A Transient Computer Model of the Human Thermal Response and Thermal Comfort Perception

by

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An Advanced Independent Study Project

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Abstract

The mathematical Gagge/ Pierce Foundation Two Node Model of the human thermoregulation is applied in two computer programs. Several modifications especially with regard to a transient comfort index have been made. One program is a ready-to-use component for the modular transient simulation program TRNSYS, the other is an interactive simulation program; both provide the transient or steady thermal body state, sensible and latent heat flow, temperatures of skin, core and clothing as well as comfort vote indices.

Keywords: Simulation, human thermophysiology, thermal comfort, thermal balance, transient development of body states.

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Table of Contents

Chapter 2   The Fanger Steady State Model

Chapter 8   Individual Influences on the Thermal Perception   Comfort

Chapter 9   Conclusion

Appendix

List of Figures

Figure   Description   **Page**

List of Tables

Introduction

In western society life takes place mostly indoors. The goal of heating and climatizing is to provide favorable conditions in this environment for human comfort during all activities. So far importance was mostly only given to several ambient quantities without taking into account physiological responses of the human body (for instance changes in activity/ metabolism). Therefore building simulation was usually done only with indoor parameters. However there is a big field for improvements by an analysis of the human thermal response and the interactions between humans and the environment.

Giving the thermophysiological response, the human thermal model, presented in this report provides the tool for realizing more complete system simulations. The psychological and sociological aspects are not taken into account. Hence the approach for a thermal comfort index in the presented model is only a physical one and is based on the grade of thermal imbalance and mean body temperature respectively.

The Gagge/Pierce Foundation two node thermophysiological model applied in the present study is based on a two node representation of the human body; the core node is the interior of the body and is regulated to maintain nearly constant temperature. The ratio of skin node to core node is adjusted according to thermal signals as well as the other determining body state variables like sweating rate, shivering and skin blood flow. The metabolic energy is created in the core node with part of it going to produce useful work. Heat is transferred to the skin node by conduction and blood flow. Sensible and latent heat are transferred directly to the environment through the respiratory tract. Energy leaves the skin surface and is transferred through a clothing layer to the environment by convection, evaporation and radiation.

The balance of these energy terms produces a thermal state of the body as given by the core, skin and clothing temperature as well as the actual skin to core ratio.

The thermal comfort perception is determined by the Fanger Predicted Mean Vote PMV, which provides the com;fort vote for a steady body state and the transient Mean Body Temperature Vote created in the present study. A third comfort vote is the Predicted Percentage Dissatisfied PPD.

Two computer programs applying the improved Two Node Model algorithm are provided by the present study. One is to be used inter-actively and gives a detailed information about the instantaneous or steady human body state, the other is a ready-to-use component for the modular transient simulation program

TRNSYS and provides only outputs affecting the environment and concerning comfort perception for control purposes.

After a concise description of the fundamental human thermal parameters in chapter 1, the Fanger steady state model providing the standard steady state comfort index Predicted Mean Vote PMV is analyzed in chapter 2.

The Gagge/ Pierce Foundation Two Node Model is explained in chapter 3 and chapter 4 contents the derivation of the new transient comfort index Mean Body Temperature Vote MBTV for the Two Node Model, which is based on the mean body temperature. The further chapters 5 and 6 describe the program algorithms and the TRNSYS configuration; in chapter 7 the validation including simulation results is given and chapter 8 provides an overview over further environmental and behavioral influencing factors.

Chapter 1

The Human Body - Determined By Thermal Parameters

1.1   Overview

The thermal behavior of the human body is characterized by several fundamental quantities concerning metabolism, efficiency, clothing insulation and the environment.

For being able to concentrate on the characteristics of the human models described in the following chapters, the basic information about variables and units is provided separately in this section.

1.2   Activity and Metabolism

The human body continuously generates heat, with an output varying from about 100 W for a sedentary person to 1000 W for a well trained person exercising strenuously. The heat is not generated uniformly throughout the body, nor is it dissipated uniformly. However for most engineering applications, it is

sufficient to consider the body as uniform in temperature when describing heat dissipation to the environment.

The total metabolic heat M produced within the body is the energy required for the person's activity M_{act} plus the energy produced by shivering M_{shiv} in cold body states. The standard unit is 1 met = 58.2 W/m^2, which equals the heat produced by a sedentary average person. The heat flow is related to the Dubois average body surface area A_{Du} (see following), which is 1.8 m^2 for an average adult of 70 kg body mass.

Table 1.1: Metabolic Rate at Different Typical Activities

RESTING:		
Sleeping		0.7
Reclining	0.8	
Seated, quiet	1.0	
Standing, relaxed	1.2	
WALKING:		
0.89 m/s		2.0
1.34 m/s		2.6
1.79 m/s		3.8
DRIVING:		
Car	1.5	
Heavy Vehicle		3.2
DOMESTIC WORK:		
House cleaning		2.0 to 3.0
Cooking		1.6 to 2.0
Washing by hand		2.0 to 3.6
Ironing		2.0 to 3.6
Shopping		1.4 to 1.8
OFFICE WORK:		
Typing		1.2 to 1.4

| Miscellaneous work | 1.1 to 1.4 |
| Drafting | 1.1 to 1.3 |

LEISURE ACTIVITIES:
| Dancing, social | 2.4 to 4.4 |
| Tennis, singles | 3.6 to 4.6 |

(Source: ASHRAE Fundamentals Handbook '89)

In a variety of experiments the metabolism rates have been measured by the rate of respiratory oxygen consumption and carbon dioxide production or, less accurately, by correlations between heart rate and metabolism. Table 1.1 gives standard values for the specific activities listed with accuracy +/- 10% for values of M<1.5 met, which is sufficiently accurate for most engineering purposes.

1.3   Mechanical Efficiency

In the body heat balance the rate of work accomplished W must be considered. It is defined in the same units as metabolism M and usually expressed in terms of body's mechanical work efficiency:

$$we = \frac{W}{M}$$

(1.1)

It is unusual for we to be more than 5 to 10%/ for most activities it is close

to zero because the mechanical work produced is small compared to M; especially for office activities. The maximum value is about 20% on a bicycle ergometer (Nishi 1981). For some cases, e.g. walking up a certain grade. the work can be calculated directly.

1.4   The Dubois Average Surface Area ADu

Since the heat exchange by radiation, convection and evaporation is related directly to the body surface, their magnitudes as well as all other heat flows are related to this average area for standard purposes. It is

defined by:

$$A_{Du} = 0.202 m^{0.425} h^{0.72} \qquad (1.2)$$

where A_{Du} [m²], m = body mass [kg], h = body height [m]

For an average person of m = 70 kg and h = 1.7 m the area is A_{Du} = 1.8 m².

A correction factor must be applied to the heat transfer terms from the skin to account for the increase in actual surface area of the clothed body A_{cl}. The correction factor is defined as:

$$f_{cl} = \frac{A_{cl}}{A_{Du}} \qquad (1.3)$$

and can be approximated by:

$$f_{cl} = 1 + 0.25 I_{cl} \qquad (1.4)$$

where I_{cl} is the clothing insulation value (see beyond).

1.5   The Thermal Clothing Insulation:

Clothing insulation is usually described as single equivalent uniform layer over the whole body. Its insulation value is expressed in terms of 'clo'-units, defined as

$$1 \text{ clo} = 0.155 \frac{m^2 K}{W}$$

I_{cl} is the so-called intrinsic clothing insulation value, which means, that only the resistance to sensible heat from the skin through the clothing layer is considered.

Clothing insulation can also be expressed as a total clothing insulation It; a measure of the total resistance to sensible heat transfer between the skin and the environment. It also includes convection and radiation from the clothing surface:

$$I_t = I_{cl} + \frac{1}{0.155 f_c h} \tag{1.5}$$

However its value depends on the value of the overall heat transfer coefficient h, which in turn depends strongly on environmental conditions. Evaluations of It made for one condition are not likely to be valid for others and therefore for further considerations only Icl is used. Heat loss by convection and radiation is then considered separately.

The crucial quantity for heat flow calculations however is the thermal resistance value Rcl, derived from I_{cl}:

$$R_{cl} = 0.155 I_{cl} \quad \left[\frac{m^2 K}{W} \right] \tag{1.6}$$

I_{cl} is usually measured on heated manikins and standard values for engineering applications are tabulated for typical indoor

clothing ensembles as shown in Table 1.2 (ASHRAE Fundamentals Handbook'85). This table of measured values can be used to describe an ensemble comparable to the one in question. For the case that none of the ensembles matches to this, the ensemble insulation can be estimated from the insulation of tabulated individual garments by using a summation formula:

$$I_{cl} = 0.835 I_{cl,i} + 0.16 \qquad (1.7)$$

Table 1.2   Typical Insulation Values for Clothing Ensembles

Ensemble Description	fcl	Icl [clo]
MEN		
Walking shorts, short sleeve shirt	0.41	1.11
Fitted trousers,short-sleeve shirt	0.50	1.14
Fitted trousers, long-sleeve shirt	0.62	1.19
Same as above, plus suit jacket	0.96	1.23
Loose trousers, long-sleeve shirt, long sleeve sweater, T-shirt	1.01	1.28
Loose trousers, long-sleeve shirt, long-sleeve sweater, suit jacket, long underwear, T-shirt	1.30	1.33
Sweat pants, sweat shirt	0.77	1.19
WOMEN		
Knee-length skirt, short-sleeve shirt, panty hose (no socks), sandals	0.54	1.26
Knee-length skirt, long-sleeve shirt, full slip, panty hose (no socks)	0.67	1.29

Knee-length skirt, long-sleeve shirt, half-slip,
  panty hose (no socks), long-sleeve sweater   1.10   1.46
Ankle-length skirt, long-sleeve shirt, suit
  jacket, panty hose (no socks)   1.10   1,46
Long-sleeve coveralls, T-shirt   0.72   1.23
Overalls, long-sleeve shirt, long underwear tops
  and bottoms, flannel long-sleeve shirt   1.00   1.28

(Source: ASHRAE- Fundamentals Handbook'89; data can have an error +/-20%.
Unless otherwise noted, all ensembles include briefs or panties, shoes, and socks)

1.6 The Evaporative Resistance of Clothing

Analogous to Rcl, the intrinsic evaporative resistance of clothing, Re,cl is a measure of the resistance to latent heat transfer from the skin through the clothing layer. The total evaporative resistance Re,t also accounts for the air layer an the clothing surface by including the evaporative heat transfer coefficient he:

$$R_{e,t} = R_{e,cl} + \frac{1}{f_{cl}h_e} \quad \left[\frac{m^2 Pa}{W}\right]$$

(1.8)

Here the forcing quantity is the vapor pressure difference between skin and environment, which in turn depends on sweating rate and skin temperature. The evaporative skin heat loss is then:

$$E_{sk} = w\frac{P_{skin,sat} P_{vap,amb}}{R_{e,t}}$$

(1.9)

(w is the fraction of wetted skin surface)

So far sensible and evaporative (latent) heat loss have been treated as two distinct phenomena. In actuality the two forms are

closely related. Latent heat transfer depends on the evaporation of moisture and dissipation of the resulting vapor. The convective transfer coefficients for sensible heat h_c and mass hm are linked by the so-called Lewis Relation.

The evaporative heat transfer coefficient used here equals the mass transfer coefficient multiplied by the latent heat of vaporization. Thus, the latent heat transfer is equal to the energy required to vaporize the moisture on the skin. The Lewis Relation defined in terms of the evaporative heat transfer coefficient is then:

$$LR = \frac{h_e}{h_c}$$

(1.10)

The value of LR depends on temperature and pressure, but is relatively constant. It is approximately 16.5 K/kPa at typical indoor conditions and is essentially independent of temperature and pressure between 25 and 40 C. (ASHRAE-Fundamentals handbook'89, ch.8). With this relation the combined heat flow Qcomb can be calculated knowing only the convective heat transfer coefficient h_c, which in comparison with he is relatively easy to determine:

$$Q_{comb} = h_c (t_{sk} - t_a) + h_e (p_{sk,s} - p_a)$$

$$= h_c[(t_{sk} - t_a) + LR (p_{sk,s} - p_a)]$$

(1.11)

However LR applies to a completely wetted surface in forced convection. To take this into account a correction factor for the

clothing is necessary, for which several approaches have been made. Here the clothing vapor permeation efficiency icl by Oohori /2/ is being applied. It is defined by the relationship:

$$i_c LR = \frac{h_{e,cl}}{h_{cl}} = \frac{\frac{1}{R_{e,c}}}{\frac{1}{R_{cl}}}$$

(1.12)

Values of icl for common indoor clothing ensembles have been found to be typically about 0.45 in measurements by McCullogh /2/.Now the total evaporative resistance $R_{e,t}$ can be calculated as a function only of R_{cl} and h_c and needn't be tabulated:

$$R_{et} = \frac{R_{cl}}{icl\ LR} + \frac{1}{f_{cl}LRh_c}$$

(1.13)

1.7   Environmental Parameters

The parameters describing the thermal environment that must be measured or otherwise quantified, if accurate estimates of the human
thermal response are to be made, are divided into two groups - those that can be measured directly and those that are calculated from other measurements.

1.7.1 Directly Measured Parameters

The parameters used here to describe the thermal environment are (1) air temperature ta, (2) relative humidity rh respective water vapor pressure pa, and (3) air velocity vel.

1.7.2   Calculated Parameters

The mean radiant temperature t_r is one of the key variables in making thermal calculations for the human body. It is the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure. Measurements of the globe temperature, air temperature and the air velocity can be combined to estimate the mean radiant temperature. However mostly tr is calculated by a second method from measured values of the temperature of the surrounding walls and surfaces and their positions with respect to the person. This is a common matter of radiative heat exchange theory and hence needn't be discussed here in detail.

Chapter 2

The Fanger Steady State Model

2.1 Introduction

The Fanger Model /1/ is designed to provide an analysis of the human body state with respect to the thermal comfort. In comparison with the Two Node Model, described in chapter 3, which actively simulates inter-nal body responses like e.g. blood flow according to environmental influ-ences, the Fanger Model provides only static values.

The model is used in the present study and provides a standard method for calculating the grade of thermal comfort based on reliable validation measurements. The crucial variable which is explained in chapter 2.5 is the so-called Predicted Mean Vote variable PMV of thermal comfort, which is defined in a range from -3 (for cold) to +3 (for hot) and based on an empirical formula derived from a variety of measurements. Physically the PMV value is based on the grade of thermal imbalance between metabolism and heat loss respective heat gain. Hence this model only considers the overall heat balance without respect to

responses within the body. Several parts of this heat balance are also used in the Two Node Model described in chapter 3.

2.2 The Body Heat Balance

It can be assumed, that for long exposures to a constant but not too extreme thermal environment with a constant metabolic rate, a heat balance for the human body will exist, because the purpose of the thermo-regulatory system of the body is to maintain a essentially constant internal body temperature. This heat balance means that the internal heat production equals the heat dissipation and that there is no heat storage within the body. The heat balance can be formulated as:

$$M - W - E_{diff} - E_{sw} - E_{res} - C_{res} = K_{cl} = R + C \qquad (2.1)$$

where: M   = metabolic heat production

W   = external work

E_{diff} = the heat loss by vapor diffusion through the skin surface

E_{sw} = the heat loss by evaporation of sweat from the skin surface

E_{res} = the latent respiration heat loss

C_{res} = the sensible respiration heat loss

K_{cl} = the heat transfer from the skin to the outer surface of the clothing (conduction through the clothing)

R   = the heat loss by radiation from the outer surface of the clothed body

C   = the heat loss by convection from the outer surface
of the clothed body

The double equation (2.1) expresses that the internal heat production M minus the external work W and the heat loss by evaporation from the skin ($E_{diff} + E_{sw}$) and by respiration ($E_{res} + C_{res}$) is equal to the heat con-ducted through the clothing (K_{cl}) on the one hand, and equals the dissipated heat at the outer surface of the clothed body by radiation and convection (R + C). (It is assumed, that the evaporation corresponding to E_{sw} and E_{diff} takes place at the skin surface - see Fig. 2.2).

Figure 2.1   The Heat Balance of the Human Body
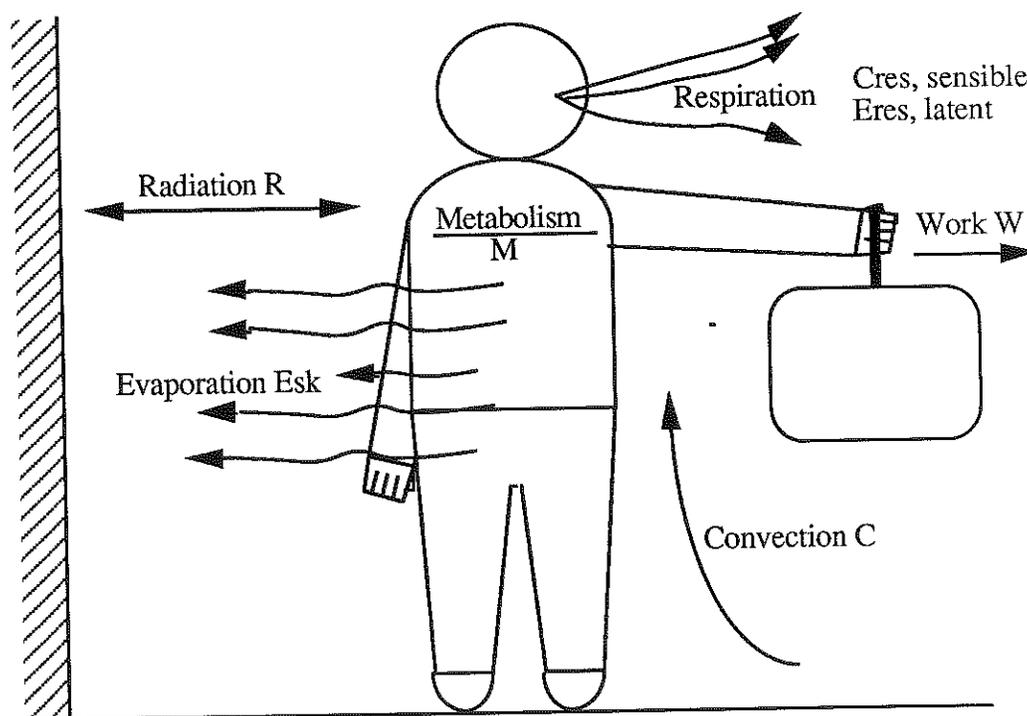
Here as in all following chapters the heat flows are all related to the Dubois Area A_{Du} , which provides a standardized way of calculating.

2.2.1 Heat Loss By Skin Diffusion

One part of the latent heat loss is water vapor diffusion through the skin, a process not subject to thermoregulatory control, but due to natural skin humidity. Fanger assumes the magnitude of the diffusion per unit area to be proportional to the difference between the saturated water vapor pres-sure at the skin $p_{sk,s}$ at skin temperature and the partial water vapor

Figure 2.2 Scheme of Sensible Heat Exchange
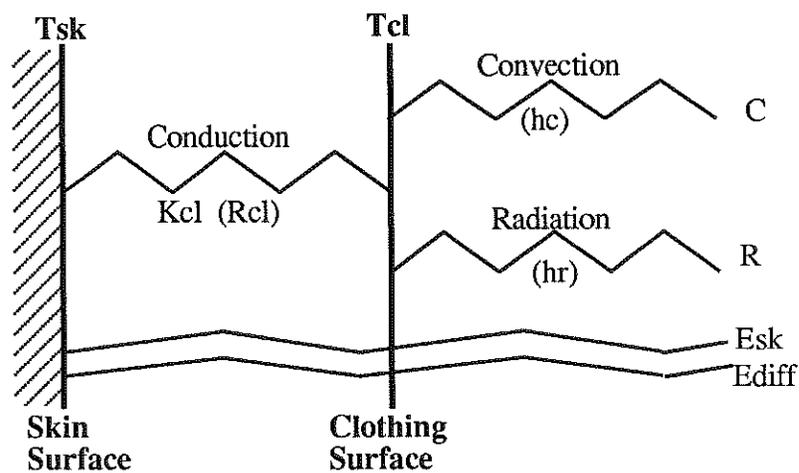
pressure p_a in the ambient air. From steam tables $p_{sk,s}$ can be found as a function of t_{sk}. For 27 C < t_{sk} < 37 C he gives the

following linear expression as an approximation with less than 3% error:

$$p_{sk,s} = 0.256 t_{sk} - 3.37 \ [kPa] \tag{2.2}$$

With this approximation Fanger describes E_{diff} as a function only of p_a and t_{sk}:

$$E_{diff} = 3.052 \ (0.256 t_{sk} - 3.37 \ p_a) \ \left[\frac{W}{m^2}\right], \ (p_a \ in \ kPa)$$

$$(2.3)$$

The factor 3.052 consists of the evaporation heat of water and an empirical permeance coefficient of the skin.

2.2.2 Latent Respiration Heat Loss

Deep in the lungs the inspired air reaches a wet surface equilibrium with body temperature. As the air moves outward through the respiratory tract some heat is transferred back to the body and water is condensed, but in common environments the expired air is at higher temperature and water vapor content than the inspired air. Breathing therefore results in a latent heat loss from the body, which is a function of ventilation and the difference in water content between expired and inspired air:

$$E_{res} = \dot{V}(x_{ex} - x_{amb}) h_{water} \ \left[\frac{W}{m^2}\right] \tag{2.4}$$

$$\dot{V} \qquad = air \ ventilation \ [kg/hr]$$

$$X_{ex} / X_{amb} \quad = \text{humidity ratio of expired/ inspired air}$$
$$[\text{kg water/ kg dry air}]$$

Based on data analyses the following approximation has been found for the mean ventilation for the most types of work:

$$\dot{V} = 0.006 \ \dot{M} \tag{2.5}$$

The difference in humidity ration between expired and inspired air has been found to be:

$$X_{ex} - X_a = 0.029 - 0.8 X_a \tag{2.6}$$

X_a can be substituted by (p_a in mmHg):

$$X_a = 0.622 \frac{p_a}{P - p_a} \cong 0.0008 p_a \tag{2.7}$$

This provides (p_a in mmHg):

$$X_{ex} - X_a = 0.029 - 0.0006 p_a \tag{2.8}$$

Substituting the expressions for (V) and (X_{ex} - X_a) in equation (2.4) pro-vides the following formula for the latent respiration heat loss:

$$E_{res} = 0.01725 \ M \ (5.8 \ p_a) \quad (p_a \text{ in kPa}) \quad [W/m^2]$$
$$= 0.0023 \ M \ (44 \ p_a) \quad (p_a \text{ in mmHg}) \tag{2.9}$$

2.2.3   Sensible (Dry) Respiration Heat Loss

The temperature difference between inspired and expired air causes this sensible heat loss; it can be expressed as:

$$C_{res} = V c_p (t_{ex} - t_{amb}) = 0.0014 M (t_{ex} - t_{amb}) \qquad (2.10)$$

Measurements lead to the average value of $t_{ex} = 34$ C. Since the dry respiration loss is small compared with other terms, this constant average value is sufficiently accurate and (2.10) can be written as:

$$C_{res} = 0.0014 M (34 - t_a) \qquad [W/m^2]$$

(2.11)

2.2.4   Heat Loss by Radiation

Radiant heat exchange takes place between the human body and its surroundings due to surface temperature differences. This radiation heat
loss can be described by the Stefan Boltzmann's law:

$$R = e s [(t_{cl} + 273)^4 - (t_r + 273)^4] \qquad [W/m^2]$$

(2.12)

where: e = emittance of the outer surface of the clothed body

s = 5.768 10^{-8} W/m²K⁴ , the Boltzmann constant

t_{rad} = mean radiative temperature (see chapter 1.6.2)

There is however the difficulty, that the human body is shaped irregularly and some interradiation between body parts occurs. Therefore a factor f_{eff} for the effective radiation area is introduced. Its value was empirically found to be $f_{eff} = 0.72$. In chapter 1.3 the area increase factor f_{cl} due to clothing was introduced and must also be applied. With a mean value $e = 0.97$ for the emittance of human skin and clothing the heat exchange by radiation is:

$$R = 3.95 \cdot 10^{-8} f_{cl} \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] \quad [W/m^2]$$

(2.13)

2.2.5 Heat Loss by Convection

The convective heat loss from the outer surface of the clothed body can be expressed as:

$$C = f_{cl} h_c (t_{cl} - t_a) \quad [W/m^2] \qquad (2.14)$$

The magnitude of h_c depends on the type of convection process. For low air velocities, such as still air, the heat transfer takes place by free convection, so that h_c is a function of the temperature difference $(t_{cl} - t_a)$. For higher air velocities forced convection exists and h_c then is a function of the velocity.

