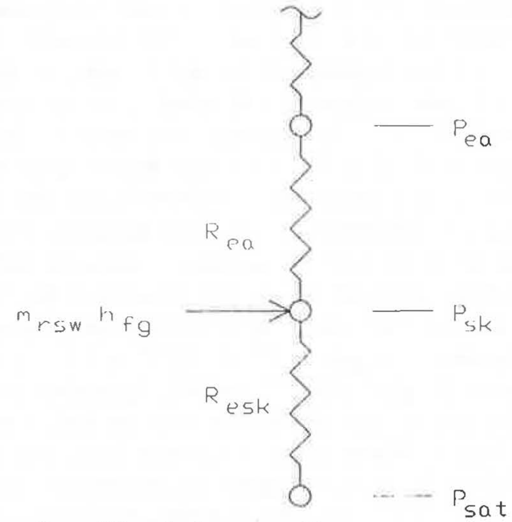

Figure 2 *Mass balance at skin.*

P_{sat} = saturation pressure at the skin temperature, kPa (psi),
$P_{sk,i}$ = skin vapor pressure, kPa (psi),
$P_{ea,i}$ = vapor pressure corresponding to R_{ea}, kPa (psi),
h_{fg} = heat of vaporization for water (sweat), J/g (Btu/lbm).

This equation can be solved for the skin vapor pressure:

$$P_{sk,i} = \frac{P_{sat} \cdot R_{ea,i} + P_{ea,i} R_{esk} + m_{rsw} \cdot h_{fg} \cdot R_{ea,i} \cdot R_{esk}}{R_{ea,i} + R_{esk}}. \quad (9)$$

The skin vapor pressure is subject to the limitation

$$P_{sk,i} \le P_{sat}(T_{sk,i}). \quad (10)$$

The evaporative heat loss from the skin is then calculated by

$$q_{se,i} = \frac{P_{sk,i} - P_{ea,i}}{R_{ea,i}} \quad (11)$$

where

q_{se} = evaporative heat loss from the skin, W/m^2 (Btu/h·ft^2).

Moisture accumulation on the skin may alter these relationships in transient situations. The accumulation of moisture on the skin is given by

$$dm_{s,i}/dt = m_{rsw} + \frac{P_{sat} - P_{sk,i}}{R_{esk} \cdot h_{fg}} - \frac{P_{sk,i} - P_{ea,i}}{R_{ea,i} \cdot h_{fg}}. \quad (12)$$

Theoretical calculations show that the sweat glands on the body are sufficiently close together that any time there is moisture present at the glands, for most purposes, the skin vapor pressure is equal to the saturated vapor pressure. Thus, Equations 8 through 11 apply as long as there is no net accumulation of moisture on the skin and Inequality 10 is at the limiting value anytime there is moisture on the skin. Once moisture has accumulated on the skin, it must evaporate completely before the vapor pressure can fall below the saturated pressure. There is also an upper limit on the amount of moisture that can accumulate. Berglund (1971) has shown that this maximum amount corresponds to a uniform sweat layer of approximately 35 μm (1.38 × 10^{-3} in.) for a nude person or 35 g/m^2 (0.0072 lbm/ft^2). Quantities greater than this amount run off. For parts of the body covered with clothing, this excess moisture may be picked up by the fabrics. However, this effect has not yet been modeled, and the same upper limit is applied to all parts of the body.

These equations apply to a single uniform segment. It should be realized that the skin vapor pressure and the moisture accumulation may vary considerably from segment to segment.

Interfacing the Models

Interfacing the segmented two-node model with the transient clothing model is straightforward; an overview is given in Figure 3. A separate segment in the two-node model is established for each subsegment in the clothing model. The regulatory sweat rate m_{rsw} is determined by the two-node model and is considered uniform over the whole body. The skin temperature and the skin vapor pressure are calculated for each segment. Given these skin conditions, the clothing model is used to determine the dry (sensible) and evaporative (latent) heat loss from each segment. The clothing model also calculates the dry and latent heat loss from the clothing surface to the environment.

Although the interface is straightforward, careful attention must be paid to timing of the calculations. The clothing model uses a variable time step. The time step for each subsegment is determined separately and may vary as conditions change. This variable time step is used to minimize computer time. During sharp transients, such as step changes in the environment, these time steps often become much less than one second. On the other hand, the time step requirements for the two-node model are not so demanding. A fixed, six-second time step is normally used. The skin moisture accumulation calculations are more analogous to the calculations in the clothing model than they are to the other calculations in the two-node model. These calculations are carried out with the clothing model calculations rather than with the other two-node model calculations. Details of the actual computer code are presented in a separate report (Jones 1991).