In comprehensive investigations by Nielsen and Pedersen /2/, using both subjects and manikins, the following formula for hc was developed:

$$h_c = 2.38(t_{cl} - t_a)^{0.2} \quad [W/m^2K]$$

(2.15)

For the case of forced convection in a range up to v=2.6 m/s the convective heat transfer coefficient was given:

$$h_c = 12.1\sqrt{v} \quad [W/m^2K]$$

(2.16)

Although the body position and velocity direction will have a certain influence on hc, Fanger assumes equation (2.16) to give a reasonable approximation for seated or standing persons. For moving persons however the relative velocity has to be used.
Undoubtedly there will exist a transition zone between pure free convection and pure forced convection, where both temperature difference and velocity influences the heat transfer. Fanger proposes to calculate h_c for both free and forced convection and to use the larger value:

$$h_c = \left\{ \begin{array}{ll} 2.38(t_{cl}-t_a)^{0.25} & \text{for } 2.38(t_{cl}-t_a)^{0.25} > 12.1\sqrt{v} \\ 12.1\sqrt{v} & \text{for } (2.38t_a)^{0.25} < 12.1\sqrt{v} \end{array} \right\}$$

(2.17)

These cases mean that for common conditions the free convection formula is used for v < 0.1 m/s and the forced convection formulas for v > 0.1 m/s, which is a reasonable threshold.

2.2.6   The Detailed Heat Balance Equation

Substituting all the heat loss terms derived above into the double heat balance equation (2.1) provides:

$$M (1 - w_e) - 0.3052 (0.256 t_{sk} - 3.37 p_a) - E_{sw}$$

$$0.0173 M (5.86 p_a) - 0.0014 M (34 - t_a) =$$

$$\frac{t_{sk} - t_{cl}}{0.155 I_{cl}} =$$

$$3.9541 0^8 f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl} - t_a) \qquad (2.18)$$

2.3   The Thermal Comfort Conditions

2.3.1   Sweat Secretion and Skin Temperature

Comfort under steady state conditions, which exclusively is considered here, requires as prerequisite the satisfaction of the heat balance equation (2.18). Physically this means that the body can maintain a reasonable constant internal temperature. For a given activity level, clothing and environmental parameters, the only quantities, which can be adjusted by the human thermoregulatory system to satisfy the heat balance are sweat secretion E_{sw} and skin temperature t_{sk}.

The thermoregulatory system can maintain this heat balance within a wide range of ambient conditions, providing a certain combination of t_{sk} and E_{sk}.

However the satisfaction of the heat balance equation (2.18) is far from being a sufficient condition for thermal comfort. Within the wide range of ambient conditions for which the heat balance can be maintained, there is only a narrow interval, which will create thermal comfort. Corresponding to this is a narrow interval of mean skin temperature $t_{sk,comf}$ and sweat secretion $E_{sw|comf}$.

Experimental values for this mean skin temperature and sweat secretion were found in a study by Fanger for subjects at different activity levels subjectively expressing thermal comfort. The figures (2.3) and (2.4) show the obtained regression curves of mean skin temperature and mean sweat secretion as a function of the activity level. The sweat secretion was found by subtracting the diffusive and latent respiration heat losses from the total water vapor loss, which in turn can be measured as weight loss of the subjects.

The functional dependency between mean skin temperature, sweat secretion and activity level is:

$$t_{sk} = 35.7 - 0.0275 \qquad [C]$$

(2.19)

$$E_{sw} = 0.421 (M - 5\varepsilon \qquad [W/m2]$$

(2.20)

The equations (2.19) and (2.20) can be considered as second and third condition for thermal comfort.

These comfort values for skin temperature and sweat secretion do not significantly change with different clothing insulations, wind velocities or other temperature combinations, which has been investigated in above mentioned experiments of Fanger. For example for thicker clothing the

Figure 2.3   Mean Skin Temperature as a Function of Metabolism in thermal comfort:

tsk(M)|comfort
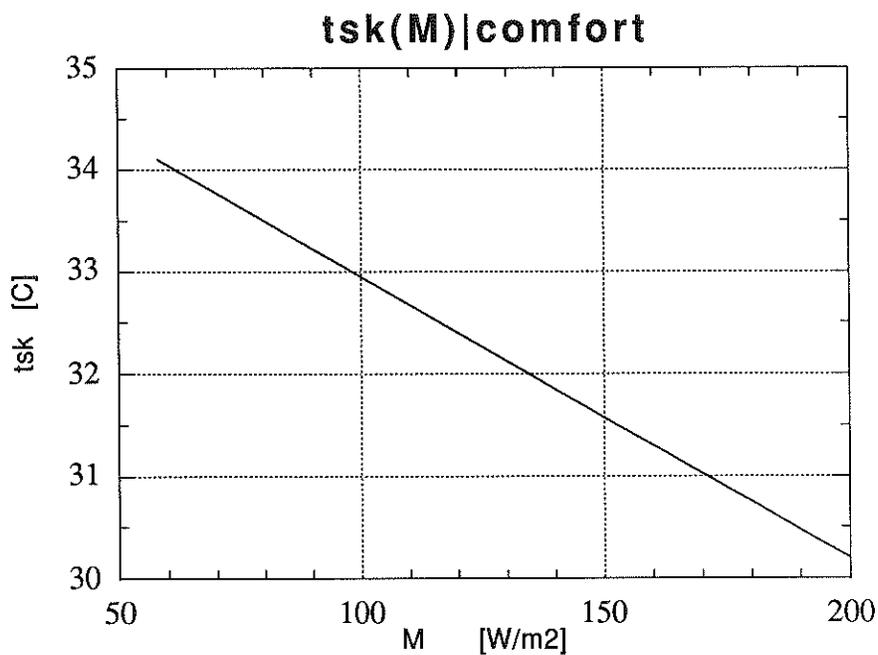
Figure 2.4 Evaporative Heat Loss as a Function of Metabolism in Thermal Comfort

Esk(M)|comfort
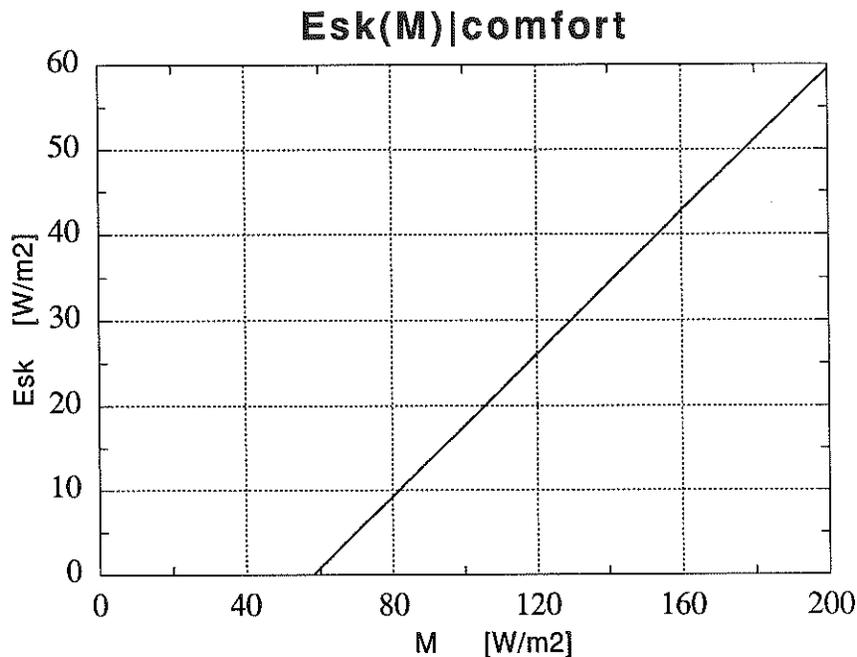
ambient temperature has to be much lower for providing the same heat loss, thus keeping t_{sk} nearly constant.

2.4   The Comfort Equation

Now the expressions for sweat secretion (2.19) and skin temperature (2.20) in comfort condition can be inserted in the heat balance double equation (2.18), thus obtaining a equation whose satisfaction means at the same time satisfaction of the three basic comfort conditions - the comfort equation:

$$M (1 - we) - 3.052 (5.77 - 0.007 M - p_a) - 0.42 (M - 58.$$
$$0.0173 M (5.8 - p_a) - 0.0014 M (34 - t_a) =$$
$$\frac{35.7 - 0.0275 M t_{cl}}{0.155 I_{cl}} =$$

$$3.954 \cdot 10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_r+273)^4] + f_{cl}h_c(t_{cl}-t_a)$$

<div align="right">(2.21)</div>

The left side of the double equation can be used to get an expression for tcl, which in turn can be inserted on the right side of equation (2.21), thus creating the final version of the comfort equation, which then contains only ambient parameters plus the metabolism rate.

Fanger used this equation to plot numerous comfort diagrams providing relations between ambient parameters for thermal comfort as illustrated as an example in figure (2.5):

Figure 2.5   Example for a Fanger Comfort Diagram

Comfort tr(ta)

M = 150 W/m2
Icl = 0.5 clo
rh = 50%
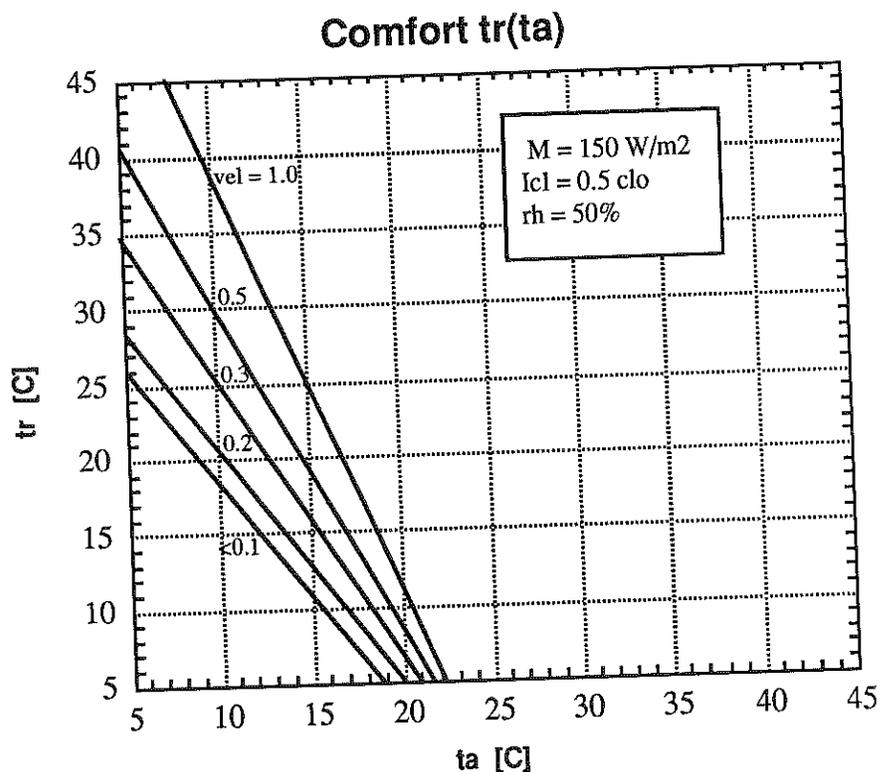
The Graphs in this figure represent the conditions for thermal comfort. It can be seen that 1) the required t_a for comfort can be the lower, the higher t_r is given - which is applied in connection with radiative heating systems 2) the higher the wind velocity, the higher is this required t_a.

Figure 2.6 shows the ambient temperature required for thermal comfort. It is a function of metabolism M and clothing insulation I_{cl} [clo], if the air and radiative temperature are assumed to be equal.

2.5   The Predicted Mean Vote PMV

The condition for optimal thermal comfort is the satisfaction of the comfort equation described in chapter 2.4. On the other hand the equation

Figure 2.6   The Required Temperature for Thermal Comfort

ta(M)|PMV=0
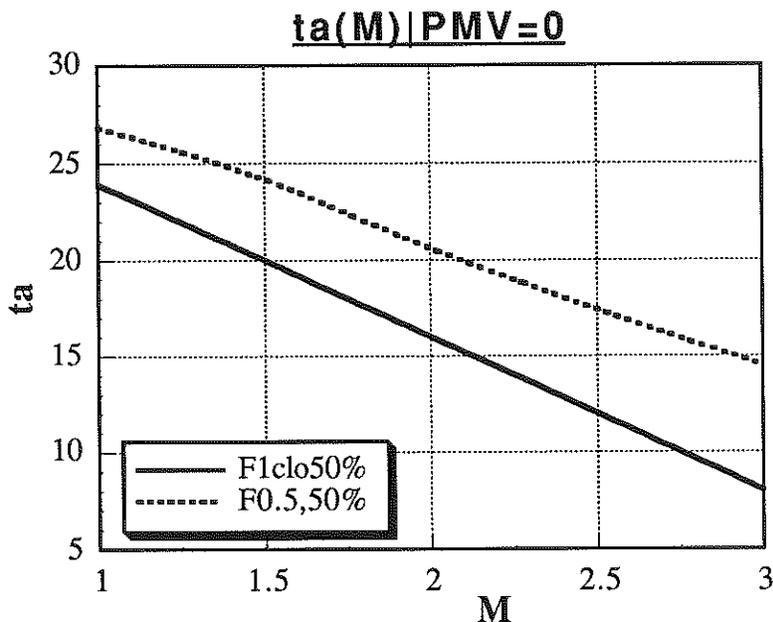
only provides information about how the ambient variables should be combined in order to create optimal thermal comfort.

In an arbitrary climate however the variables cannot be expected to satisfy the equation, nevertheless it can be used to derive an index which makes a prediction of the thermal sensation. Fanger has named this index the Predicted Mean Vote, which describes thermal sensation for any given combination of activity level, clothing insulation and the other thermal environmental parameters. The scale is defined in a range from

-3 to +3 as:

+3	hot
+2	warm
+1	slightly warm
0.0	neutral
-1	slightly cool
-2	cool
-3	cold

The connection to the thermal variables is the assumption that the degree of discomfort is greater the more the 'load' on the thermoregulative system deviates from the comfort condition. This load Fanger defined as the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level:

$$L = \text{(Actual heatproduction)} - \text{(Heatloss for comfort c}$$

(2.22)

$$L = M - W - E_{diff} - E_{res} - C_{res} - R_{(sk|comf)} - C_{(sk|comf)} - E_{sw|comf}.$$

(2.23)

where R and C are the radiative and convective heat loss calculated with the skin temperature for the comfort condition.

As an example for a warm environment with 35 C and 2 met, the heat production is 116 W/m^2. The heat loss for the comfort condition of 2 met is however much lower since especially $E_{sk|comf}(2met)$ is much lower than the actual value E_{sk}. This is due to the fact that in comfort conditions there is not much sweating. Hence the body is burdened with a high 'warm heat load' and the thermal comfort vote will be 'hot'.

In the comfort condition the thermal load is zero. Else it is either positive (in warm environments) or negative (in cold environments). Out of thorough analyses of measurement data involving a subjective vote Fanger finally extracted the correlation formula between the Predicted Mean Vote and the load L:

$$PMV = (0.303 e^{-0.036 M} + 0.028)$$

(2.24)

where

$$L = M (1 - w_e) - 3.052 (5.77 - 0.007 p_a M - 0.42 (M - 58.2$$

$$0.0173 M (5.86 p_a) - 0.0014 M (34 a)$$

$$3.9541 0^{-8} f_c [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl} - t_a)$$

(2.25)

The clothing temperature tcl (for comfort) can be determined iteratively out of the right side of the comfort heat balance equation (2.21) as:

$$t_{cl} = 35.7 - 0.0275 \, M \, (1-v$$
$$0.155 I_{cl} [3.954 \, 0^8 \, f_c [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_c \, h_c \, (t_{cl} - t_a)$$

$$(2.26)$$

The resulting votes for all different combinations of ambient parameters were tabulated by Fanger and are used as a standard reference. The values of PMV can be expected to have the greatest accuracy in an interval from -1 to +1 since Fanger's derivation is based on experimental conditions only within this range. Hence PMV values smaller than -2 or greater than +2 are recommended to be used with care.

Moreover, the influence of gender, race, acclimatization and asymmetric temperature fields (see chapter 8) contributes to the fact that PMV can provide only an average value. Figure (2.7) gives an example for PMV as a function of ta.

A drawback of this index PMV however is, that its use is limited to steady state considerations without respect to actually transient body state developments. This drawback is however overcome by the Mean Body Temperature Vote MBTV derived in chapter 5, which is a fundamentally new comfort index created in the present study .

Figure 2.7   PMV as a function of ta

PMV (ta)|M, Icl

2met,1clo
2met, 0.5clo
1met 1clo
1met, 0.5 clo
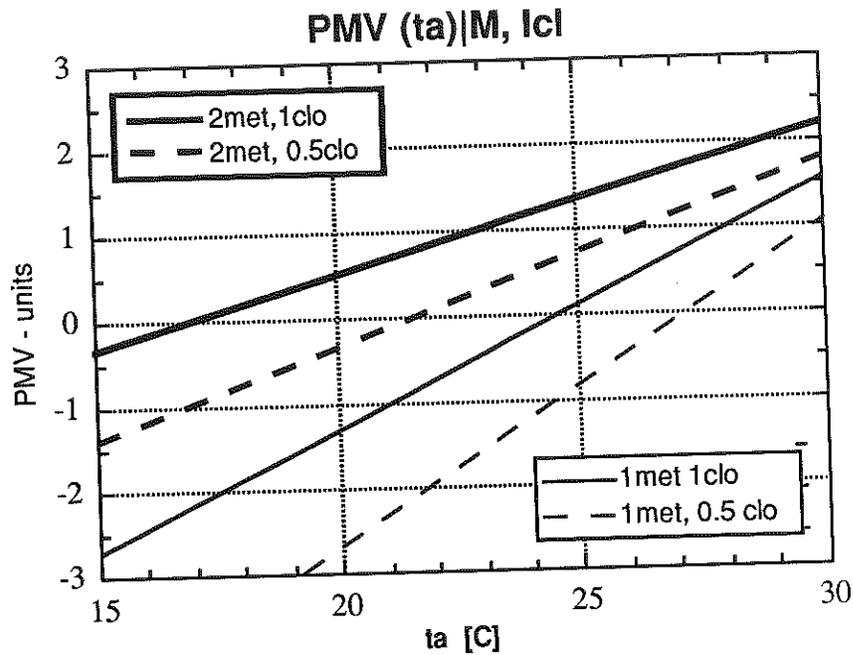
2.6   The Predicted Percentage Dissatisfied PPD

The PMV index gives the Predicted Mean Vote of a representative group of persons exposed to a given combination of environmental variables. However it is difficult to interpret what the magnitude of PMV determined in a practical case can imply. For instance a value of +0.4 between neutral and slightly warm is not known yet whether to be acceptable or dissatisfying. It is therefore reasonable to state what percentage of persons can be expected to be dissatisfied, since this can be directly interpreted.

A relationship between PMV and the percentage of dissatisfied was established by Fanger, calling this new index the Predicted Percentage Dissatisfied PPD. It is based on an analyse of the measurement data for the PMV index. Fanger defined the

dissatisfied as the persons voting in the experiments -2 or lower respective +2 or higher, because this correlated to the subjective perception of decided discomfort and finally gives the correlation function as:

$$PPD = 100 - 95 \cdot e^{(-0.03353 PMV^4 - 0.2179 PMV^2)} \qquad (2.27)$$

As figure (2.8) shows the curve is symmetric and PPD increases the more the mean vote deviates from zero. Already with a mean vote of 0.5 there are twice as many dissatisfied than at the minimum point and then PPD increases quite rapidly.

Figure 2.8   PPD as a Function of PMV

PPD (PMV)
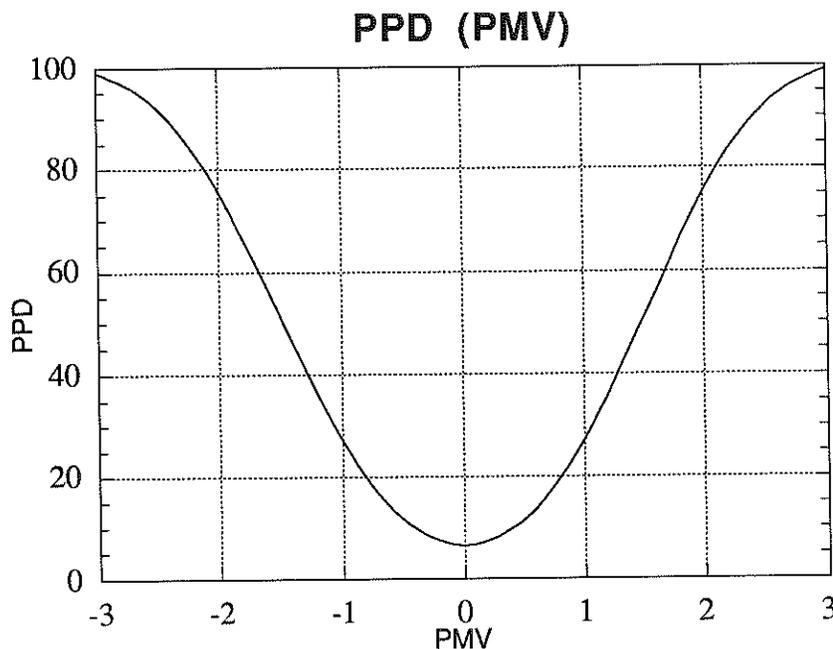
It can be seen that it is impossible to satisfy all persons in a large group exposed to the same climate. Even in a perfect environment with PMV = 0 one cannot obtain a PPD value lower

than 5% for equal clothed people, since there are always individual deviations in the thermal perception. Hence the goal is to keep PPD at the minimum of 5% and not to avoid all complaints. To avoid misleading interpretations it has to be taken note of the fact, that the computer program in chapter 6 calculates PPD only for the steady state mode by using the PMV value, else it uses the transient MBTV value to take the transient development of PPD into account.

Chapter 3

The Gagge / Pierce Foundation Two Node Model

3.1 Introduction

In comparison with the static Fanger Model, which considers only the overall heat balance consisting of empirically deducted terms for the physiological activities, the Two Node Model /2/ is a physiological model. This means it consists of a controlled part (the body) and a controller (the thermophysiological system), which together form a feedback system; see figure (3.1). The body here consists of two concentric compartments, representing a core and a skin shell (see chapter 3.3).

The temperature sensation affects the thermophysiological system that sends out signals to activate the vasomotor system, the sweat system or the shivering of muscles. The strength of these signals depends on the comparison between temperature sensation and temperature set points.

In this view, high sweat activity is, for example, caused by a large offset of the core temperature. The feedback loop ensures

that the sweating no longer increases when thermal equilibrium is reached.

The model uses classic heat transfer theory as a rational starting basis and introduces empirical equations describing the effects of the above mentioned physiological regulatory control.

Figure 3.1 The Human Feedback Control System
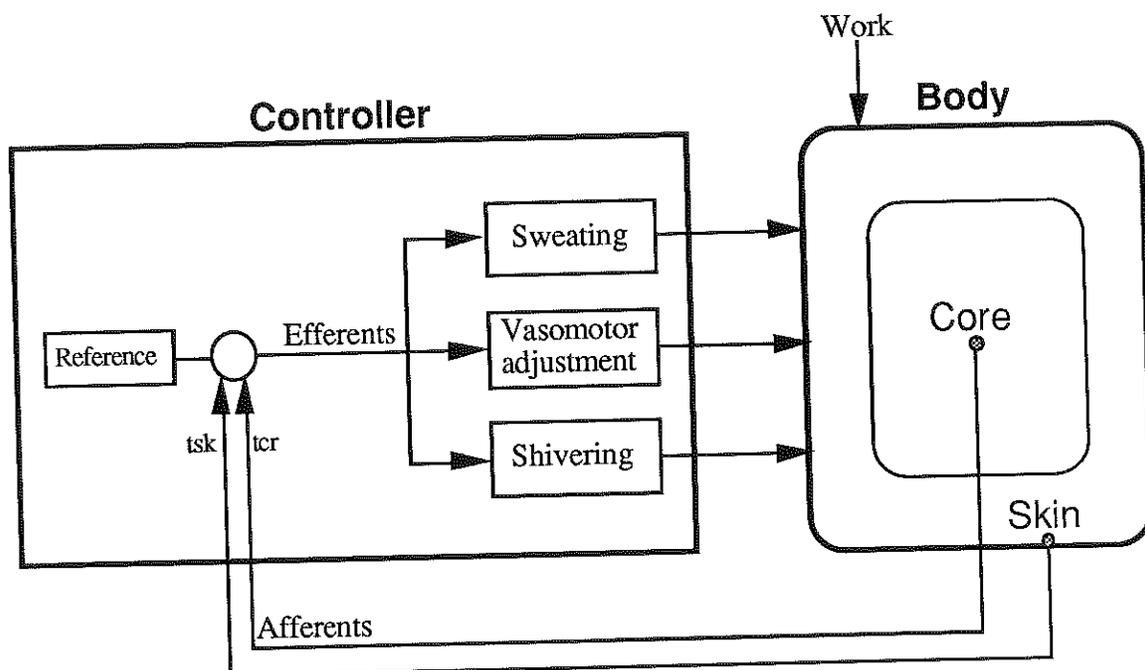
3.2   Human Thermoregulation

In the following section, the natural human thermal response to environ-mental influences is described, which is the basis on which the analogous thermoregulatory control of the Two Node Model is built on.

The body heat exchange exists in relation to zones of different physiological response. In the temperature range from e.g. 23 C to

27 C for normally clothed, sedentary people (0.6 clo) there is no body cooling or heating and no increase in evaporative heat loss. Within this zone each individual has a neutral temperature where the environment is neither too hot nor too cold, and where no action from the physiological control system is required to maintain normal body temperature.

The Cold Zone Reactions:

Over a wide range of cold external conditions, the body maintains life-sustaining conditions for crucial internal regions at the expense of an energy loss from peripheral tissues. The further the superficial tissues (e.g. hands and feet) are from the central body mass, the more readily their temperatures fall.

Hence, if the rate of heat loss from the skin to the environment increases, the body decreases the flow of blood to the skin. This cools the skin and subjacent tissues and maintains the temperature of deep tissues. The external conditions over which this occurs fall in a narrow range, called the zone of vasomotor regulation against cold.

Below this range, temperatures of superficial and deep tissues fall, unless another control reaction occurs. Then the body generates heat through muscular tension, shivering, or spontaneous activity. If the generated heat balances the increased heat loss to the environment, the deep body temperature is maintained.

If all control reactions are insufficient, the body enters the zone of body cooling. When the core temperature falls below 35 C,

people suffer major losses in efficiency; core temperatures below 31 C can be lethal.

The Warm Zone Reactions:

On this side of the neutral midpoint is also a narrow zone of vasomotor regulation against heat. The blood flow to the skin increases, when desirable heat loss to the environment is required. This increase in blood flow causes the skin surface temperature to come closer to the temperature of the deep tissues, therefore increasing the net heat loss.

If in spite of this increase in blood flow the core temperature rises to about 37 C, the body releases water from sweat glands for evaporative cooling. As long as this cooling can maintain required heat loss, the body is in the zone of evaporative regulation. The upper limit of evaporative cooling is mainly affected by the atmospheric water vapor pressure, air movement and the amount of clothing.

When this cooling is insufficient, the body is in the zone of body heating. When the core temperature rises above 38.9 C, people suffer major losses in efficiency; core temperatures above 42.8 C can be lethal.

3.3 The Two Node Transient Energy Balance

The Two Node Model represents the body as two concentric cylinders - the inner one representing the body core consisting of skeleton, muscle and internal organs and the thin, outer one

representing the skin shell (see figure 3.2). The compartments are governed by two temperatures, t_{sk} for the skin shell and t_{cr} for the core compartment, which both are distributed uniformly within the compartments.

The boundary line between the two compartments changes with respect to the skin blood flow per unit skin surface area, which in turn is regulated by the thermophysiological control. This is due to the fact that for instance for increased skin blood flow warmer core blood enters the skin node which increases its mass and temperature.

For the following derivation of the transient heat balance several assump-tions are made: the conductive heat exchange to the environment is negligible; metabolic heat production, external work and respiratory losses are associated only with the core compartment; and the core and skin

Figure 3.2   The Two Node Model in Cross Section
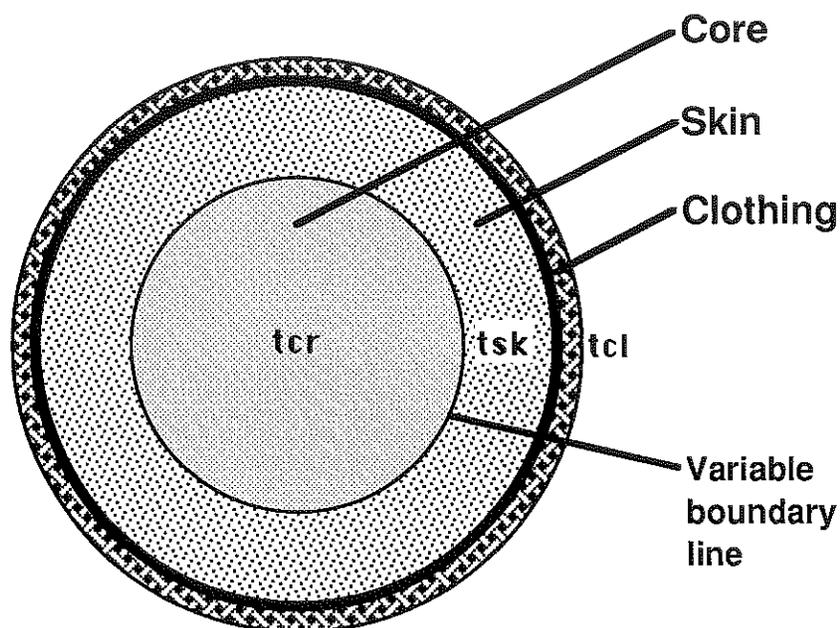
compartments exchange energy passively through direct contact and also through the thermoregulatory-controlled skin blood flow. A transient energy balance states that the rate of heat storage is equal to the rate of heat gain minus the heat loss. Having two separate compartments, the human model therefore is described by two coupled heat balance equations; one applied to each compartment:

$$S_{cr} = M - W \; C_{res} - E_{res} - Q_{cr \; - \; sk} \qquad (3.1)$$

$$S_{sk} = Q_{cr \; - \; sk} \; C - R \; E_{sk} \qquad (3.2)$$

where M = metabolism
S_{cr} = rate of heat storage in the core compartment
S_{sk} = rate of heat storage in the skin compartment
$Q_{cr \; - \; sk}$ = rate of heat transport from the core to the skin by

both conduction through the tissue and convection through the blood flow (see chapter 3.5.2)

The rate of storage for the compartments can also be written in terms of the thermal capacity and time rate of change of temperature in each compart-ment:

$$S_{cr} = (1\ a)\ m c_{p,b} \frac{dt_{cr}}{da} \tag{3.3}$$

$$S_{sk} = a\ m c_{p,b} \frac{dt_{sk}}{da} \tag{3.4}$$

where   m = body mass

  a = m_{sk}/m = fraction of skin mass to body mass; it depends on

  the rate of blood flowing to the skin node. An empirical

  equation for this relation is described in chapter 3.5.

  $c_{p,b}$ = specific heat capacity of the body tissue = 0.97 Wh/kgK

  a = time [sec]

The equations (3.3) and (3.4) are the crucial connection to the temperature changes in the compartments, which in turn then govern the thermoregulatory control (see chapter 3.5).

3.4   Heat Exchanges with the Environment

The terms in the heat balance concerned with environmental heat exchange can be taken over from the Fanger Model - see chapter 2.2.

The main difference is the derivation of E_{diff} and E_{sk}, since Fanger expressed those only for comfort condition and here they are the

principal part of the control mechanism in the warm regulation zone (see chapter 3.4.2). Another minor difference is the use of linearized terms for the convective and radiant heat transfer coefficients described in the following section:

3.4.1 Dry Heat Loss by Radiation and Convection

For the Two Node Model the radiative heat loss R is expressed in terms of the difference between the clothing temperature t_{cl} and radiative temperature t_r and a linearized radiant heat transfer coefficient h_r:

$$R = h_r f_{cl} (t_{cl} - t_a) \qquad (3.5)$$

where h_r can be calculated by:

$$h_r = 4 e s \frac{A_{rad}}{A_{Du}} \left[\frac{t_{cl} + t_r}{2} + 273 \right]^3 \qquad (3.6)$$

where e = average emissivity of the clothed body = 0.97
s = Boltzmann constant
A_{rad} = effective radiation area of the body
(A_{rad}/A_{Du} = 0.72 as an average)

The equation (3.6) has to be solved iteratively, since t_{cl} in turn is affected by h_r.

The convective heat loss varies linearly with the temperature difference between the ambient temperature t_a and the clothing temperature t_{cl}:

$$C = h_c f_{cl} (t_{cl} - t_a) \qquad (3.7)$$

For higher accuracy, the model uses the highest value for h_c calculated from either activity movement, air velocity or a minimum value due to free convection. These take also the ambient air pressure into account:

$$h_{c,act} = 5.66[(M-49.5)p_a]^{0.3} \qquad (3.8)$$

$$h_{c,vel} = 8.6[vel\, p_a]^{0.5} \qquad (3.9)$$

$$h_{c,min} = [3\, p_a]^{0.5} \qquad (3.10)$$

Finally R and C can be combined to express the total dry (sensible) heat loss:

$$dry = f_{cl}[h_c\,(t_{cl} - t_a) + h_r\,(t_{cl} - t_r)] \qquad (3.11)$$

3.4.2 The Evaporative Skin Heat Loss

The total evaporative heat loss from the skin is a combination of the evaporation of sweat secreted due to thermoregulatory control mechanisms E_{rsw} and the natural diffusion of water through the skin E_{diff}:

$$E_{sk} = E_{rsw} + E_{diff} \qquad (3.12)$$

The regulatory sweating evaporative heat loss is directly proportional to the regulatory sweat generated:

$$E_{rsw} = m_{rsw} h_{H_2O}\, 1/360 \qquad (3.13)$$

where m_{rsw} = rate at which sweat is generated [g/m^{2}h] due to the

thermoregulatory control (see chapter 3.5)

h_{vap} = heat of vaporization of water = 2448 J/kg

The portion of the skin that must be wetted to evaporate the regulatory sweat is:

$$p_{rsw} = \frac{E_{rsw}}{E_{max}} \qquad [\%] \qquad (3.14)$$

where E_{max} is the maximum evaporative potential, that occurs when the skin surface is completely wetted. It is a function of the vapor pressure difference between skin and environment:

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{e,t}} \qquad (3.15)$$

where $R_{e,t}$ is the total evaporative resistance of clothing and air layer; see

equation (1.13) in chapter 1.6

With no regulatory sweating the average skin wettedness due to diffusion has been found to be approximately 0.06 for not too extreme environ-mental conditions like for example desert or tropical climate, where the value can be as extreme as 0.02 respective 0.1.

However with regulatory sweating the 0.06 value applies only to the portion of the skin which is not covered with regulative sweat (1 - p_{rsw}) and the diffusion evaporative heat loss is:

$$E_{diff} = (1 - p_{rsw}) \, 0.06 \, E_{max} \qquad (3.16)$$

Now the actual skin wettedness p_{wet} can be determined, given the maximum evaporative potential E_{max} and the regulatory sweat genera-tion E_{rsw}:

$$p_{wet} = (1\ p_{rsw}) + p_{rsw} = 0.06 + 0.94 \frac{E_{rsw}}{E_{max}}$$ (3.17)

Finally the total evaporative heat loss due to diffusion and regulatory sweating can also be calculated as:

$$E_{sk} = p_{wet}\ E_{max}$$ (3.18)

It has to be remarked, that the thermoregulatory control does not regulate skin wettedness, but rather regulates the sweat rate m_{rsw}. Skin wettedness is then an indirect result of the relative activity of the sweat glands and the evaporative potential of the environment.

Skin wettedness of 1.0 is the upper theoretical limit; in practice however the limit is lower due to nonuniform sweat production, clothing influence and dripping. This is taken into account by introducing an upper limit variable, called evaporation efficiency, up to which p_{rsw} is limited. If this amount of wettedness is exceeded dripping results. This efficiency is a function of the air velocity, since this causes the dripping and was empirically found to be:

$$eveff = \frac{0.59}{vel^{0.0i}}$$ (3.19)

3.5   The Thermoregulatory Control Mechanisms

In comparison with the natural human thermoregulation, described in chapter 3.2, the following mathematical thermoregulatory control acts in an analogous way with regard to regulated skin blood flow, sweating rate and shivering.

3.5.1   The Regulatory Signals

When the body is able to maintain its thermal equilibrium with the environment with minimal regulatory effort, it is in a state of physiological thermal neutrality, which means that the average core and skin temperature are at their neutral values:

$$t_{sk,n} = 33.7°C \tag{3.20}$$

$$t_{cr,n} = 36.8°C \tag{3.21}$$

Empirical relationships derived from laboratory experiments describe how the above thermoregulatory control processes (so-called vasomotor regulation, sweating, and shivering) are governed by temperature signals from the skin and core. Five signals, representing deviations from the neutral set points, trigger these processes. The signals are written in terms of actual temperature t and neutral temperature t_n, such that they only take on positive values:

(3.23)

warm signal from the core: warmcr =   0   for

$t_{cr} \leq t_{cr,n}$

$$t_{cr} - t_{cr,n} \qquad \text{for } t_{cr} > t_{cr,n}$$

cold signal from the core: $\qquad \text{cold}_{cr} = 0 \qquad \text{for } t_{cr} \geq t_{cr,n}$

$$t_{cr,n} - t_{cr} \qquad \text{for } t_{cr} < t_{cr,n}$$

warm signal from the skin: $\qquad \text{warm}_{sk} = 0 \qquad \text{for } t_{sk} \leq t_{sk,n}$

$$t_{sk} - t_{sk,n} \qquad \text{for } t_{sk} > t_{sk,n}$$

cold signal from the skin: $\qquad \text{cold}_{sk} = 0 \qquad \text{for } t_{sk} \geq t_{sk,n}$

$$t_{sk,n} - t_{sk} \qquad \text{for } t_{sk} < t_{sk,n}$$

warm signal from the body: $\qquad \text{warm}_{b} = 0 \qquad \text{for } t_{bm} \leq t_{b,n}$

$$t_{bm} - t_{b,n} \qquad \text{for } t_{bm} > t_{b,n}$$

The average temperature of the human body, t_{bm}, can be calculated by the weighted average of the skin and core temperatures:

$$t_{bm} = a\, t_{sk} + (1 - a)\, t_{c} \qquad (3.23)$$

The neutral mean body temperature $t_{b,n}$ is calculated from the neutral skin and core temperature in the same manner. The value

of the weighting coefficient a depends on the rate of blood flow to the skin (see chapter 3.5.3) and represents the fraction of the total body mass concentrated in the skin compartment.

3.5.2 Skin Blood Flow and Heat Transport

The so-called vasomotor activity consisting of vasodilation and vaso-constriction is controlled by the warm and cold temperature signals from the core and skin, respectively. Normal blood flow for sedentary activity at thermally neutral body conditions is approximately 6.3 kg/m^2h.

Vasodilation is governed by warm signals from the core. For each 1C increase above $t_{cr,n}$, blood flow increases by 200 kg/m^2h. The warm signals from the skin play a more important role in the body temperature regulation by governing sweating rather than vasodilation, and hence its effect on dilation is neglected.

Vasoconstriction is governed by cold signals from the skin, and for each one degree decrease below $t_{sk,n}$, the blood flow encounters a proportional increase in resistance. A cold signal from the core causes also vaso-constriction, but not as rapidly as a cold signal from the skin, and its effect is consequently neglected. The effects of core and skin temperature deviations on blood flow can be expressed mathematically as:

$$\dot{m}_{bl} = \frac{6.3 + 200 \text{ warmcr}}{1 + 0.5 \text{ coldsk}} \left[\frac{kg}{m^2 h} \right] \tag{3.24}$$

The blood flow is limited to the range $0.5 < m_{bl} < 90$ kg/m²h. In the Two Node Model, heat is transferred from the core to the skin passively (by direct contact) and through the skin blood flow. Hence the combined thermal exchange between core and skin can be written as:

$$Q_{cr-sk} = (K + C_{p,bl}\dot{m}_{bl})(t_{cr} - t_{sk}) \qquad (3.25)$$

where:
 K = heat conductance between the core and skin
  = 5.28 W/m²K
 $C_{p,bl}$ = specific heat capacity of blood
  = 4.187 kJ/kg K

3.5.3   The Fractional Skin Mass a

Changes in m_{bl} influence the effective masses of the skin and core compartments by changing the thermal resistance of the skin layers and the depth of the temperature gradient from the skin surface to the internal core. Since the Two Node Model assumes that each compartment is of a uniform temperature, this is equivalent to changing the fractional mass of the skin compartment.

For example, in cold environments, blood flow to the skin lowers and the skin and fat become isolated from the core. The temperature gradient reaches deeper into the body and thus a increases.

The effect of blood flow on the relative masses of the skin and core compartments was determined as:

$$a = 0.04178 + \frac{0.7455}{m_{bl} + 0.585} \qquad (3.26)$$

During thermal equilibrium and while sedentary, $a \approx 0.1$. With exercise or overheating, circulation to the extremities increases and the skin layer becomes more closely coupled to the core, producing finally a minimum value of $a \approx 0.05$. When the body is exposed to cold, circulation to the extremities decreases and the skin layer becomes less closely coupled to the core, resulting in a higher value of a. As indicated in equation (3.24), m_{bl} and consequently a are both determined by the deviations of t_{cr} and t_{sk} from their neutral values.

3.5.4   The Regulatory Sweating

The sweat glands are activated by warm signals from both the core and the skin, and sweating is expressed in terms of the warm signal from the weighted average body temperature and a factor including the skin signal:

$$\dot{m}_{rsw} = 170 \, warmb \, (warmsk / 10)7 \quad \left[\frac{g}{m^2 \, h}\right] \qquad (3.27)$$

The value of m_{rsw} calculated in equation (3.27) is then used to determine E_{rsw} in equation (3.14).

3.5.5   Shivering

Generating additional metabolic heat through shivering and muscle tension is a much more effective mechanism for maintaining the body's heat balance in extremely cold weather conditions than vasoconstriction of the blood vessels. Shivering can raise M as much as about four times its normal sedentary value. Metabolic energy production due to shivering requires simultaneous cold signals from both the skin and core, and is related to the two signals by the expression:

$$M_{shiv} = 19.4 \text{ coldsk coldcr} \qquad [W / m^2] \qquad (3.28)$$

The total metabolic energy M is then the sum of the shivering energy Mshiv and the metabolic heat generated due to activity Mact:

$$M = M_{act} + M_{shiv} \qquad [W / m^2] \qquad (3.29)$$

It has to be remarked that Mshiv as well as Mact is assumed to be generated only in the core compartment, since there the most muscles are located.

Chapter 4

The Transient MBTV Comfort Index

4.1   Introduction

Fanger's Predicted Mean Vote PMV for thermal comfort, described in chapter 2.5 is applicable only for steady state conditions of the human body. However the practical interest is much more on how a person perceives the thermal environment in a transient development of body adjustments. For instance an exposure to cold environments causes a 'very cold'-vote only after a certain time and not immediately, as the Fanger PMV suggests.

The transient Pierce Two Node Model however so far also failed to create a transient comfort index that met the above mentioned require-ments. The equation (2.24) for the PMV calculation was first applied to the actual transient heat loss values and not the static ones for Fanger's $t_{sk|comfort}$:

$$PMV = f(L)$$

$$\text{Fanger: } L = M - W E_{diff} - E_{res} - C_{res} - R_{(sk|com)} - C_{(t_{sk|com})} - E_{sw|comf}$$

$$\text{Pierce: } L = M - W E_{diff} - E_{res} - C_{res} - R_{actual\ \delta k} - C(actual\ \delta k - E_{sw|comf}$$

It was thought that this would provide a transient PMV. This led of course to completely wrong values, since for instance in an exposure to a cold environment the body reduces the (transient) dry heat loss (R + C) by decreasing t_{sk}, hence the 'thermal load' L decreases and PMV then gives the impression of an increasing comfortable environment! This is shown schematically in fig (4.1):

Figure 4.1 Wrong and expected developments of a transient comfort index
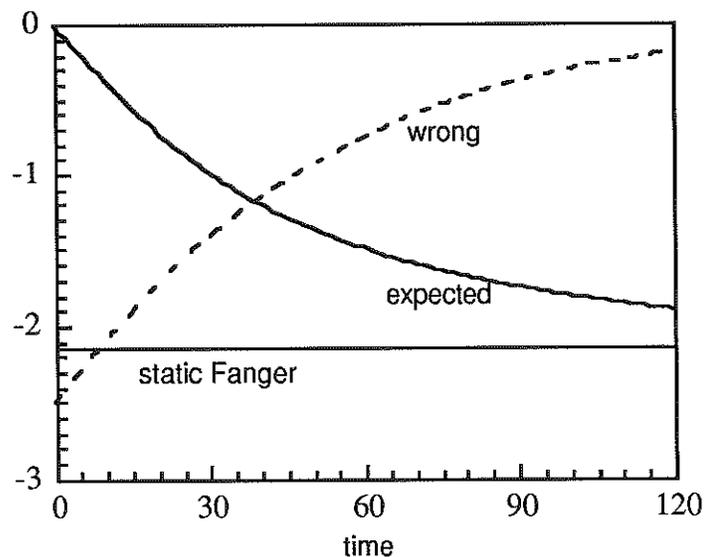
The actually expected development for a cold environment however should just go the other way round; from comfortable in the very first moment to increasing uncomfortable, finally reaching Fangers static PMV value.

Therefore the Mean Body Temperature Vote MBTV was created as a transient comfort index to meet the desired criterion and is described in the following section.

4.2 The Mean Body Temperature Vote MBTV

The basic idea for the derivation of this index is the fact, that for each static PMV value, which in turn depends on the ambient parameters, there corresponds a discrete mean body temperature $t_{bm|steady}$ (see equation 3.23) reached in steady state condition. For cooler environ-ments this mean body temperature $t_{bm|steady}$ is lower and for warm environments it is higher. This has been found in a variety of test runs with the Two Node Model.

Further it can be assumed, that this mean body temperature $t_{bm|steady}$ then can be used directly as a basis for thermal comfort calculations, once the exact correlation between PMV and $t_{bm|steady}$ is found.

This correlation provides the possibility to calculate a transient PMV out of the transient mean body temperature $t_{bm}(t)$, therefore here called Mean Body Temperature Vote MBTV. Thus MBTV gives the instan-taneous comfort vote for the instantaneous state in a transient develop-ment of thermal body state regulations. Since it is derived directly from the PMV value its values lie within the same range from -3 for 'very cold' to +3 for 'very hot'.

The difficulty however was to find this correlation between PMV and the mean body temperature $t_{bm|steady}$, since several ambient parameters affect the PMV value on the one hand and the $t_{bm|steady}$ value on the other hand. In a diversity of simulations with above

mentioned Two Node prototype program it was found that this correlation between PMV and $t_{bm}|steady$ is mainly dependent on the metabolism rate and clothing insulation value Icl; hence only these two parameters were used to design a correlating function. The error due to neglecting the relative humidity and air velocity is small compared with the error the correlation function provides.

The only way to determine this function was to plot representative graphs for PMV as a function of t_{bm} and to approximate these graphs with functions for MBTV.

As it can be seen in the figures (4.2), (4.3), (4.4) and (4.5), the graphs show always a sharp bend at the mean body temperature $t_{bm}=36.5$ C and two nearly linear branches connected at this point. The reason for this shape is that beyond $t_{bm}= 36.5$ C, which represents the neutral reference temperature for the Two Node Model, the skin ratio increases and skin temperature decreases significantly due to maintain the heat balance, thus providing a low t_{bm} although Fanger's PMV is not very low yet.

On the warm side, above $t_{bm}=36.5$ C, the skin ratio can hardly decrease anymore and the body begins to sweat; thus already a slight body temperature increase means real heat stress and then PMV increases rapidly. The corresponding ambient temperatures for the points are also given in the figures (4.2) to (4.5).

These graphs were approximated by linear functions for MBTV, which is also shown in above figures. The graphs for MBTV are already plotted according to the final formula. The approximation was made in this way, that the error around PMV=0 is kept at a

minimum - however at the expense of higher errors especially in the cold zone beyond PMV=-2. This provides however a more exact determination of MBTV around the neutral point and makes possible a comfort controller using MBTV and aiming on this point.