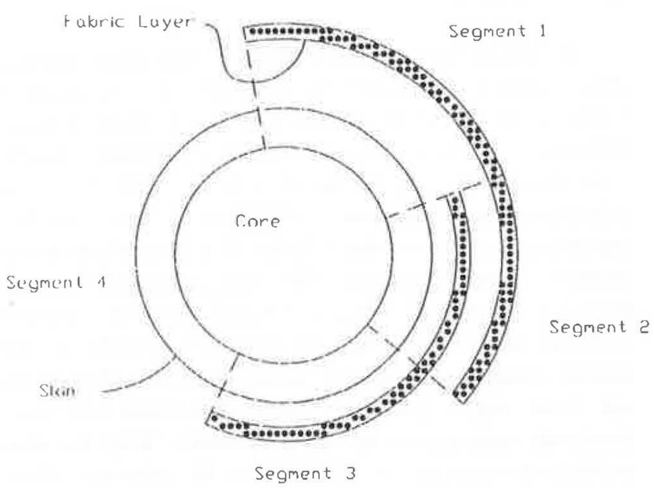

Figure 3 Combined clothing-body model.

APPLICATIONS

The combination of the models can be applied to a wide variety of situations where transients are of interest and a fair amount of detail in the heat flows from the body is needed. Several examples will follow to demonstrate the type of information that can be obtained.

Case 1

This example shows what happens when a person who is wearing clothing appropriate for a cool environment moves to a much warmer environment and/or begins to exercise. The person is wearing 1 clo of wool clothing described by Jones (1991). Initially the person is sedentary in an environment with an air temperature and mean radiant temperature of 20°C (68°F) with a 30% relative humidity. The person moves to another location with an air temperature and mean radiant temperature of 27°C (81°F) with 60% relative humidity and is also engaged in moderate activity of two met. Ambient air velocity is approximately 0.2 m/s (40 fpm) in both cases.

Case 2

Case 2 is a continuation of case 1. The person works in the warm environment until the end of 120 minutes. At that time, the person is exposed to an elevated air velocity of 1 m/s (200 fpm) while resting.

Case 3

The third example is unrelated to the first two. The person is wearing a man's business suit (Jones 1991) while standing in a heavy mist waiting for a bus. The air temperature and the mean radiant temperature are 25°C (77°F), there is no wind, and the humidity is 100%. The mist is adding 100 $g/h \cdot m^2$ (0.02 $lbm/h \cdot ft^2$) of moisture to the outer surface, clothing or skin. The person then enters the bus where the air and mean radiant temperatures are 24°C (75°F) and the relative humidity is 70%.

Simulation results are presented in Figures 4 through 12. In Figures 4, 7, and 10, the total (dry plus evaporative) heat flows from the skin and to the environment are compared. It is seen in each case that the total heat flows do not differ greatly. This result is to be expected, since the clothing has a small thermal capacitance. The mix of the dry and evaporative heat flows is shown in Figures 5, 8, and 11. Here it is seen that there is a big difference between what happens at the skin and what is transmitted to the environment. This difference is due to moisture storage in the clothing. Finally, simulations were conducted for each case using the traditional (unsegmented) two-node model and a steady-state representation of the clothing insulation (no moisture or heat storage in the clothing). These results are presented in Figures 6, 9, and 12. It is seen that the mix of the evaporative and dry heat