Figure 4.2   PMV as a Function of tbm|steady state
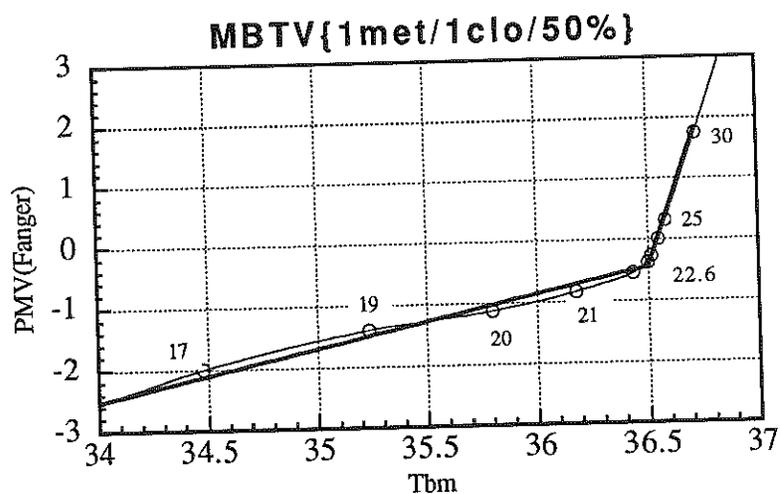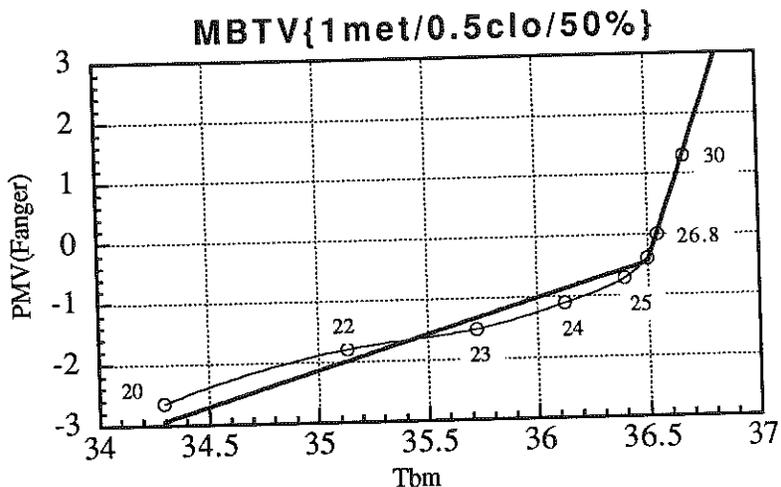
Figure 4.3   PMV as a Function of tbm|steady state

MBTV{1.2met/0.5clo/50%}

MBTV{1.2met/1clo/50%}

MBTV{1.6met/0.5clo/50%}
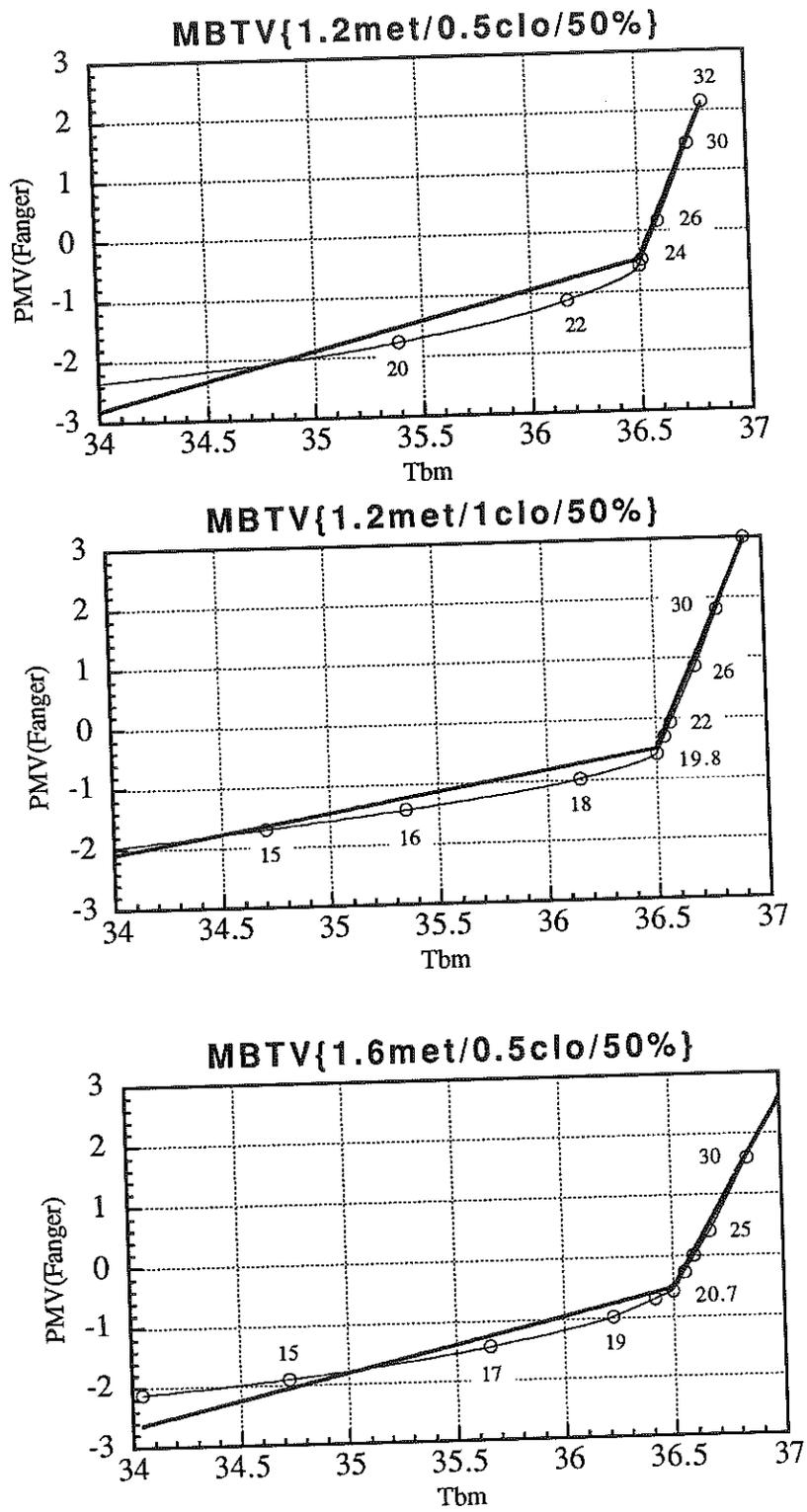
Figure 4.4   PMV as a Function of tbm|steady state

MBTV{1.6met/1clo}/50%

MBTV{2met/0.5clo/50%}

MBTV{2met/1clo/50%}
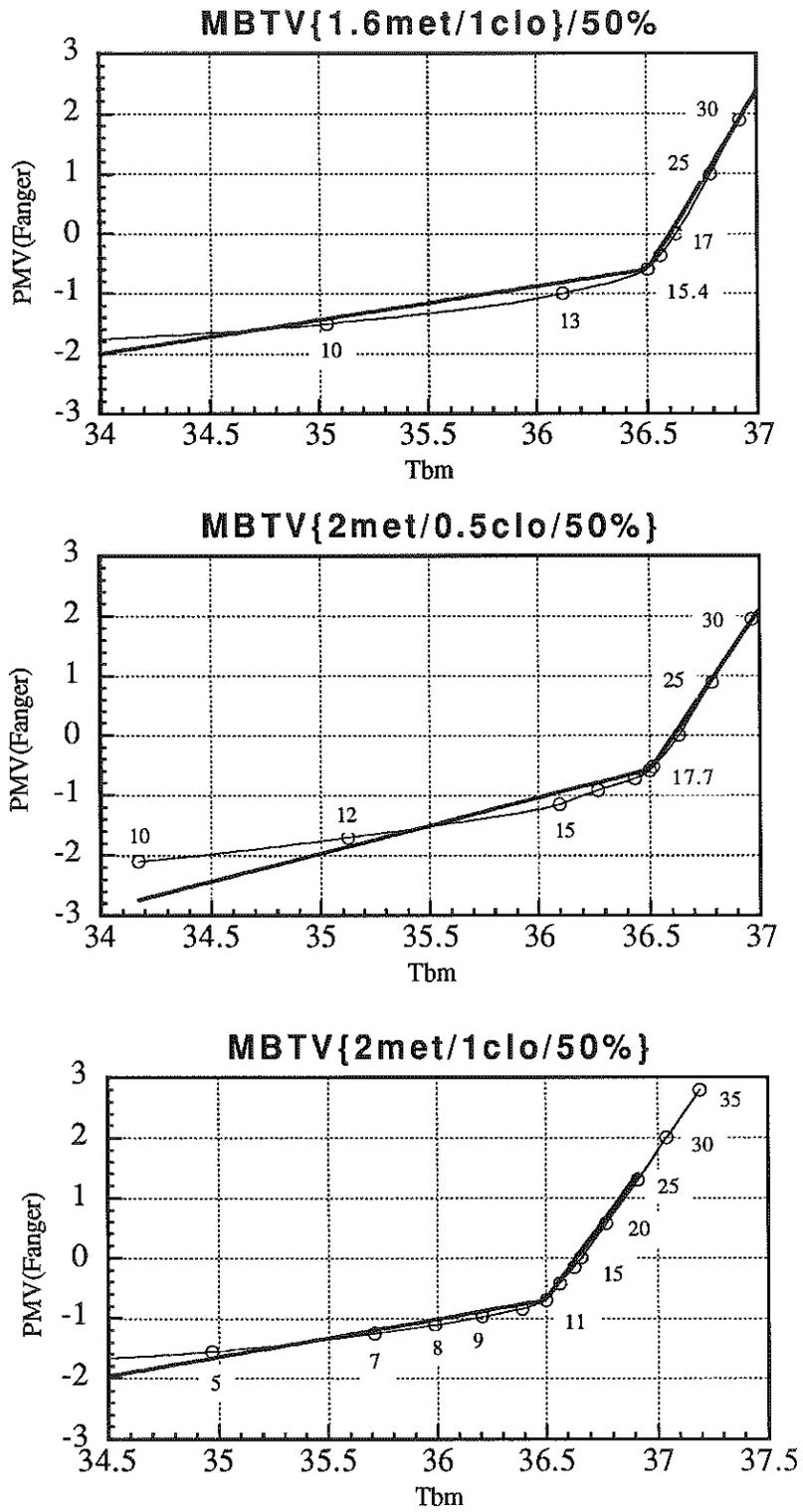
Figure 4.5   PMV as a Function of tbm|steady state

MBTV{3met/0.5clo/50%}

MBTV{3met/1clo/50%}
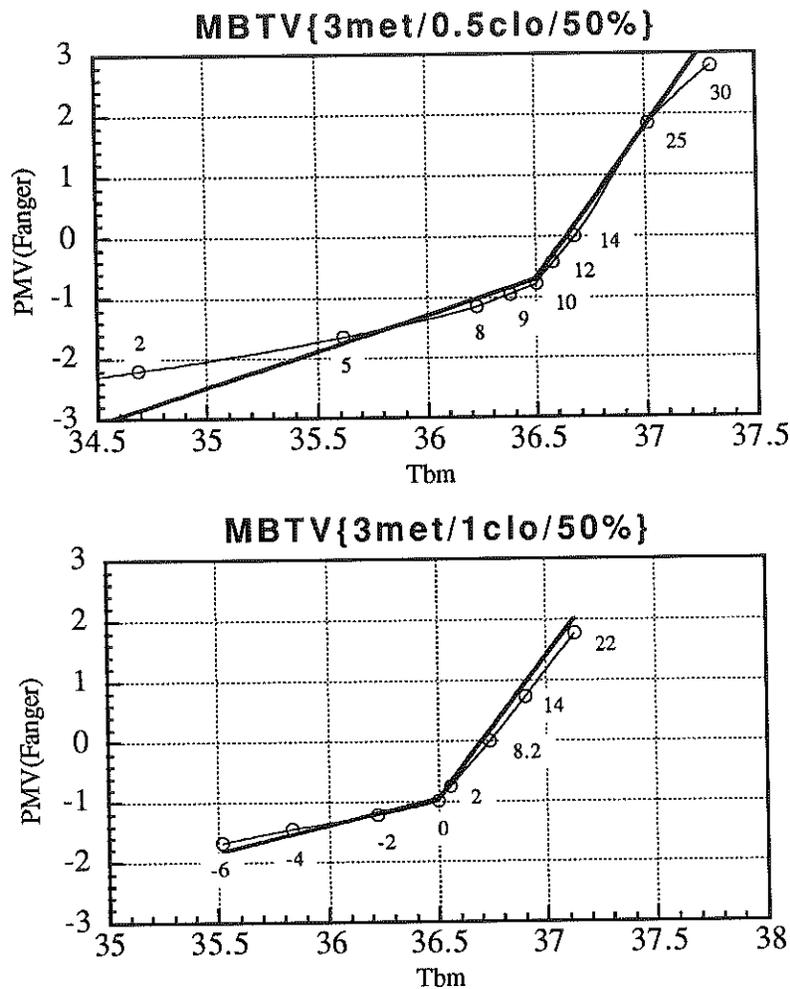
The reason for the slightly cool PMV / MBTV-value at t_{bm}=36.5 C is that Fanger's scale evaluates the conditions leading to the reference temperatures of the Two Node Model on this slightly cool value. However this does not affect the absolute accuracy of the MBTV calculation.

In order to get a correlation function between PMV and $t_{bm|steady}$ for a continuous range of metabolism and clothing insulation values l_{cl}, the slopes of the branches in the hot and cold zone as well as the location of the reference point were extracted and plotted as shown beyond in the figures (4.6), (4.7) and (4.8).

Applying interpolation software the approximation functions for the slopes and the reference point were found, thus combined defining the MBTV(t_{bm})-function.

To take the clothing influence into account, the approximation functions are shifted respective rotated in dependence of the insulation value I_{cl}. The error of MBTV due to the approximation is smaller than 0.07 PMV-units within the range -0.6<PMV<+0.6 and even decreases strongly the higher the metabolism M is given. This can be seen directly in the figures (4.2) to (4.5) above, since the plotted approximation is already the final MBTV-function.

Figure 4.6   The Slope 'mpos' of the warm side
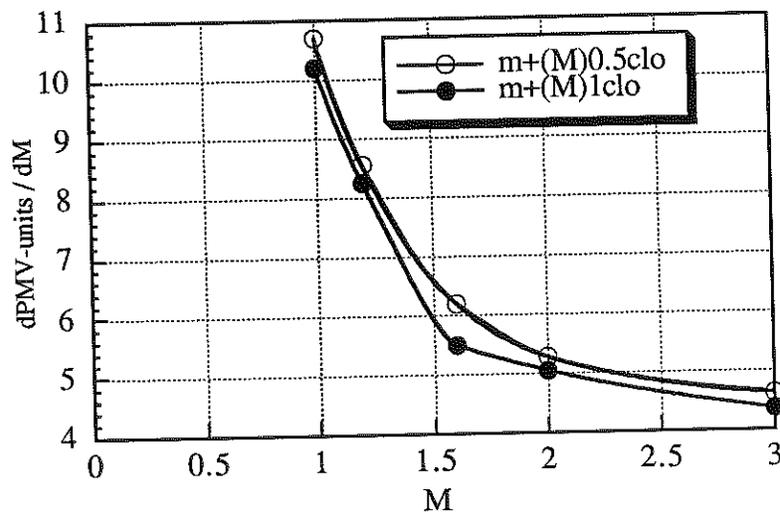
Figure (4.6) shows the slope of MBTV on the warm side as a function of the metabolism and I_{cl}. It has been approximated for I_{cl}=0.5 by a very well fitting function of the fourth order, which then is shifted by 0.6 PMV-units for each 1.0 I_{cl}-change:

$$mpos = 41.2 - 54.21\,M + 31.48\,M^2 - 8.29M^3 + 0.83M^4 - 0.6\,I_{cl}$$

$$(4.1)$$

Figure (4.7) shows the slope of MBTV on the cold side as a function of the metabolism. It has been approximated for I_{cl} = 1.0 by a function of the fourth order which then is shifted by 0.6 PMV-units for each 1.0 I_{cl}-change. Although the error for 0.5 clo then seems to be high on the first view, the absolute magnitude does not strongly affect MBTV, since the slopes on the

Figure 4.7   The Slope 'mneg' of the cold side
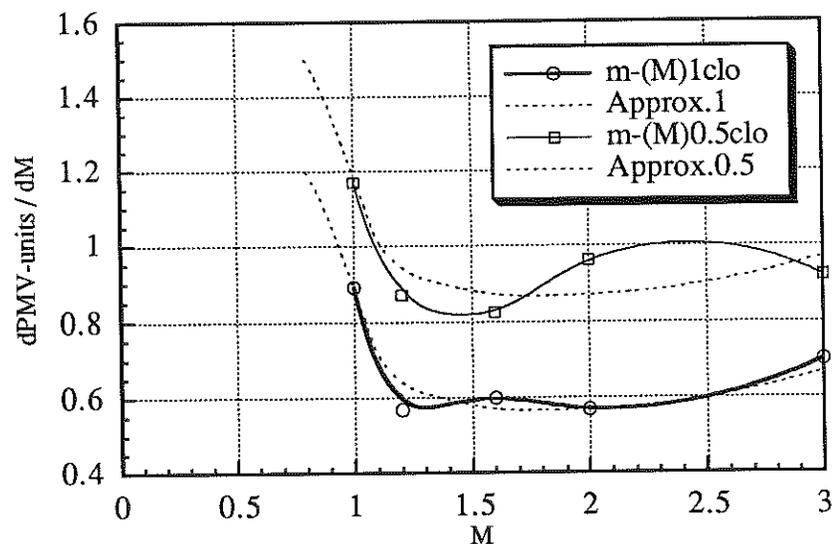
cold side are relatively small. The approximation function is given by:

$$mneg = 6.77 - 11.33\,M + 8.32\,M^2 - 2.64M^3 + 0.31M^4 - 0.6\,I_{cl}$$

$$(4.2)$$

Figure 4.8 Location of the Reference Point tbm=36.5
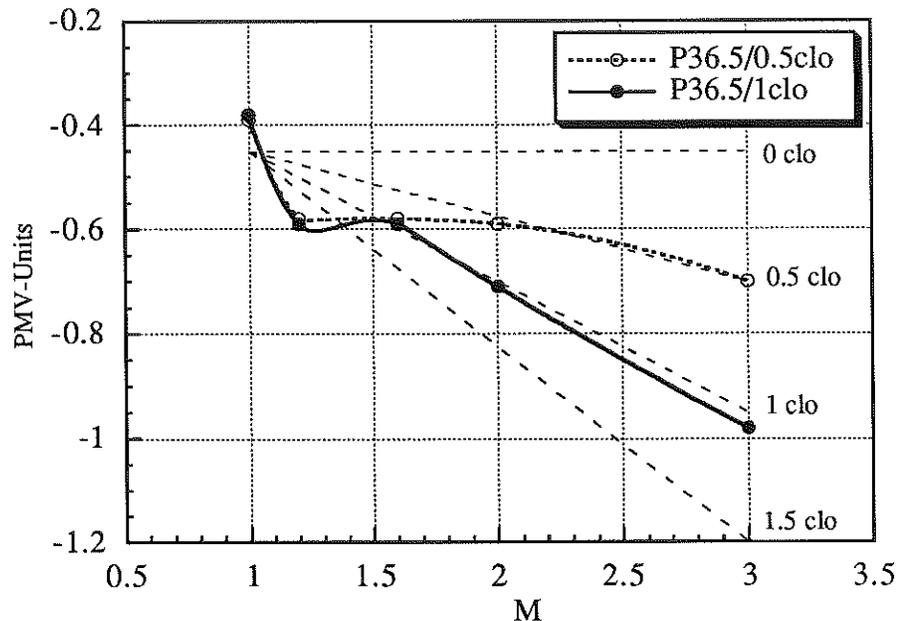
Figure (4.8) shows the location function for the $t_{bm}=36.5$ reference point as a function of the metabolism and I_{cl}. Here the linear approximation had to be made with a linear function rotated in dependence of the clothing insu-lation I_{cl}. On the first view the accuracy seems not to be very high, however absolutely looked at it, the errors are only fractions of 0.1 PMV-units and decrease with increasing M. The function is given by the expression:

$$point(M, I_{cl}) = -0.45 - 0.25 (M - 1 \qquad (4.3)$$

The final version of the function MBTV(M,I_{cl}) now can be given as a combination of the reference point function (4.3) and the linear slope functions (4.1) and (4.2):

for $t_{bm} < 36.5$: MBTV = point($M_{,cl}$) - mneg($M_{,cl}$) [36.5 t_{bm}]

$$\text{for } t_{bm} \geq 36.5: \quad MBTV = point(M_{cl}) + mpos(M_{cl}) \cdot t_{bm} - 36.5 \tag{4.4}$$

$$\tag{4.5}$$

This MBTV function was implemented in the Two Node algorithm and provides an excellent means to indicate thermal body states with regard to thermal comfort and their transient developments, as it will be seen in chapter 8 (validation).

Chapter 5

The Computer Program

5.1   Overview

The Fortran program describing the human thermal exchange and comfort implements all of the equations for heat exchanges , the thermo-regulatory system and the comfort indices described previously. It consists of three subroutines, each representing one major section of the simulation task:

-the central subroutine 'LOOP', which contains mainly the empirical Gagge/ Pierce Foundation equations represents the thermoregulatory system and acts in discrete minute by minute steps.

-the subroutine 'INDEX', which computes the comfort indices PMV according to Fanger and the transient Mean Body Temperature Vote MBTV as well as the Predicted Percentage Dissatisfied PPD.

-the main-subroutine 'TYPE57', which calculates general parameters and represents the numerical organisation of the 'loop'- and 'index'-calls.

These above mentioned subroutines are the ones necessary for TRNSYS-simulations; for this purpose the 'typeck'-call of TRNSYS

within the subroutine 'type57' has to be activated by deleting the asterisk in column one. Then these routines can be compiled and linked to TRNSYS. Further

information about the use within TRNSYS is provided in Chapter 6.

The program 'HUMAN' was created to be used independent of TRNSYS; it replaces the basic TRNSYS 'deck'-functions and provides the possibility to run the human model interactively without connection to further simulation elements like heating systems or buildings. Additionally, the output is much more detailed with regard to characterizing human body state variables. To run the human model in this version the above mentioned 'typeck'-function within 'type57' has to be deleted. The resulting hierarchy of the routines can be seen in figure 5.1.

The actual Fortran-programs are to be found in the appendix 1, however a schematically description is given in the following sections:

5.2   The 'HUMAN' Interactive Program

As already mentioned, this program acts interactively and independent of TRNSYS. Its purpose is to provide a much more time saving simulation alternative if only the human body state is of interest. Additionally it provides 14 more body state variables than the TRNSYS

output and therefore it is also much better for detailed analyses, whereas

for TRNSYS only thermal quantities and comfort votes are of interest.

However in HUMAN the body simulation always starts with the body state initial values given in the parameter section of this routine, which is usually the neutral state - whereas TRNSYS offers the possibility to simulate a whole chain of actions like entering a cold room for a certain

Figure 5.1 The Program Hierarchy
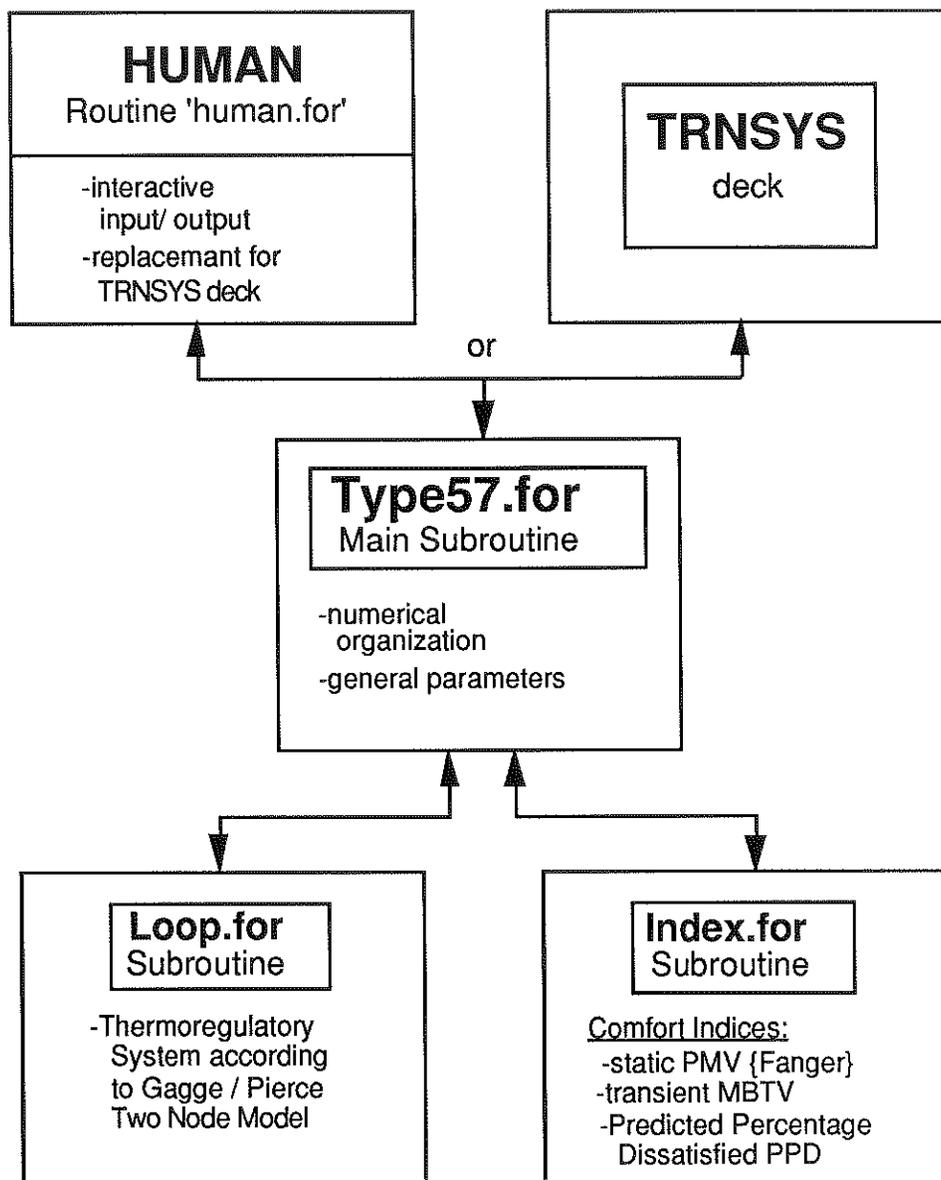
time, then doubling of the metabolism and finally to put on additional garments (see chapter 7). With HUMAN this were to be made with three separate runs with the end values of the previous one as initial values for the next one.

The HUMAN program as the TRNSYS version offer two calculation modes; one for calculating the transient development with outputs for each given timestep (mode ≠ 0) and a second one for

calculating the steady body state values for the given environment without respect to timesteps (mode = 0).

The parameters are the same as for the TRNSYS 'deck' - see chapter 6.

The inputs are simulation time [h], timestep for outputs [h], the mode of calculation (see above), ambient and radiative temperature [C], metabolism [met - see chapter 1], clothing insulation [clo -see chapter 1], relative air humidity [0-1], air velocity [m/s], work efficiency [0-1..see chapter 1] and ambient air pressure [bar].

The outputs are the same as in TRNSYS (see chapter 6) and additional Eres, Edif, Esk, Cres, Dry, the absolute heat flow imbalance 'store' [each in W/m2], tbm [c] , generated sweat Ersw [W/m2], pwet [0-1], Emax [W/m2], hr [W/m2K], the amount of sweat dripping drip [g/m2h], skin blood flow skblf [kg/m2h].

An example for a simulation-output of the interactive HUMAN-program can be found in appendix 2.

5.3   The 'Human' Main Routine

The main purpose of this main routine for the HUMAN interactive program is to replace the basic functions of TRNSYS: organizing the time steps and assigning and plotting the input-/ output-values respectively.

Figure 5.2 Flow Diagram for the 'human'-routine

```
                ┌─────────────────────────┐
                │ general parameters      │
                │ initial values          │
                └─────────────────────────┘
                            │
                            ▼
        ┌───────────┬───────────────────────────────┐
        │  Input    │ simulation time, timestep, mode of │
        │           │ calculation, ta, tr,M, lcl, rh, vel, │
        │           │ we,pa                         │
        └───────────┴───────────────────────────────┘
                            │
                            ▼
   ┌──▶ ┌───────────────────────────────────────────┐
   │    │ for given time and timestep (in minutes)  │
   │    ├───────────────────────────────────────────┤
   │    │       Call Type57 (transfer variables)    │
   │    └───────────────────────────────────────────┘
   │                        │
   │                        ▼
   │    ┌───────────┬───────────────────────────────┐
   │    │  Output   │ PMV, MBTV, PPD, Qsens, Qlat, tsk, │
   │    │           │ tcr, tcl, alpha, time, Eres, Edif,Esk │
   │    │           │ Cres, Dry, Store, tbm, Ersw, pwet, │
   │    │           │ Emax, hr, drip, skbf          │
   │    └───────────┴───────────────────────────────┘
   │                        │
   └────────────────────────┘
```
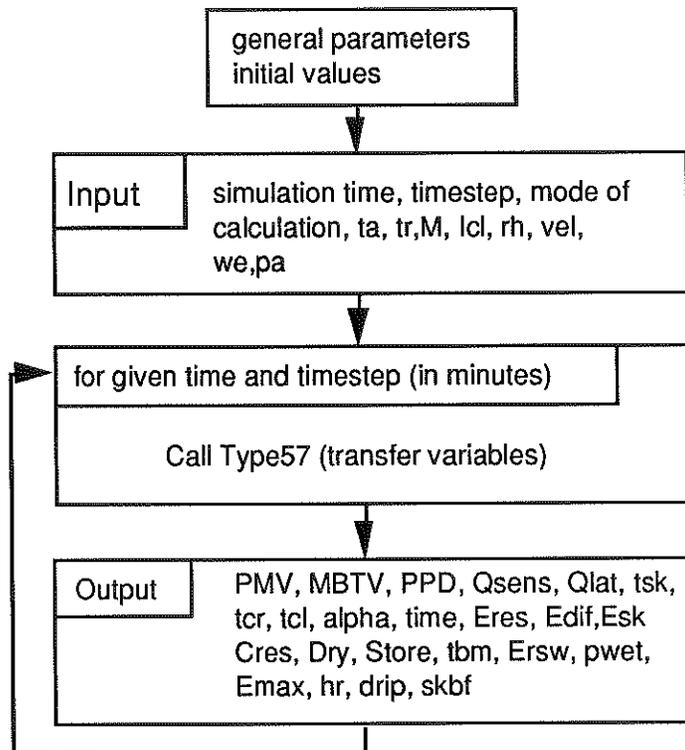
5.4   The 'Type57'-Subroutine

This main-subroutine is the one called by TRNSYS and HUMAN respectively. It represents the organizing subroutine, handling input/ output, calculating general parameters, determining the computing mode and calling the body 'loop' and 'index' subroutines. The stop criterion for the steady state (mode = 0) iteration is a limiting threshold for the heat flow imbalance 'store'. For the transient development the 'loop' is called (simulation-time[h]*60) times, since the loop calculates minute by minute body state changes.

Figure 5.3   Flow Diagram for the 'Type57'-Subroutine

```
┌──────────────────────────────────────────────────┐
│ Taking over of determining body state variables   │
│ from HUMAN and TRNSYS respectively.               │
└──────────────────────────────────────────────────┘
                        │
                        ▼
┌──────────────────────────────────────────────────┐
│ Calculating fcl, Rcl, eveff, hc                   │
└──────────────────────────────────────────────────┘
        │                               │
        ▼                               ▼
┌────────────────────────┐  ┌────────────────────────┐
│ for mode ≠ 0           │  │ for mode = 0           │
├────────────────────────┤  ├────────────────────────┤
│ Calculation of body    │  │ Iterative calculation  │
│ state in minute steps  │  │ of steady body state   │
│ resulting in a         │  │ for given environment  │
│ transient development  │  │ without respect to     │
│                        │  │ time-steps.            │
├────────────────────────┤  ├────────────────────────┤
│ For (time[h]*60)       │  │ Until store < 0.1      │
│ minutes                │  │      ▲                 │
│   call 'loop'          │  │      └─ call 'loop'    │
└────────────────────────┘  └────────────────────────┘
        │                               │
        ▼                               ▼
┌──────────────────────────────────────────────────┐
│ Calculating comfort indices for given body        │
│ state/environment                                 │
│            call 'index'                            │
└──────────────────────────────────────────────────┘
                        │
                        ▼
┌──────────────────────────────────────────────────┐
│ Giving back / storage of determining body state   │
│ variables to HUMAN and TRNSYS respectively        │
└──────────────────────────────────────────────────┘
```

5.5   The Central Body Controlling 'Loop'-Subroutine

This subroutine represents the Two Node Model human thermo-regulatory control. It uses the empirical equations from Gagge/ Pierce Foundation for the various regulation actions like vasoconstriction or sweat absorption (see chapter 3). Figure 5.4 above shows its algorithm schematically.

Figure 5.4 Flow Diagram of the 'Loop'-Subroutine
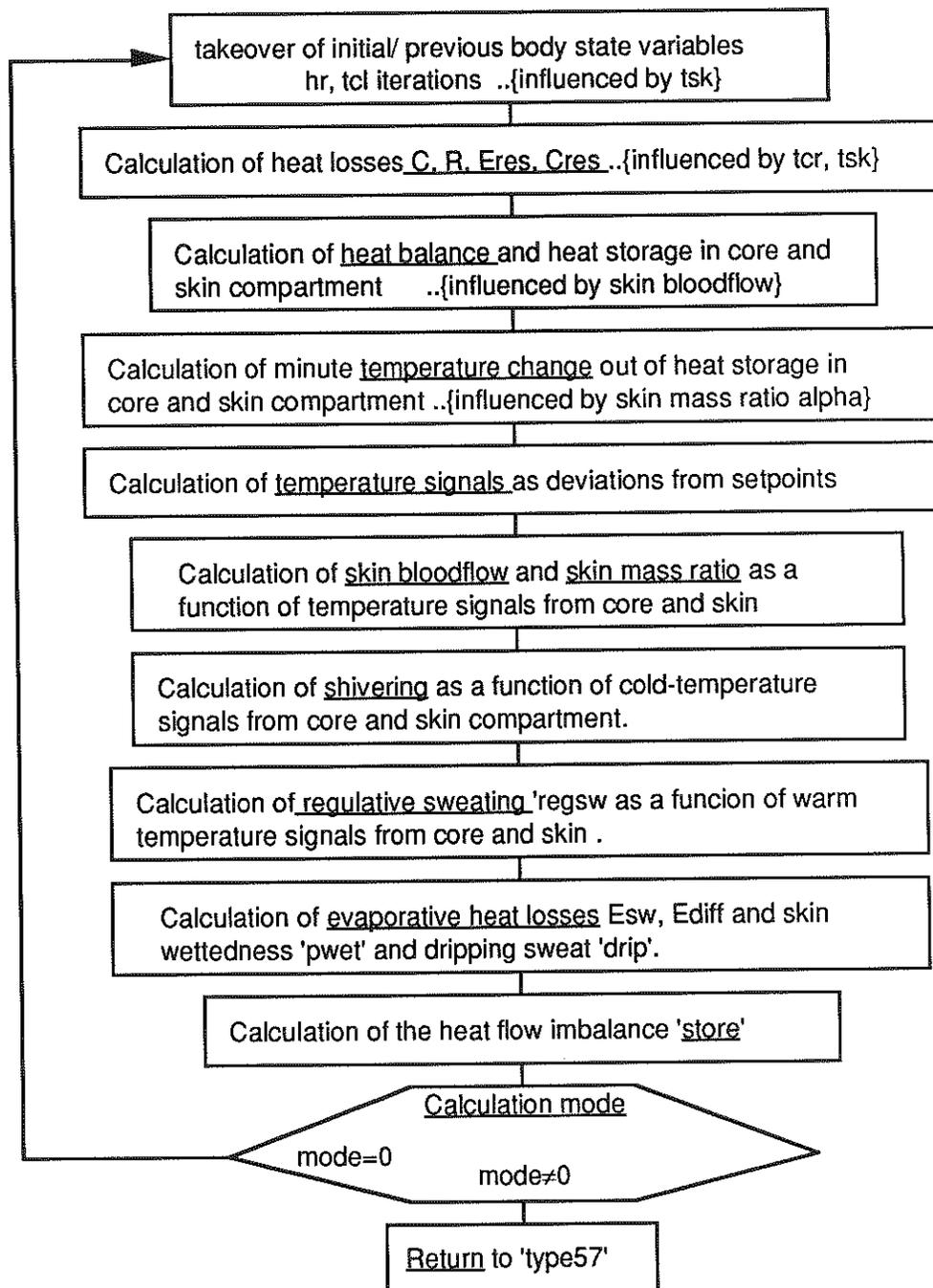
With each run through it calculates the new minute-by-minute body state variables t_{cr}, t_{sk}, alpha, skbf, E_{sk} and M regulating the

body to a final steady state heat balance. The iteration for h_r and t_{cl} is necessary because they are dependent on each other; it is done by a loop until a threshold for the t_{cl}-change is reached.

For the steady state calculation mode the 'loop' has to be called repeatedly until the heat flow imbalance 'store' diminishes under a given threshold, which however needs less than two seconds calculation time on a IBM 386 or a 'Minivax'.

5.6   The 'Index'- Subroutine

Here the comfort indices Predicted Mean Vote PMV according to Fanger, the new Mean Body Temperature Vote MBTV and the Predicted Percentage Dissatisfied PPD are calculated. The Fanger PMV-standard requires certain different approaches for calculating hc, R and tcl. The calculating of Tcl|Fanger is done with the help of a Newton iteration since this turned out to be the only stable one; the basis for this is the right side of the heat balance double equation (2.18). Figure 5.5 shows the algorithm schematically; each time of calling both paths are gone through and PPD is calculated either from MBTV (transient) or PMV (steady state/ mode=0)

Figure 5.5   The Comfort Vote 'Index'-Subroutine

```
┌─────────────────────────────────────────┐
│        Takeover of general parameters     │
└─────────────────────────────────────────┘
        │                         │
        ▼                         ▼
┌──────────────────────────┐  ┌──────────────────────────┐
│ Takeover of the actual    │  │ Takeover of environmental │
│ mean body temperature     │  │ parameters                │
└──────────────────────────┘  └──────────────────────────┘
┌──────────────────────────┐  ┌──────────────────────────┐
│ Calculating the           │  │ Calculating the static    │
│ parameters of the         │  │ heat flows and static     │
│ MBTV approximation        │  │ heat balance as well      │
│ function as a function    │  │ as the 'thermal load'     │
│ of M and Icl.             │  │ according to Fanger       │
└──────────────────────────┘  └──────────────────────────┘
┌──────────────────────────┐  ┌──────────────────────────┐
│ Calculation of MBTV as a  │  │ Calculation of PMV as a   │
│ function of the mean body │  │ function of the static    │
│ temperature.              │  │ 'thermal load'            │
└──────────────────────────┘  └──────────────────────────┘
        │                         │
        ▼                         ▼
┌──────────────────────────┬──────────────────────────┐
│ MBTV used for mode≠0      │  PMV used for mode=0      │
├──────────────────────────┴──────────────────────────┤
│ Calculation of the Predicted Percentage Dissatisfied │
│ PPD                                                   │
└──────────────────────────────────────────────────────┘
                    │
                    ▼
            ┌──────────────────┐
            │ Return to 'type57'│
            └──────────────────┘
```

Chapter 6

The Human Model within the System
Simulation Program TRNSYS

6.1 Introduction

TRNSYS is a modular system simulation program for heating, air-condi-tioning, thermal storage and solar devices. The modular structure gives the program a high flexibility in combining the different component models to an arbitrary network and reduces greatly the complexity of system simulations since it reduces a large problem into a number of many smaller problems, each of which can be solved independently. Additional components can be written and added as long as they fulfill certain structural requirements.

The final goal of the present study was to create such a TRNSYS component for the Two Node Human Model, as it will be described in chapter 6.2 and validated in chapter 7. The components can be represented by 'black boxes', with input and output connections in analogy to the real system plus a parameter information. Thus the box for the human model component was defined as shown in figure 6.1.

Figure 6.1 The Human Model Component

ta	tr	M	Icl	rh	vel	we	pa	**Parameters**
								mode
								ADu
								mb
		TRNSYS TYPE57					evefo
								icl
	Human Response and Comfort Model							chco
								tski
								tcri
								alphai
								skbfi
PMV	MBTV	PPD	Qsens	Qlat	tcl	tcr	tcl	a	Eski
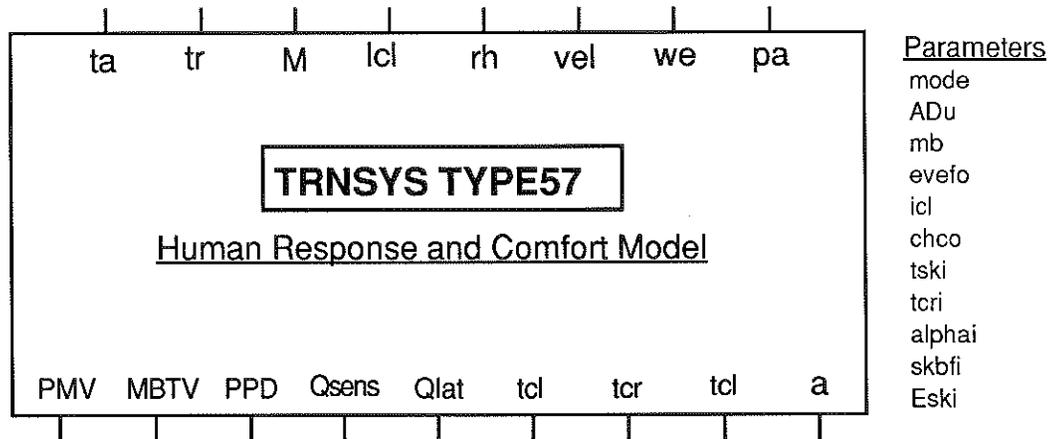
To define all the interconnections between the components, an information flow diagram, using the component boxes has to be drawn as schematically shown in figure 6.2 for an imaginary system.

Finally the flow diagram information has to be translated in a logical TRNSYS code to provide the information, where the different components get their inputs from and which parameters to use.

However since this section will give only an overview about the way of working of TRNSYS, the further description is limited to the necessary information about the human model component configuration, which the more experienced TRNSYS user needs.

Figure 6.2 Information Flow Diagram of a Building and Human System
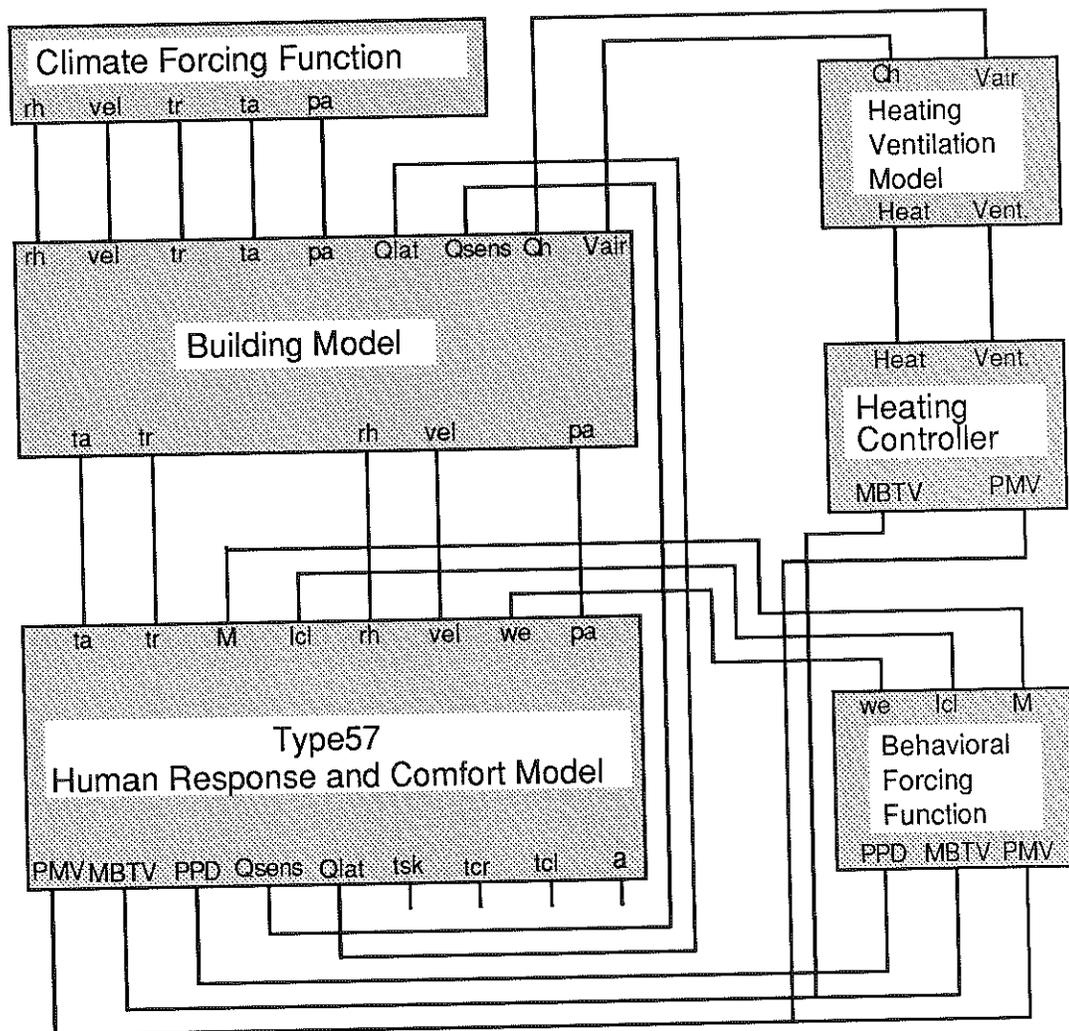
6.2 The Human Model TRNSYS Configuration

Since the program algorithm has already been described in chapter 5, the emphasis here lies on the necessary general description about the thermal Human Model a TRNSYS user needs:

Short Description of the Type57 Human Thermal Response Component:

This component models the thermal response of a human to the thermal environment. The output of the model are the sensible and latent heat flows from the human to the environment, the thermal state of the human and the thermal comfort perception in a transient development. It also offers a special calculation mode providing the values for the steady body state in the actual thermal environment.

Table 6.2 TRNSYS Configuration of the TYPE57 Human Thermal Response Component

Parameters	Description
1 iteration	mode of calculation; $mode=0$..steady state
	$mode \neq 0$ transient
2 1.4)	A_D..Dubois body surface [m^2], A_{Du} =1.8 (see capter
3	mb..body mass [kg], standard mb=70 kg
4 (3.19)	if $\neq 0$ override value for evaporation efficiency, see

5	icl..effectiveness of mass transfer for clothing layer, see chapter 1.6, (standard icl = 0.45)
6	if ≠0 override value for convective heat transfer coeffi-cient [W/m2K]
7	tski..initial skin temperature (neutral value tsk = 33.7 C)
8	tcri..initial core temperature (neutral value tcr = 36.8 C)
9	alphai..initial skin to core mass ratio (neutral alpha =0.1)
10	skbfi..initial skin bloodflow (neutral skbf = 6.3 kg/m²h)
11	Eski.initial evaporative heat loss (neutral Esk=7.3W/m²)

Inputs:

1	ta..air dry bulb temperature [C]
2	tr..mean radiant temperature [C]
3	vel..relative air velocity [m/s]
4	rh..relative air humidity [0-1]
5	M..metabolic activity [met; 1met = 58.2 W/m2], see ch. 1.2
6	I$_{cl}$..clothing insulation [clo; 1clo =0.155 Cm2/W], see 1.5

7	we..work efficiency/useful work fraction [0-1], see ch. 1.2
8	p_a..ambient air pressure [bar]

Outputs:

1	PMV..Predicted Mean Vote (static) [-3 to +3], see ch. 2.5
2	MBTV..Mean Body Temperature Vote [-3 to +3] see 4.2
3	PPD..Predicted Percentage Dissatisfied [0 - 100%], see 2.6
4	Qsens..sensible heat transfer [W]
5	Qlat..latent heat transfer [W]
6	tsk.. mean skin temperature [C]
7	tcr..mean core temperature [C]
8	tcl.. mean clothing temperature [C]
9	a..skin to core mass ratio [0-1]

Chapter 7

Validation

7.1 Investigations in the Literature

No human model can claim to be like reality, since all models are rather a mathematical description of observed phenomena than a representation of the real process. However these phenomena and their results can be mathematically modeled fairly accurate. Another question is how accurate a model's prediction should be for it to be considered accurate. At least it is important to know about the magnitude of the error of the used model.

There has been a variety of investigations comparing the results of different human model approaches with measured data /ref. 3, 4, 5, 6 /. This was done by comparing the skin- and core-temperatures of the models with the measured data from different laboratories for different clothing levels. The core temperature of the measurements was measured rectally, which causes a systematic error, since the Two Node Model 'core' has no real physiological equivalent. Additionally the always inaccurate evaluation of the clothing insulation values for the measurements

causes an error - however this error range is also present in the assessment of the model input values.

As a conclusion of above mentioned investigations the standard deviations /5/ for the Two Node Model from measured values of t_{sk} and t_{cr} can be used as an assessment of the accuracy:

Table 7.1 Standard Temperature Deviations of the Two Node Model from Measured Data

Data from:	tsk [C]	tcr [C]
Kabayashi	0.78	0.37
Young	1.88	0.67
Chappuis	0.48	0.43

(Reference /5/; Haslam, Parson Ph.D., ASHRAE transactions'88, Vol. 94)

In general the Two Node Model apparently tends to underestimate skin wettedness and core temperature and overpredict skin temperature /4/.

7.2   Simulation Results

In the present study a variety of simulations with the HUMAN program and the TRNSYS version respectively have been made, the most interesting of which are presented in this section. These plotted results can be considered as a qualitative validation, since they match all expectations for the developments of the body state values. This is shown in the following sections for

steady body state variables as well as transient developments covering temperature-, clothing-, and metabolism-changes.

7.2.1 The Steady Body State Values

In this section the values of E_{sk}, Dry t_{sk}, t_{cr} M_{shiv}, a, skbf and pwet are shown for steady state of two metabolism rates in the figures 7.1 to 7.8 as a function of the combined ambient radiant and air temperature t_o, the clothing insulation and the relative air humidity (30% and 90%). The air velocity is always vel = 0.2 m/s. The analogous comfort votes can be seen in figure 2.7 in chapter 2.5.

Figure 7.1 shows an increasing E_{sk} (skin evaporative heat loss) due to sweating, but only above a certain threshold for t_o, (combined t_a and t_r), which represents the 'warm body signal'. The higher the metabolism or the clothing insulation, the lower this threshold is located. Beyond this threshold E_{sk} is due only to skin diffusion.