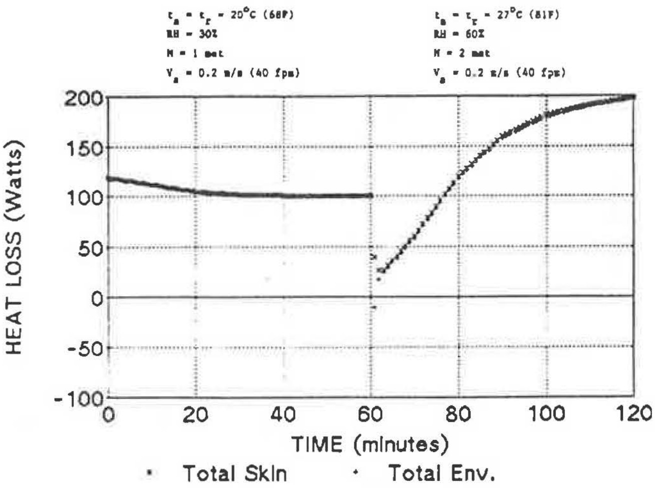

Figure 4 *Total heat flows, case 1.*

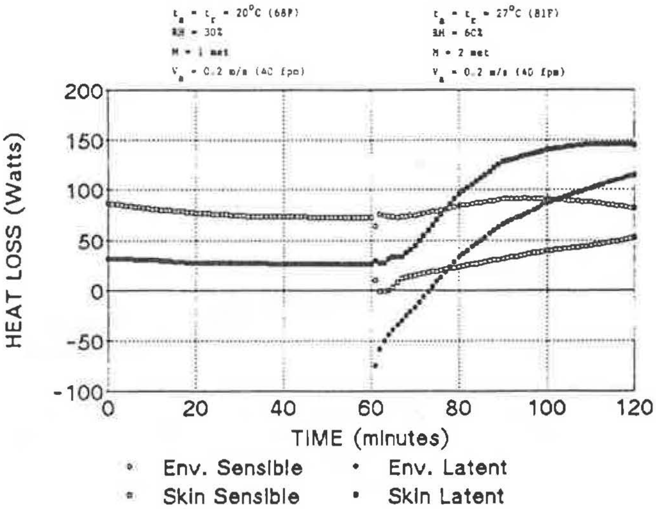

Figure 5 *Dry and evaporative heat flows, case 1.*

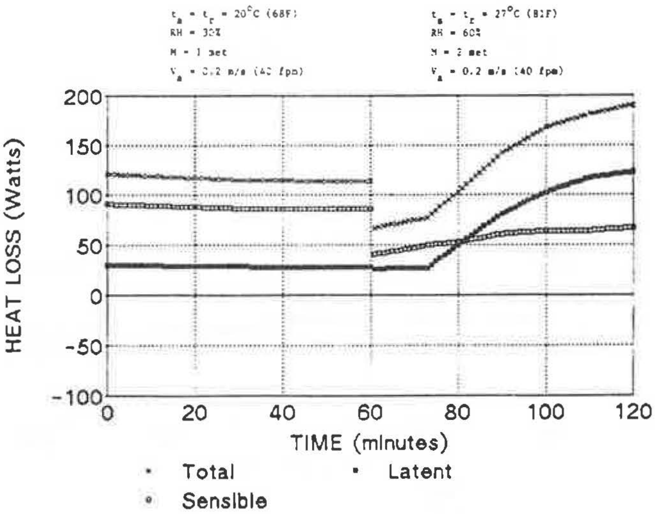

Figure 6 *Heat flows with traditional model, case 1.*

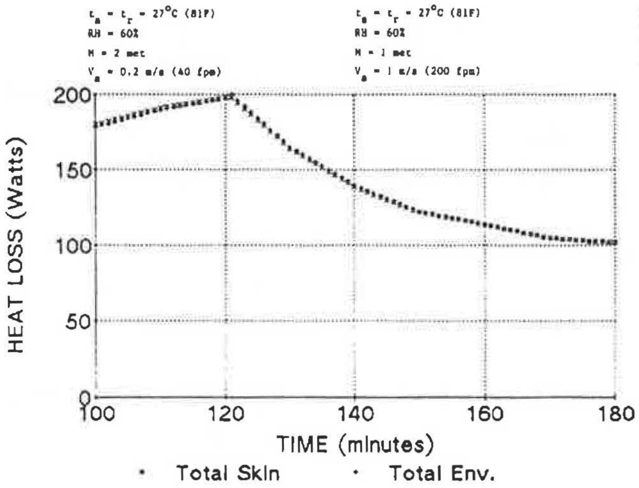

Figure 7 *Total heat flows, case 2.*

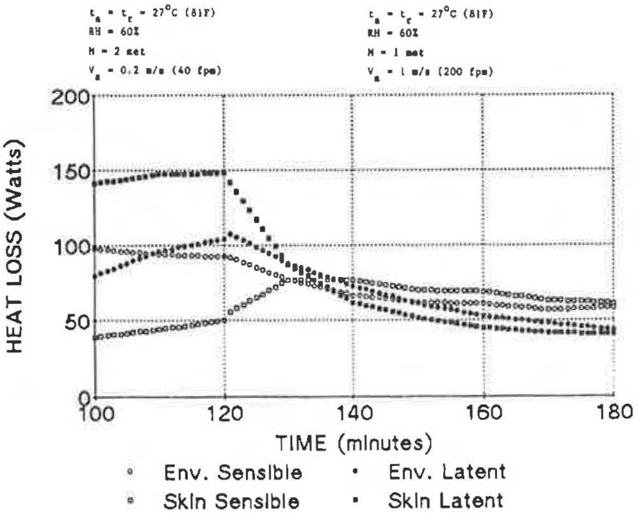

Figure 8 *Dry and evaporative heat flows, case 2.*

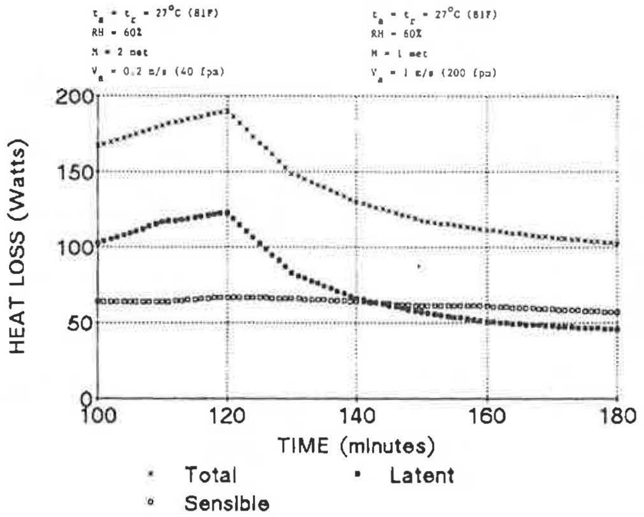

Figure 9 *Heat flows with traditional model, case 2.*

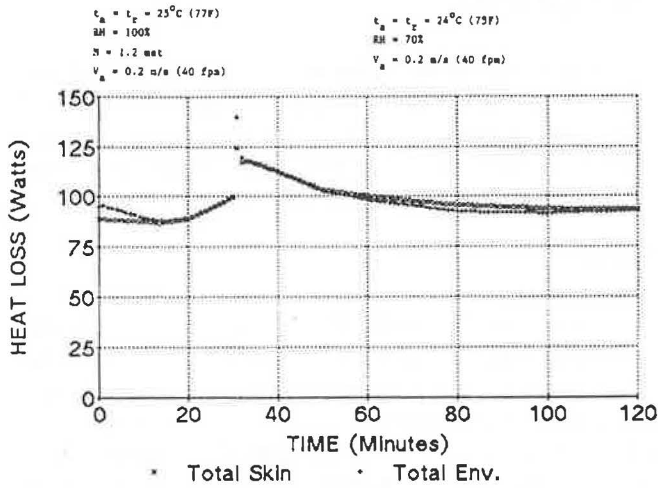

Figure 10 *Total heat flows, case 3.*

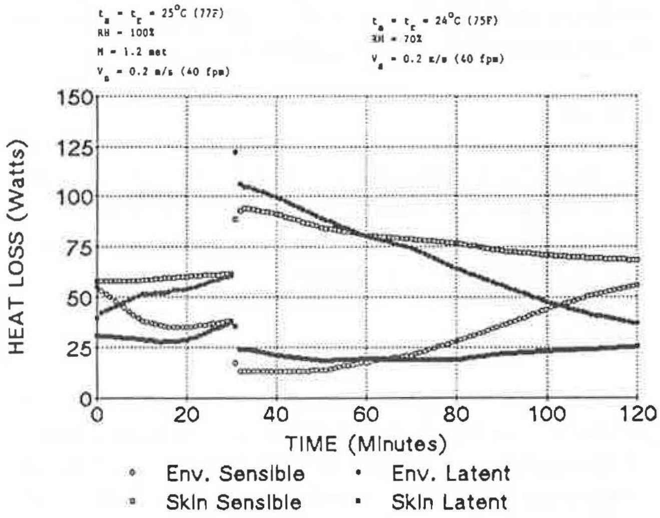

Figure 11 *Dry and evaporative heat flows, case 3.*

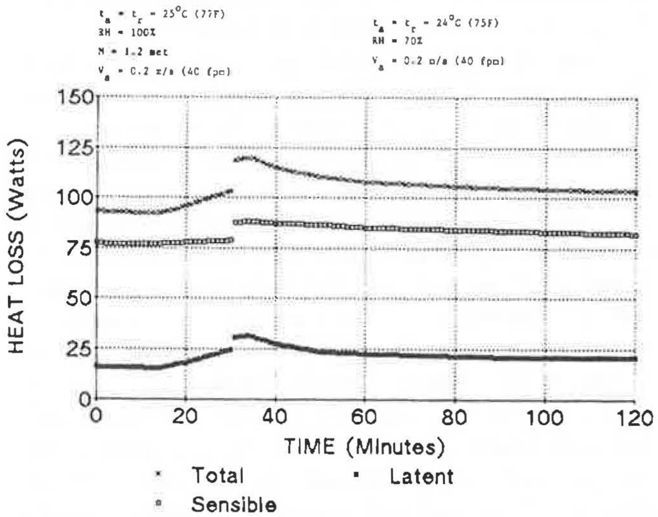

Figure 12 *Heat flows with traditional models, case 3.*

flows is different from that calculated with the transient, segmented model. The difference is most pronounced in case 3, where precipitation is present initially. The simple model does reflect the large latent load the person gives off after entering the bus.

One may be inclined to conclude that since the total heat flow from the skin is not altered greatly by the transient effects, they are not important. However, the shifting of the mix of latent and sensible heat is a reflection of the physiological impact on the body. The decreased sensible heat loss from the body in case 1 must be compensated for by increased latent heat loss. This increased latent loss is generated by increasing the sweat rate. The increased sweat rate is a result of the body being warmer. There are actually