Figure 7.2 shows a steady decreasing Dry (dry heat loss), the higher t_o - which is due to the law of convection and radiation, since t_{sk} comes closer to t_o. For higher clothing insulation or metabolism however the level of Dry increases.

Figure 7.3 shows a steady increasing t_{sk} the higher t_o; the higher the clothing insulation and metabolism, the more readily t_{sk} increases. Above t_o = 30 C the curve tends to flatten, since heat

loss due to sweat evaporation slows the increase down. The neutral value is t_{sk} = 33.7 C.

Figure 7.4 shows a relatively constant core temperature with only a slight increase; however for high air humidity the sweating does not provide anymore enough heat loss and t_{cr} increases faster above 25 C. Additionally the skin temperature in this zone is nearly as high as the core temperature, thus no more providing enough conductive heat loss. The neutral value is t_{cr} = 36.8 C.

Figure 7.5 shows increased metabolism due to shivering for cold environments; the threshold for shivering depends on metabolism and clothing insulation.

Figure 7.6 shows the skin mass to body mass ratio a increasing the colder the environment. The lighter dressed the body is, the more readily a increases. The curve flattens out the colder the environment, since shivering slows the increase down. The neutral value is a = 0.1 and the minimum is a = 0.05, which is reached in very hot environments.

Figure 7.7 shows an increasing skin bloodflow the higher t_o. The higher the relative air humidity, the more readily skbf increases due to conduct more heat towards the skin, since the skin then has nearly core temperature (see also t_{cr} and t_{sk}-development).

Figure 7.1 The Steady Body State Evaporative Heat Loss
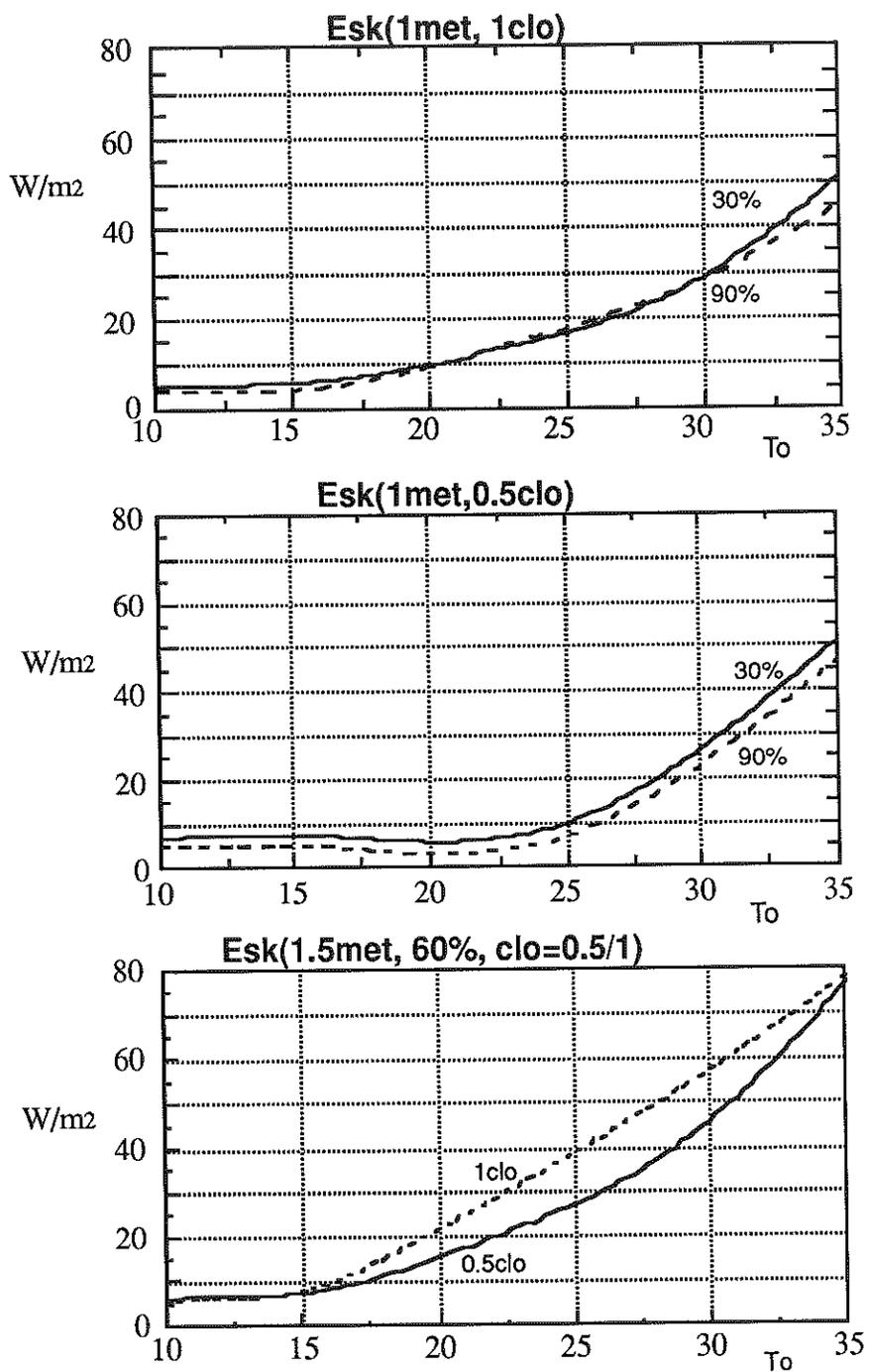
Figure 7.2 The Steady Body State Dry Heat Loss
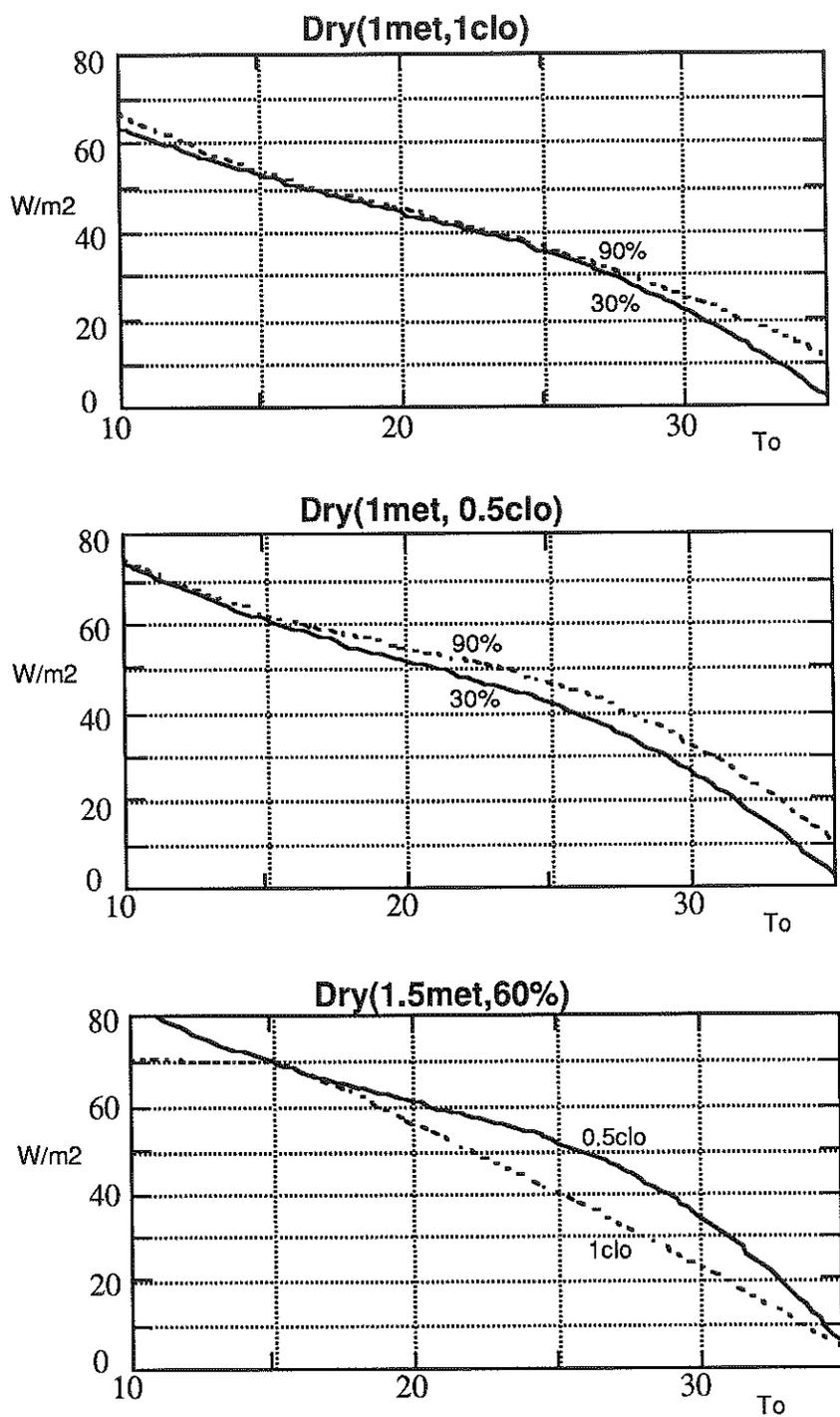
Figure 7.3 The Steady Body State Skin Temperature

tsk(1met, 1clo)

tsk(1met, 0.5clo)

tsk(1.5met, 60%)
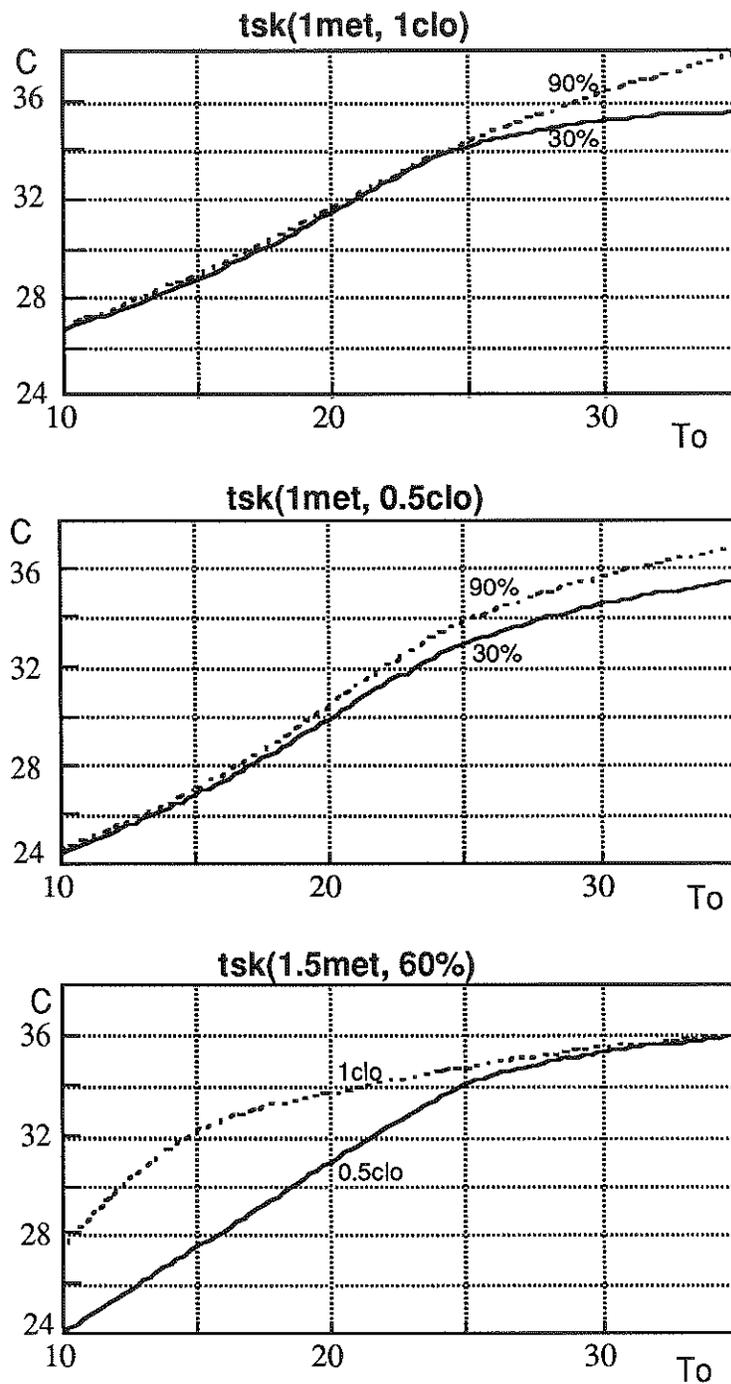
Figure 7.4 The Steady Body State Core Temperature
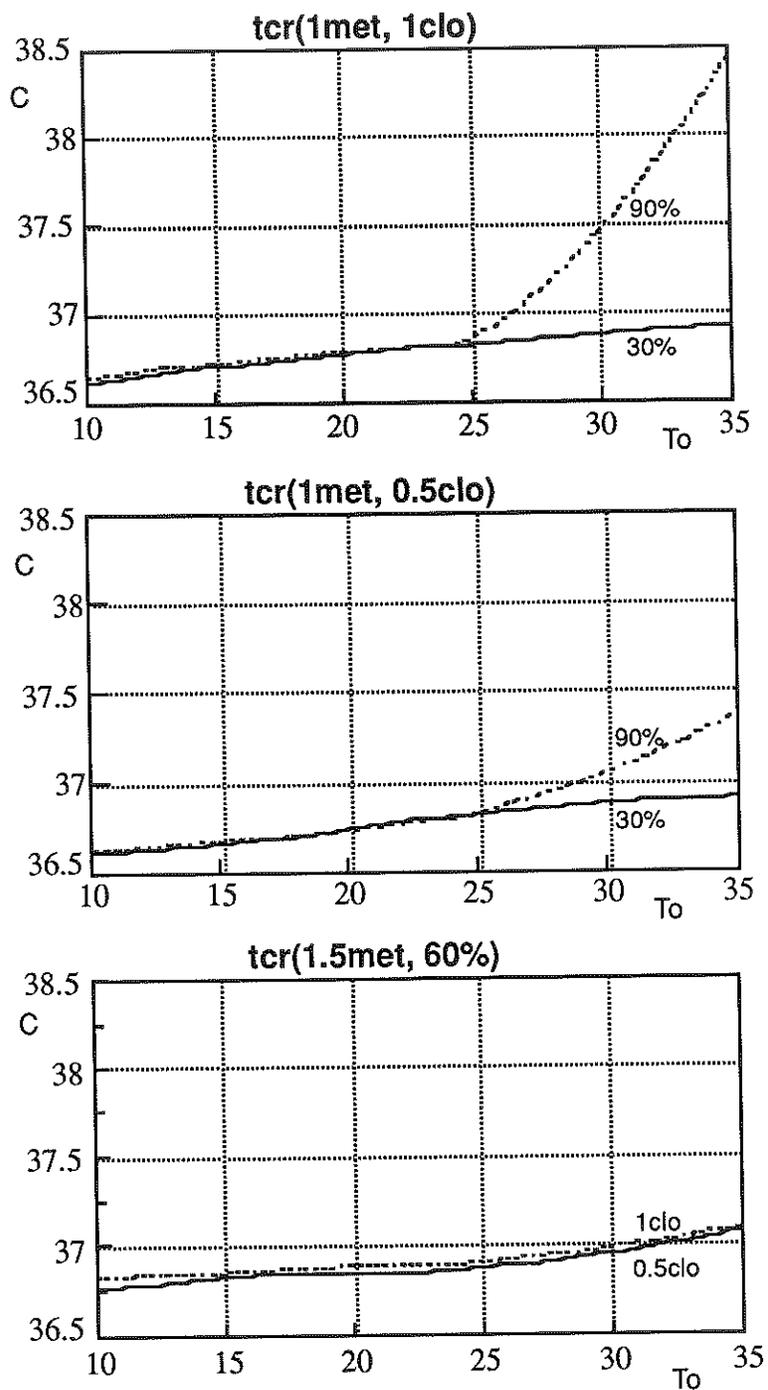
Figure 7.5 The Steady Body State Metabolism

M(1met, 1clo)

W/m2

M(1met,0.5clo)

W/m2

M(1.5met,60%)

W/m2
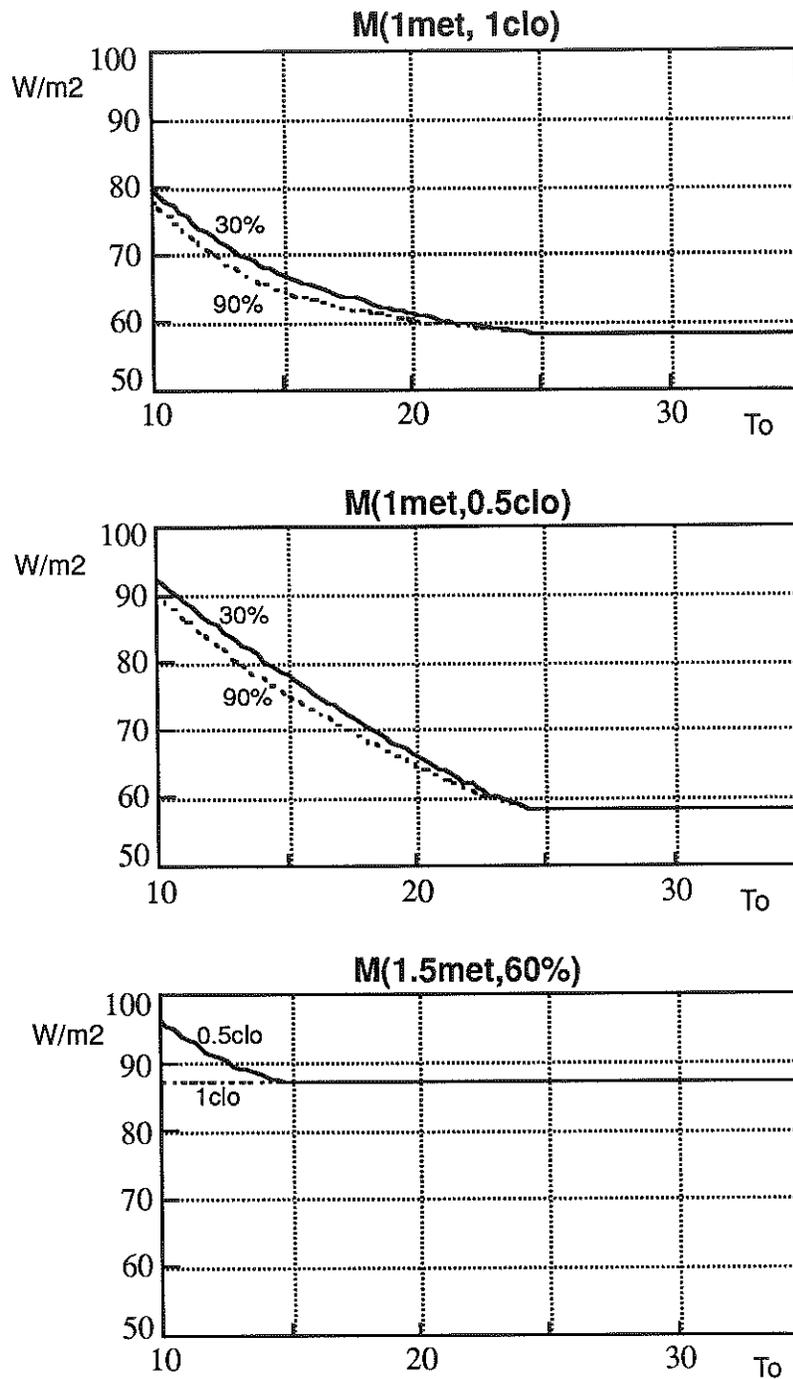
Figure 7.6 The Steady Body State Skin Mass Ratio
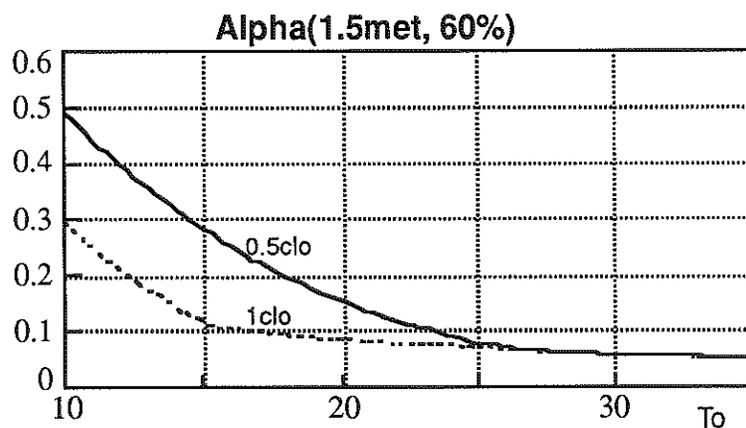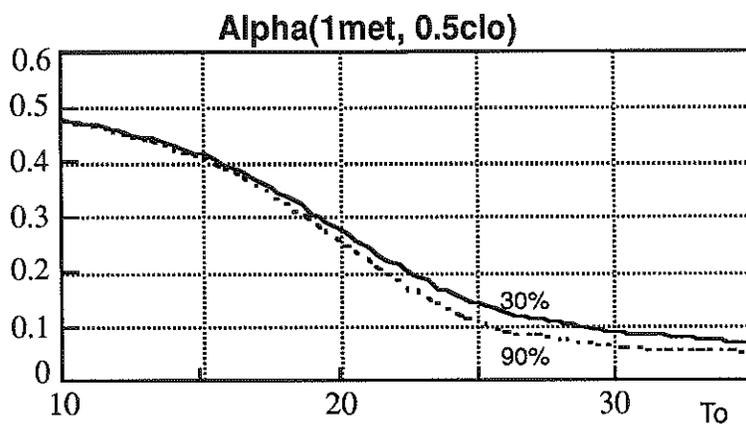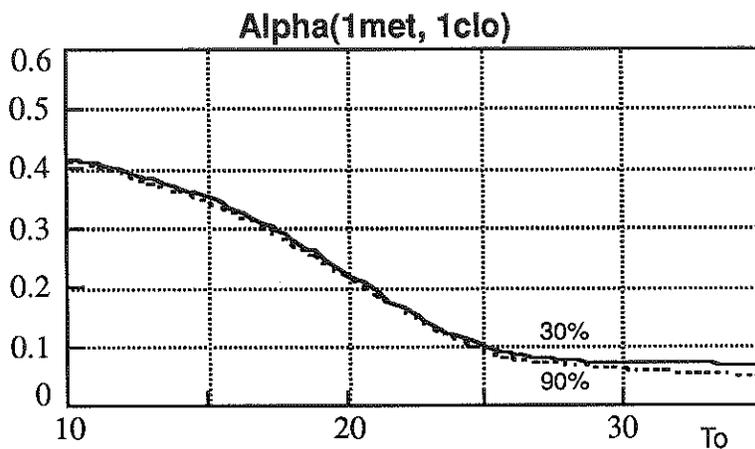
Figure 7.7 The Steady Body State Skin Bloodflow
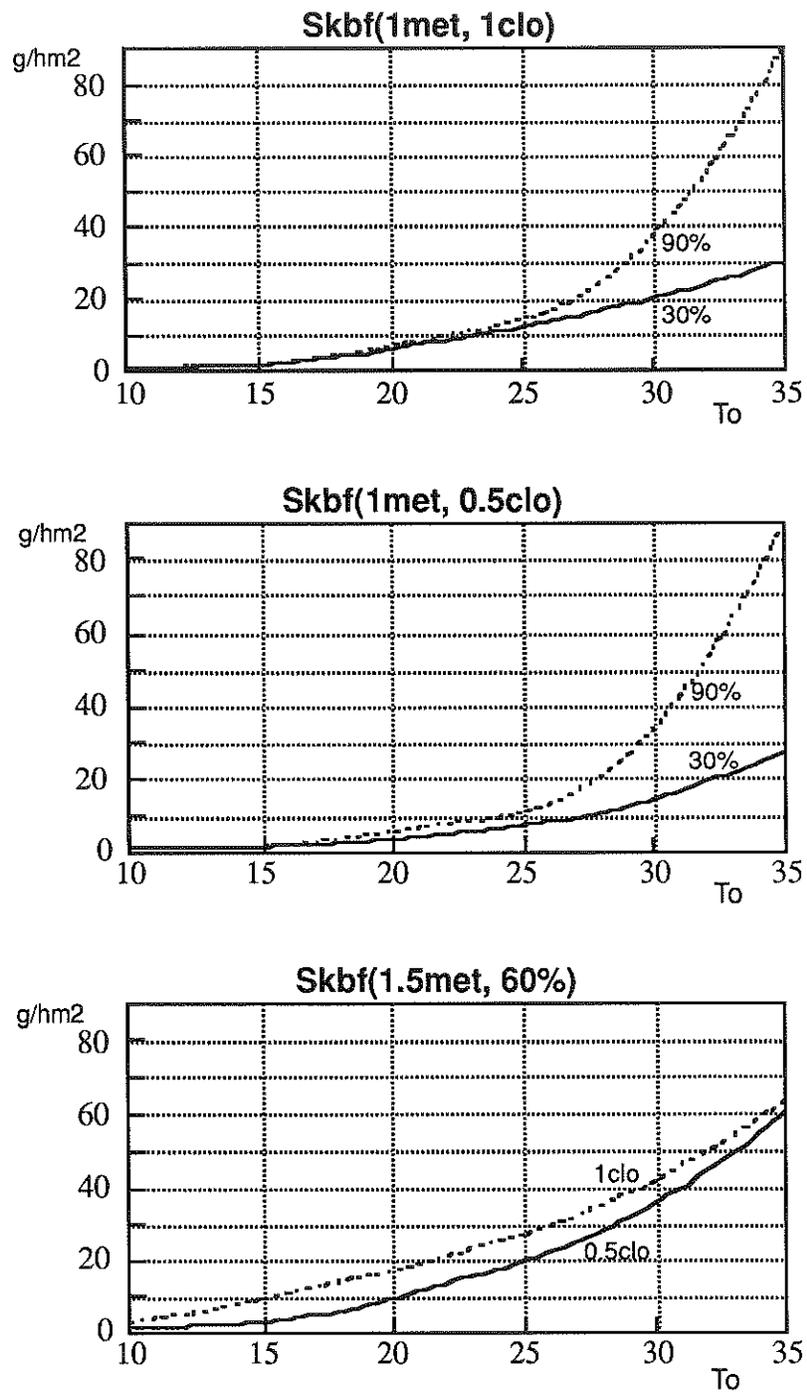
Figure 7.8 The Steady Body State Skin Wettedness

pwet(1met, 1clo)

pwet(1met, 0.5clo)

pwet(1.5met, 60%)
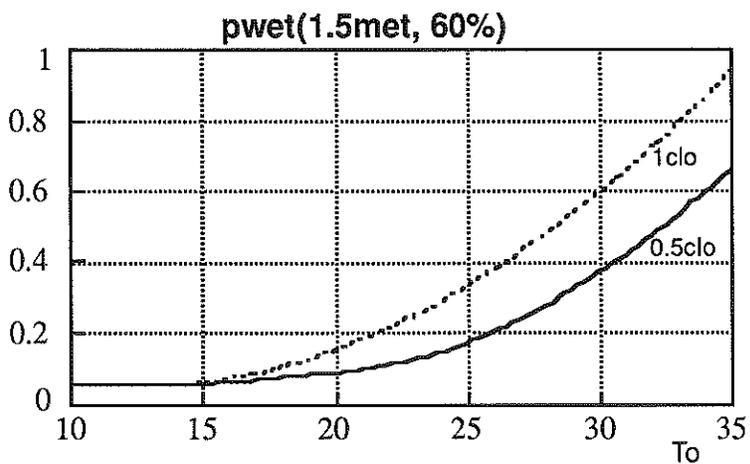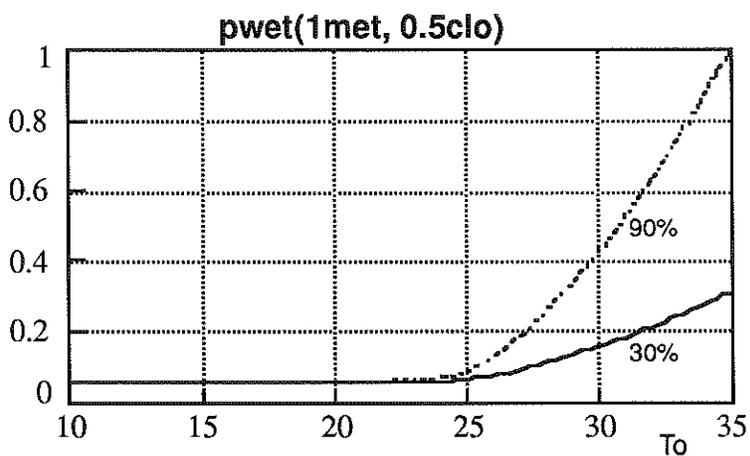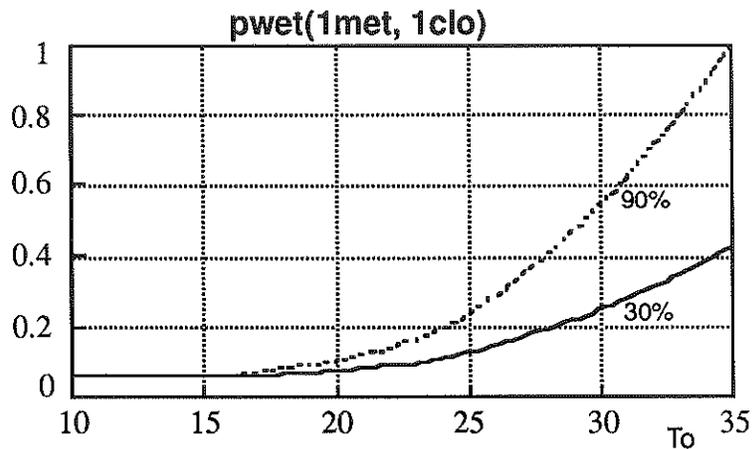
7.2.2 The Transient Body State Development

In the following figures 7.9 to 7.11 the transient developments for t_{sk}, t_{cr} E_{sk} Dry, store, skbf , a , pwet and the comfort votes PMV and MBTV are shown for three ambient temperatures with M = 1met, I_{cl} = 1.0 and 60 % relative air humidity.

Figure 7.9 shows a always relatively constant t_{cr}, however t_{sk} varies according to the ambient temperature: the higher t_o, the higher t_{sk}. E_{sk} is the higher , the higher to and Dry the higher the lower t_o. This means a dominance of Dry for cold environments and of E_{sk} for warm environments. In general the adjustments of body state variables for cold environments last significantly longer.

Figure 7.10 shows a higher skin-bloodflow, the higher t_o and a higher skin to body mass ratio a the lower t_o. Again the adjustments lasts much longer for cold environments, as it can be directly seen in the value of the thermal imbalance variable 'store'.

Figure 7.11 shows a higher skin wettedness, the higher t_o; for cold environments pwet does not change since then it represents the minimum value due to diffusion and there is no sweating. The development of the comfort vote MBTV is according to the expectation, that it finally reaches the steady state PMV-value.

Figure 7.9   Transient tsk, tcr, Esk, Dry

for M = 1met, I_{cl} = 1clo, rh = 60%

84
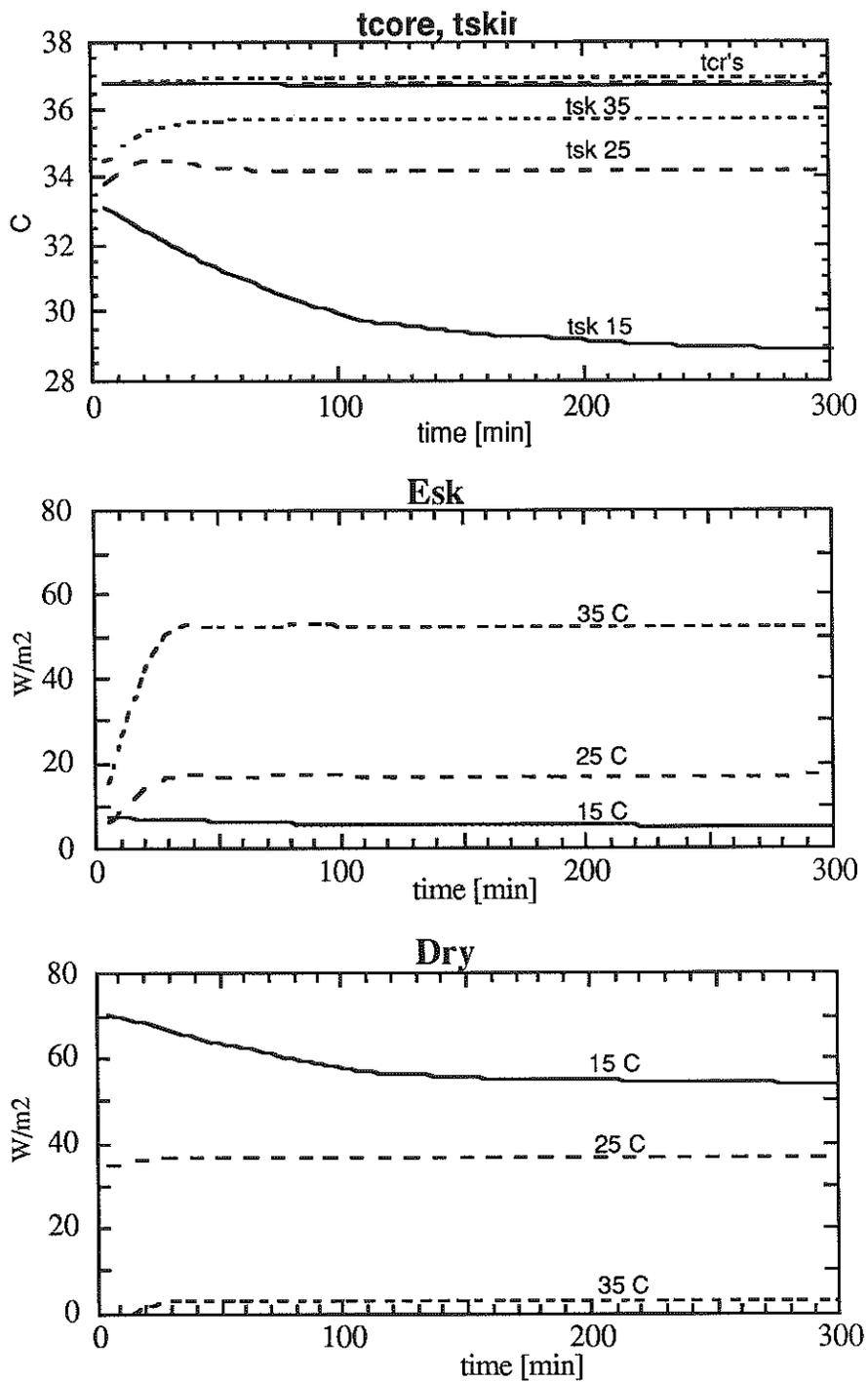
Figure 7.10   Transient Store, Metabolism, Alpha and Skin Bloodflow
for M = 1met, I$_{cl}$ = 1clo, rh = 60%
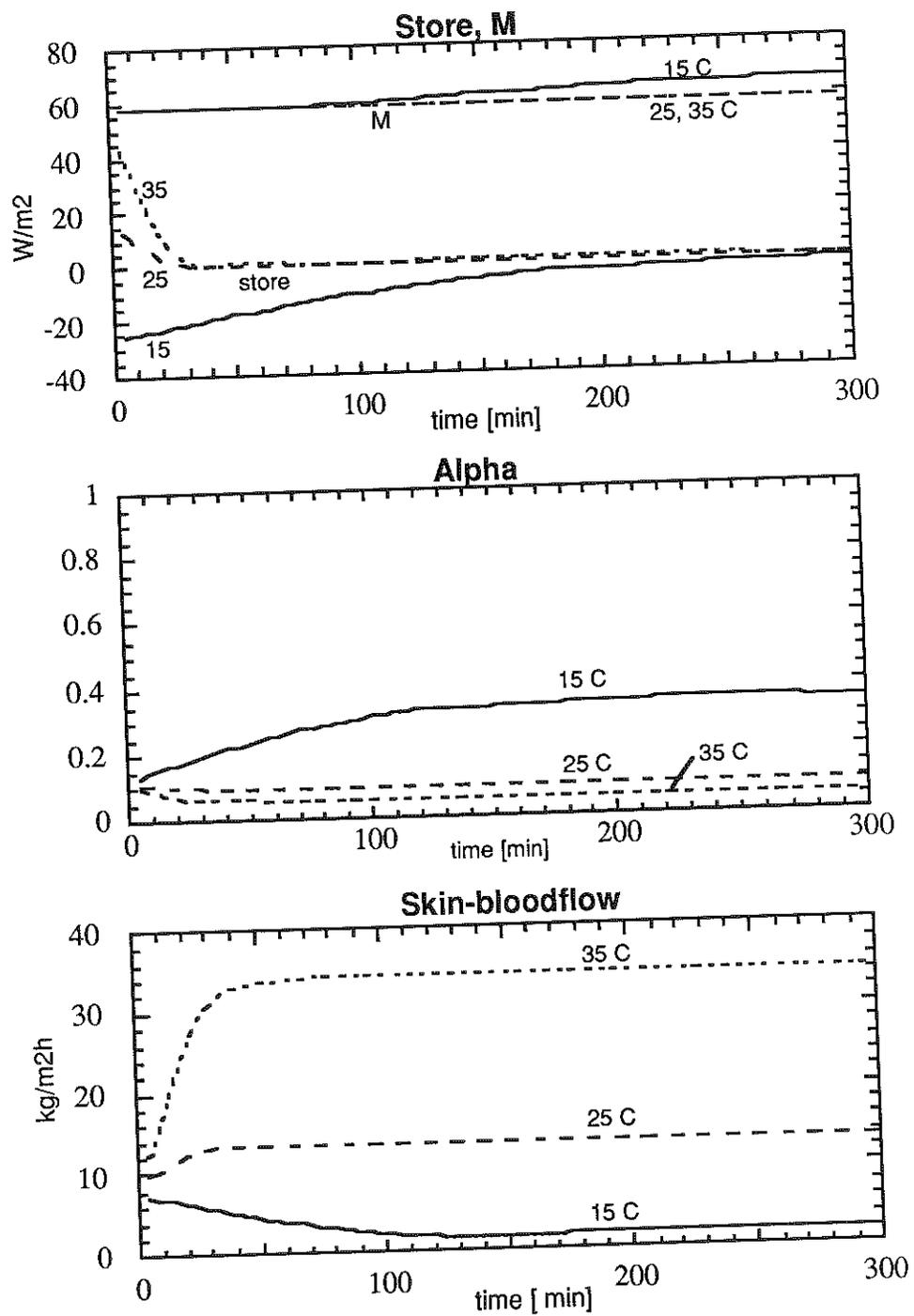
Figure 7.11 Transient Skin Wettedness and Comfort Vote

for M = 1met, I_{cl} = 1clo, rh = 60%

Skin-pwet

PMV/MBTV(t)
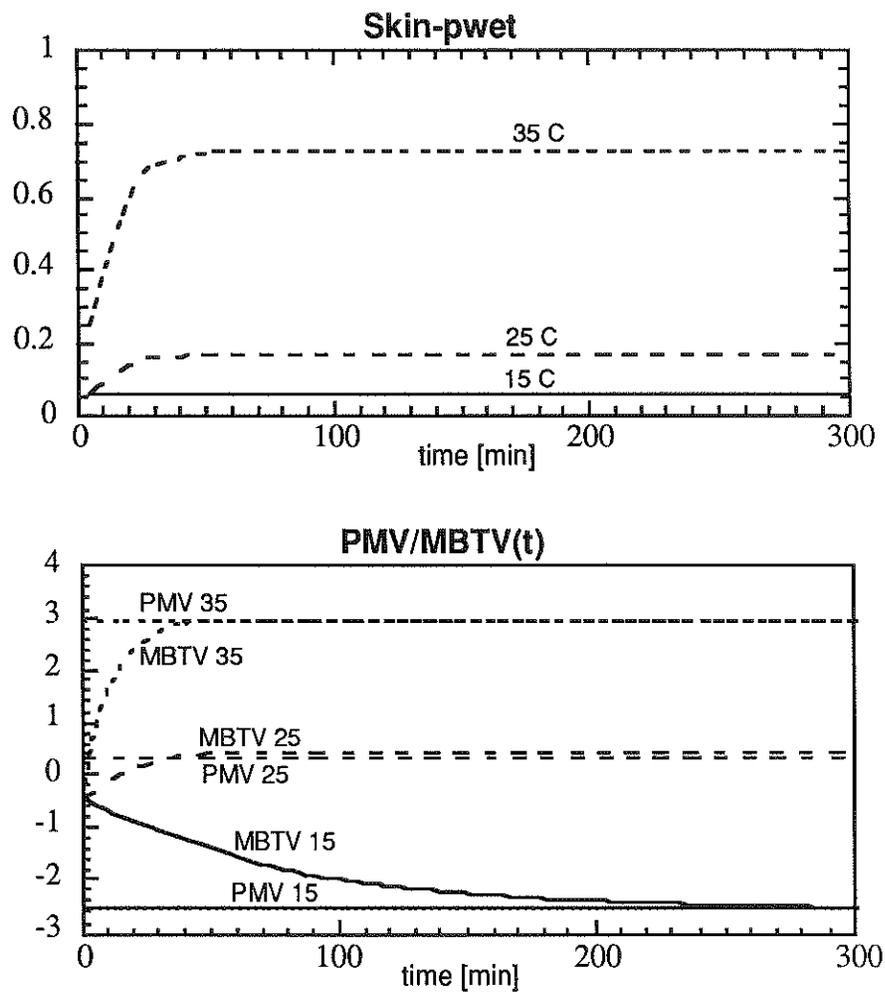
A special investigation was made about the shivering response of the Two Node Model in cold environments, since at a first glance the shivering response seemed to be too strong. However if the maximal shivering rate of three times the normal metabolism is considered, the graphs in figure 7.12 look reasonable, since the metabolism increases

Figure 7.12 The Transient Shivering

M (1met, Icl=0.5/1, rh=30/90%, t=10/15)

M (1.5met, Icl=0.5/0.7/1, rh=60/90%, t=10)

M (2met, Icl=0.5, rh=60%, t=0/5)
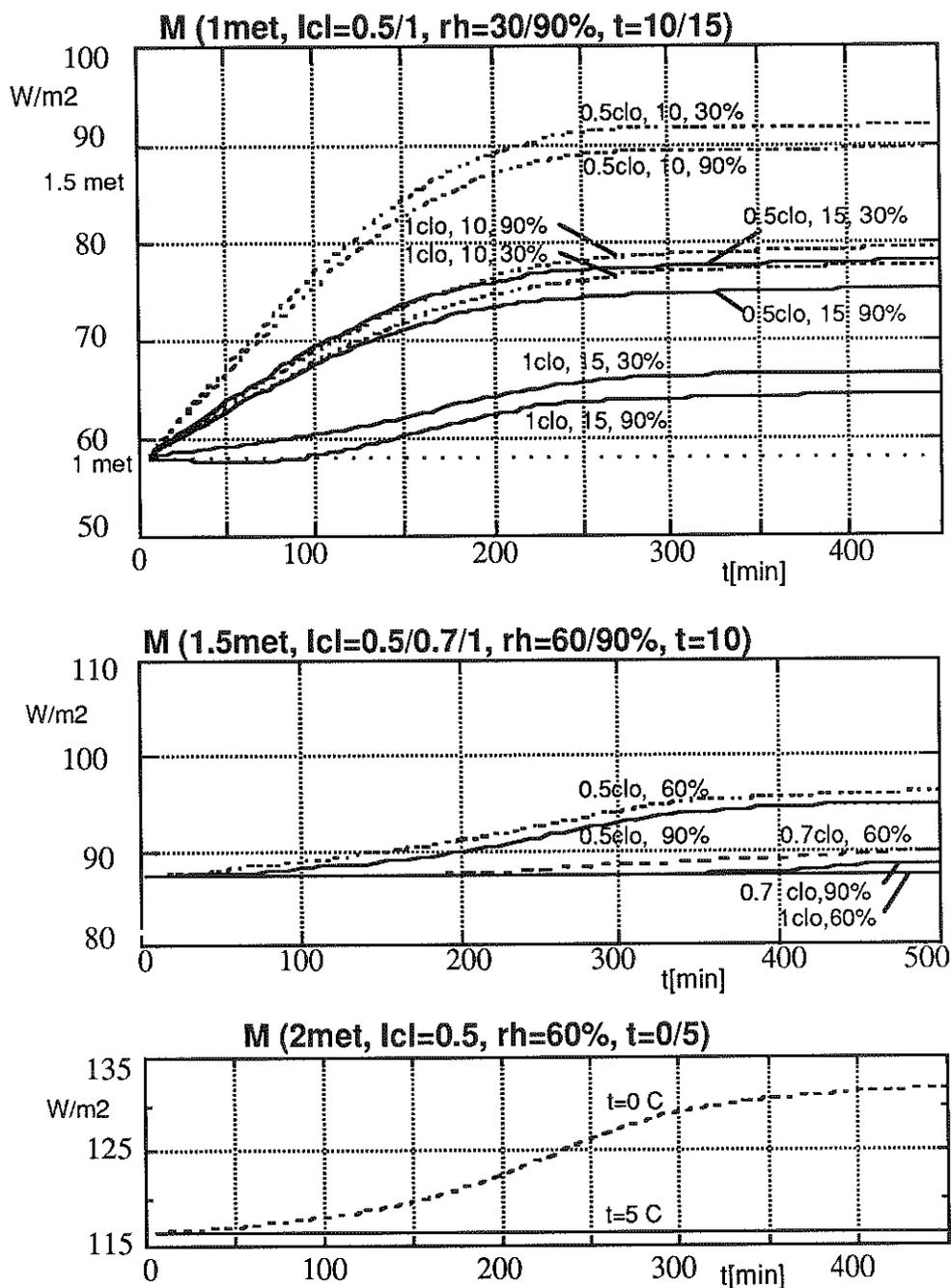
only by about 50% for the most extreme case. It has also to be taken into account, that this shivering response is the result of exposures to cold environments of up to more than eight hours.

A further investigation covered the response not only to temperature changes but also to changes in the amount of clothing, metabolism and relative air humidity. The figures 7.13 to 7.16 were obtained with the HUMAN program with initial steady body state values for the previous 'environment' and then changing the one variable in question.

Figure 7.13 shows the transient development of body state variables for a sudden change of the ambient temperature from warm to cold such as entering a cold room. E_{sk}, t_{sk} and skbf decreases as well as Dry, the latter since it is adjusted by the decreasing t_{sk}. t_{cr} stays nearly constant and the whole adjustment process lasts, as usual for cold environments fairly long. Also the development of the comfort vote from 'slightly too warm' to 'very cold' can be seen. The two fixed points for this development are the static PMV values for the begin and steady state condition.

Figure 7.14 shows the transient development of body state variables for a doubling of the amount of clothing in a cold environment. As it can be seen this is not very effective for rapidly warming up the body without additional increasing of the metabolism. tsk and skbf increases slightly , alpha decreases, but all in all the effect was only to get from the 'very 'cold'-zone to the vote of (still) 'cool'.