two important transient phenomena occurring in case 1. The first is the sorption of moisture into the clothing from the moist air and the second is the sorption of moisture into the clothing from the sweat. The initial effect at the beginning of the transient is due primarily to sorption from the environment; but as the body responds and generates more sweat to maintain its heat balance, the sorption of sweat becomes a significant factor. The opposite effect is seen in case 2, where an ''after chill'' is generated due to evaporation of moisture accumulated in the clothing and on the skin. In either case, the impact is to increase the thermal regulatory response required by the body.

CONCLUSION

A transient model of dry and evaporative heat flows through clothing systems has been successfully coupled with a segmented version of the two-node model. This combined model is capable of simulating the entire person-clothing system in transient situations. It is possible to differentiate between heat flows to and from the body and heat flows to and from the environment. In at least some cases, there is a large difference in the distribution of these heat flows between evaporative and dry components. This difference is important in addressing the impact on the body, particularly the amount of sweating required. It also may be of importance for characterizing the nature of the load generated by occupants.

REFERENCES

ASHRAE. 1981. *ANSI/ASHRAE 55-1981, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 1989. *1989 ASHRAE handbook—fundamentals.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Berglund, L.G. 1971. A theoretical and experimental study of the thermoregulatory effects of salt accumulating on human skin during sweating. Ph.D. dissertation, Kansas State University.

De Dear, R.J., H.N. Knudson, J. Pejtersen, J.W. Ring, T.L. Li, T.W. Puntener, S. Tanabe, J. Mackenprang, and P.O. Fanger. 1988. Impact of air humidity on thermal comfort during step-changes. Final Report for ASHRAE 503-RP, Laboratory of Heating and Air-Conditioning, Technical University of Denmark.

Fanger, P.O. 1970. *Thermal comfort.* New York: McGraw-Hill.

Gagge, A.P., J.A.J. Stolwijk, and Y. Nishi. 1971. An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions* 77(1).

Gagge, A.P., A.P. Fobelets, and L.G. Berglund. 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, 82(2).

Jones, B.W. 1991. Transient model of the human body and clothing systems. Technical Report 91-01, Institute for Environmental Research, Kansas State University.

Jones, B.W., M. Ito, and E.A. McCullough. 1990. Transient thermal response of clothing systems. *Proceedings of the Fourth International Conference on Environmental Ergonomics*, Austin, TX.

Rohles, F.H., and R.G. Nevins. 1971. The nature of thermal comfort for sedentary man. *ASHRAE Transactions* 77(1).

Stolwijk, J.A.J. (no date). A mathematical model of the physiological temperature regulation in man. NASA Technical Report No. NASA CR-1855.

Wissler, E.H. 1985. Mathematical simulation of human thermal behavior using whole body models. In: *Heat and Mass Transfer in Medicine and Biology*, chap. 13. A. Shitzer and R.C. Eberhart, eds. Plenum Press.