Figure 7.15 shows the transient development of body state variables for a doubling of the metabolism in a cold environment; in comparison with

Figure 7.13 Transient Development for a Change of the Temperature

for 1 met, 1 clo, 90% rh, steady state 25 C --15 C
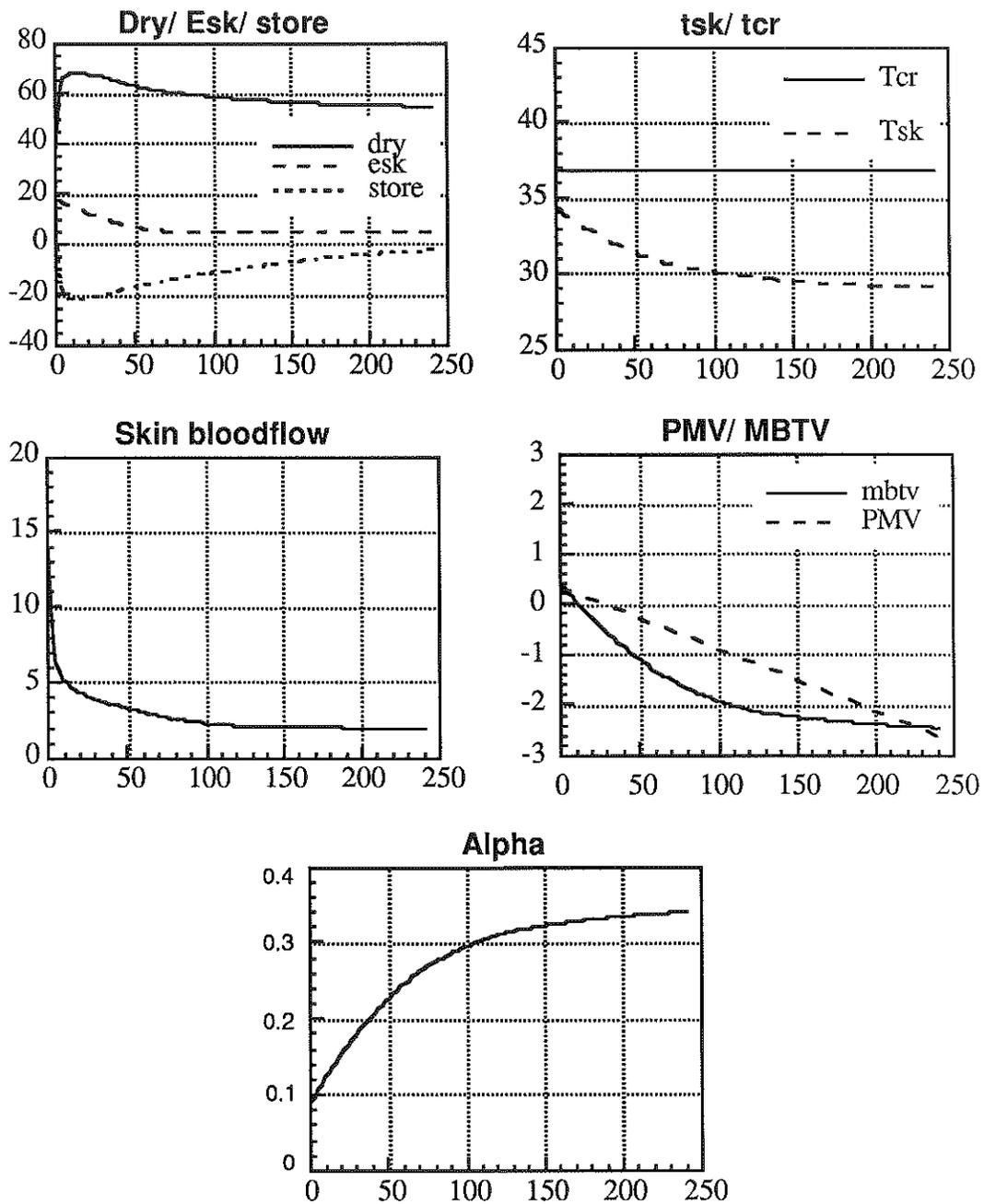
Figure 7.14 Transient Development for a Change of Clothing

for 1 met, 1 clo steady state -- 2 clo, 30% rh, 15 C
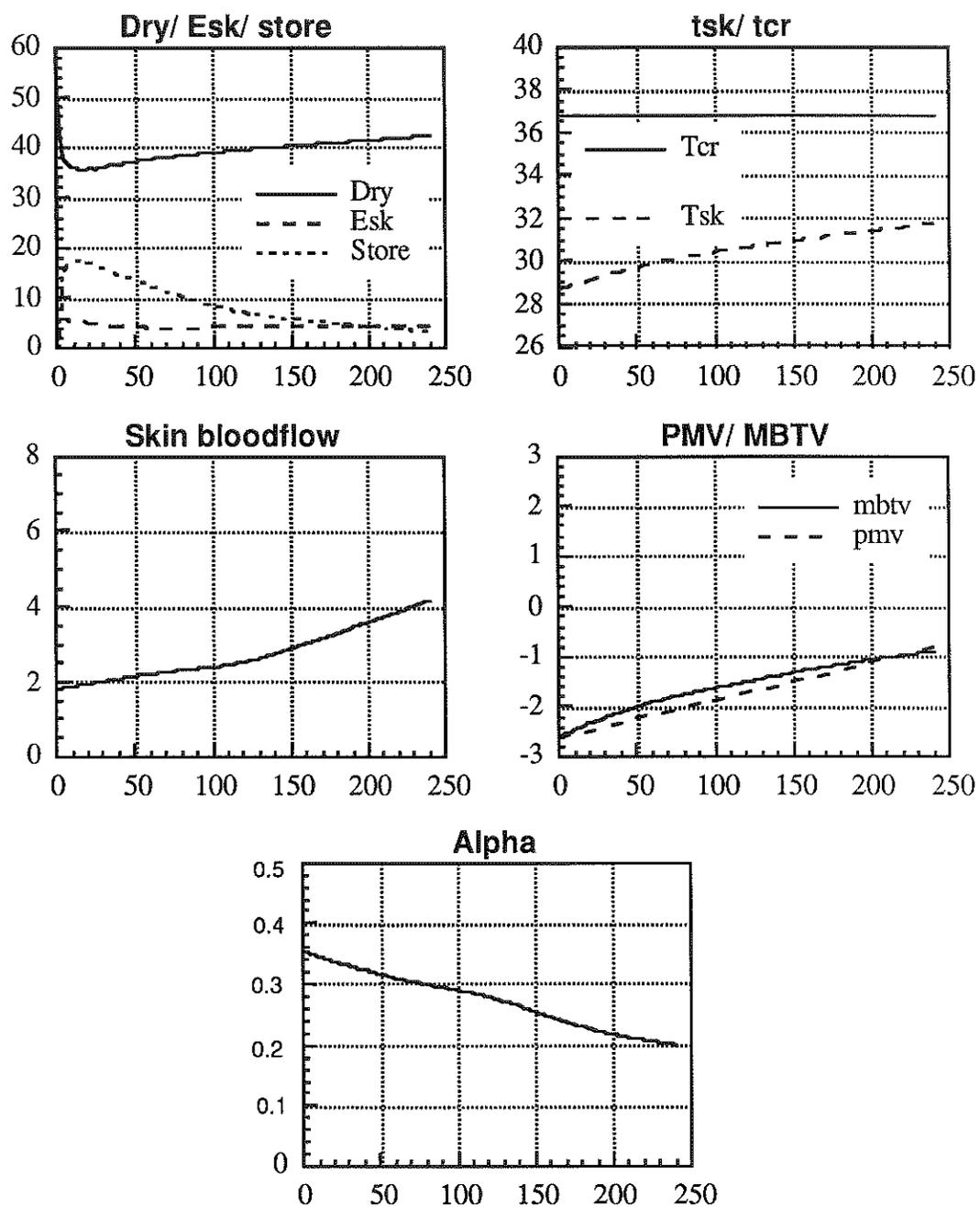
Figure 7.15 Transient Development for a Change of Metabolism

for 1 met steady state -- 2 met, 1 clo, 30% rh, 15 C

Dry/ Esk/ store

— Dry
-- Esk
···· Store

tsk/ tcr

— Tcr
-- Tsk

Skin bloodflow

PMV/ MBTV

Alpha
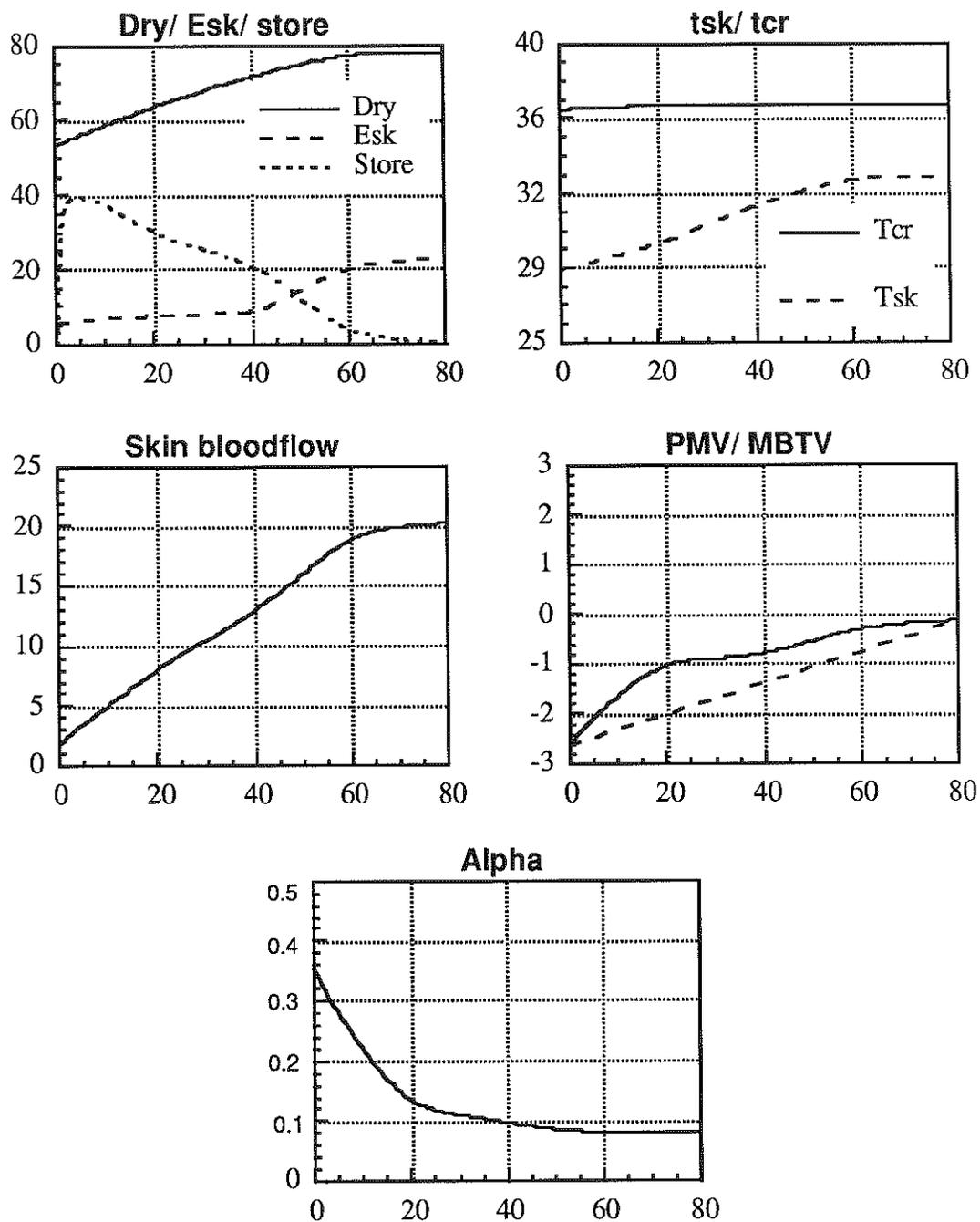
Figure 7.16 Transient Development for a Change of Air Humidity

for 1 met, 1 clo, 90% rh steady state -- 30% rh, 25 C

Dry/ Esk/ store

dry
Esk
Store

tsk/ tcr

Tcr
Tsk

Skin bloodflow

PMV/ MBTV

mbtv
pmv
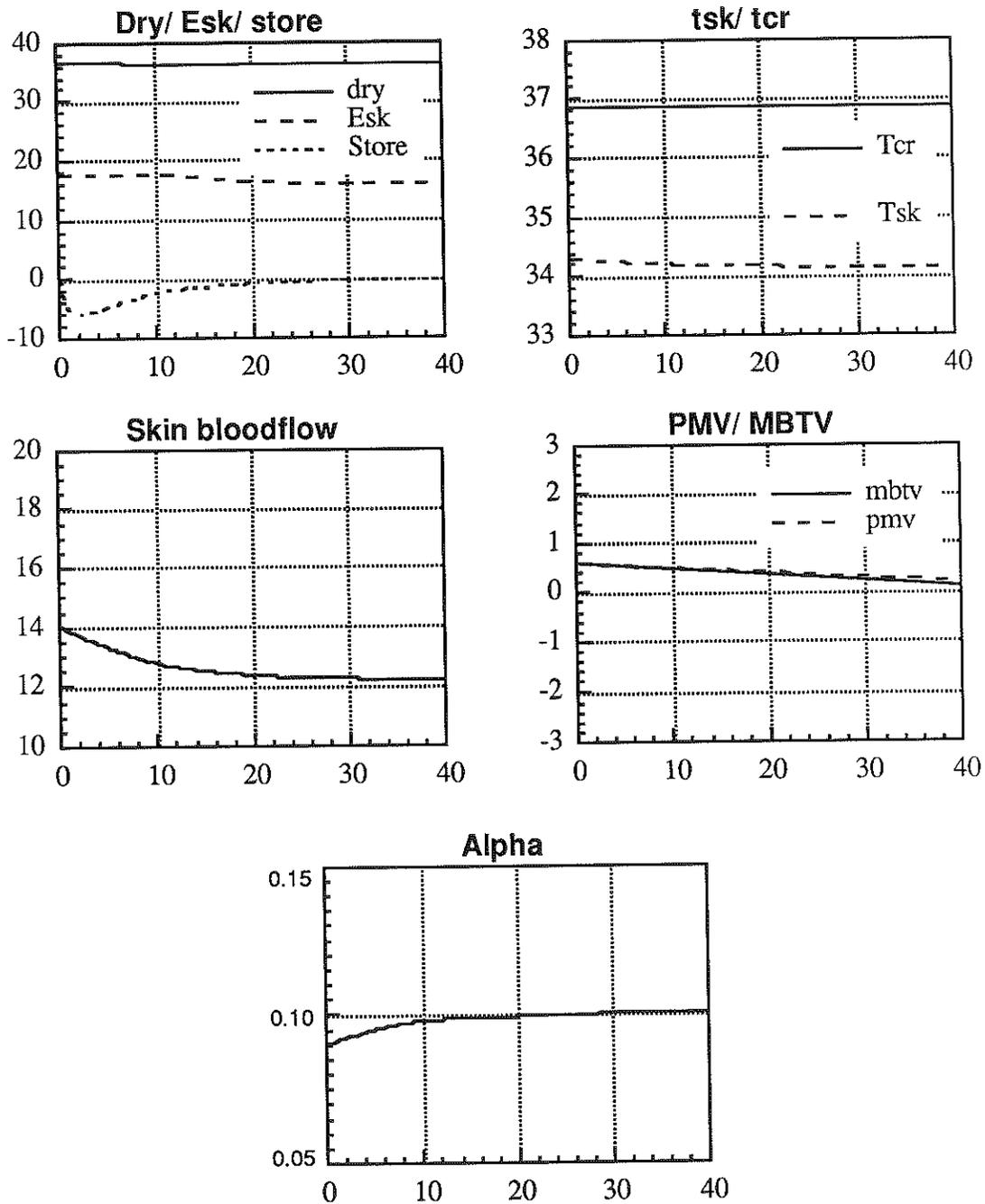
Alpha

the doubling of the amount of clothing (see figure 7.14) this is much more effective with regard to a quick warming up ('store' decreases to zero much faster). t_{sk}, skbf and Dry as well as E_{sk} increase due to the risen amount of produced heat, and alpha decreases.

Figure 7.16 shows the transient development of body state variables for a

significant change of the relative air humidity from 90% to 30% in a slightly too warm environment. This ambient parameter has the least influence on the thermal state as long as the ambient temperature is not too high, since then the body is heavily dependent of an easy evapori-sation of the sweat absorbed. The adjustment in this case is the fastest and the body state variables hardly change at all.

7.2.3   A TRNSYS-Simulation for Transient Developments

The changes in temperature, clothing insulation and metabolism described in the previous section can be combined in a component within TRNSYS. Then for instance the thermal response of a human entering a cold environment, then putting on a thick coat and finally increasing the metabolism can be simulated.   The TRNSYS-'deck' of this simulation can be seen in appendix 4. Excerpts of the resulting data are shown in figure 7.17. The most interesting graph is the transient development of the comfort vote MBTV, which is approaching the steady state PMV value with

a time delay for each new 'environment'. It has however to be remarked

Figure 7.17 Results of a TRNSYS-Simulation with Forcing Functions

Tsk(C)/Alpha(%)

Tsk
Alpha

Time[h]

PMV/MBTV(t)

PMV
MBTV

Time

Forcing Functions

Ta 25   25

Icl 15
        1.5
      0.5   0.5

M   2
        1   1

1   2   3   4   5   6   Time[h]

Predicted Percentage Dissatisfied

Qlat/Qsens(t)

Forcing Functions
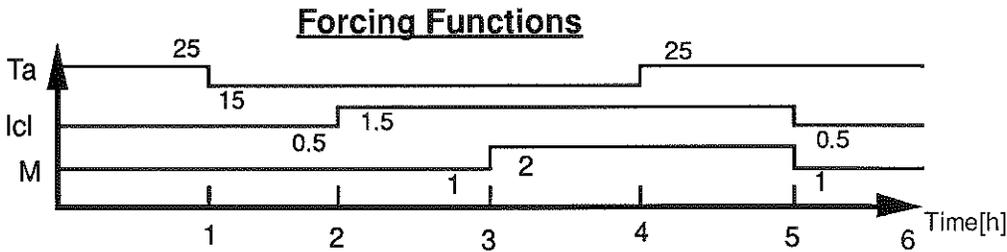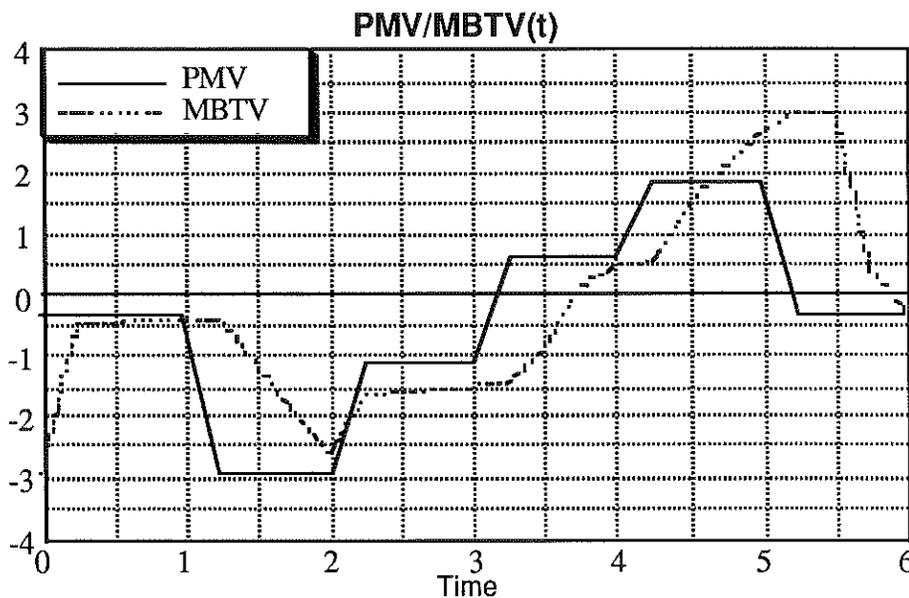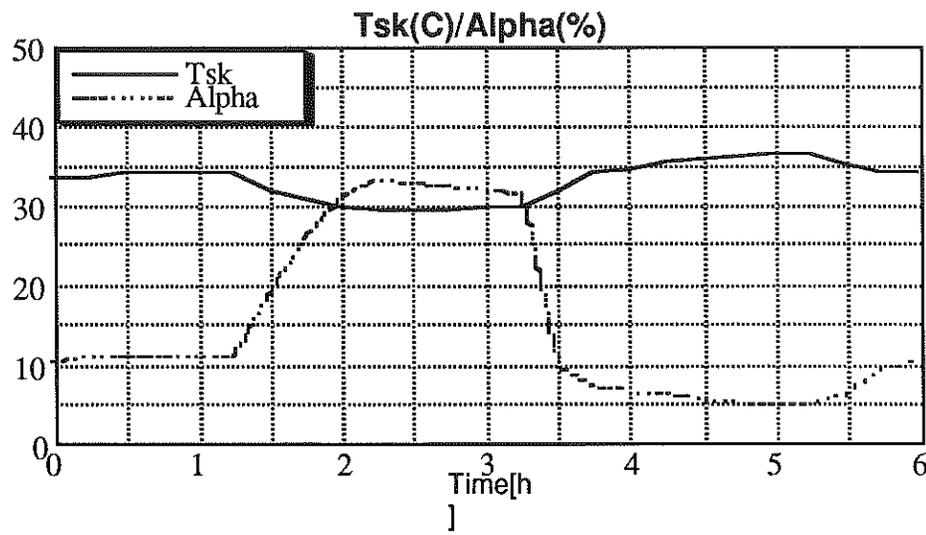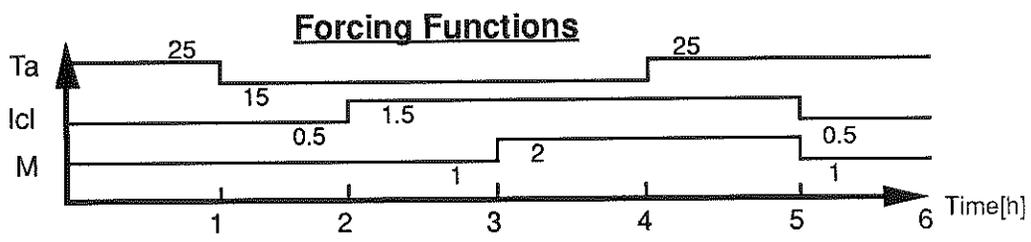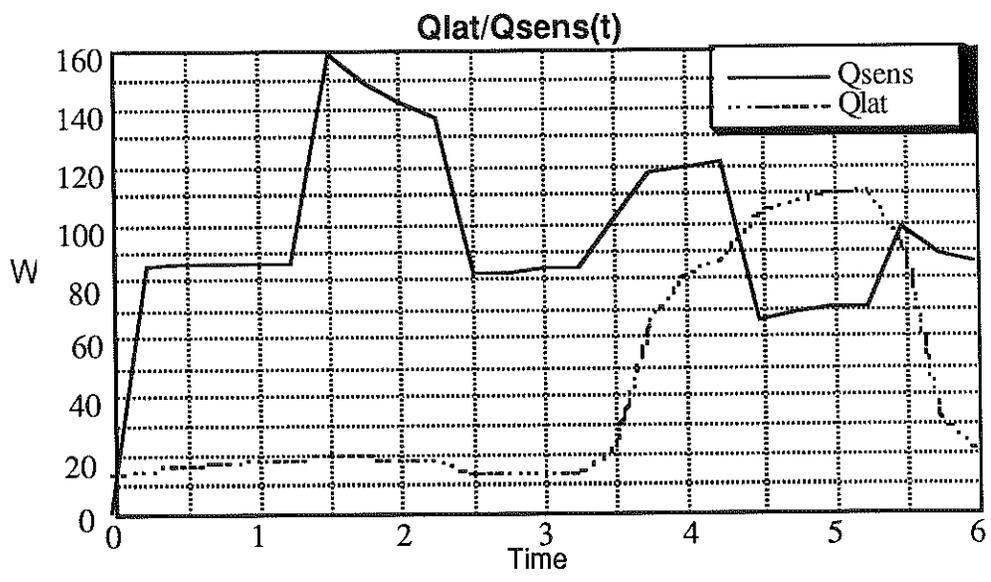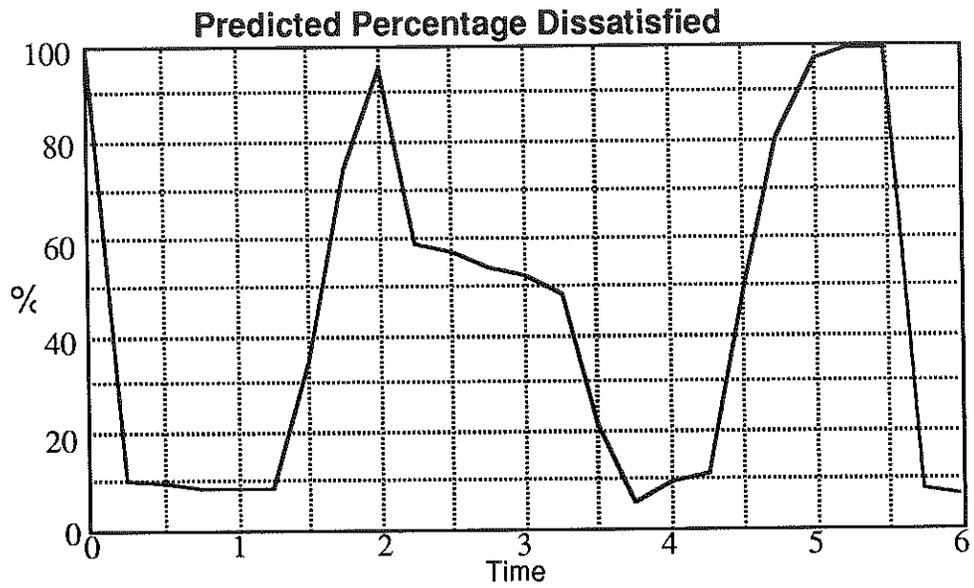
additionally, that the output of the TRNSYS simulation was done in 15-minute-steps. The Predicted Percentage Dissatisfied is directly coupled with the MBTV values and provides an excellent

correlation to the environmental impact. Q_{lat} increases significantly for warm environ-ments due to sweating (hours 3.5 to 5.5) and Q_{sens} is mainly dependent on the ambient temperature; the higher t_o the higher Q_{sens}. It also increases with higher metabolism due to increasing respiratory losses (hours 3.5 to 4.5).

7.2.4   The Limit of Evaporative Heat Loss

The absolute limit of evaporative heat loss is reached, when the whole skin surface is wet. Assuming an evaporation efficiency of eveff = 1.0 for this theoretical upper limit the corresponding mean body temperature can be obtained by calculating t_{bm} for pwet = 1. The results are given in figure 7.18 and can be used to evaluate the danger of failing body cooling.

Figure 7.18   The Limits of Evaporative Heat Loss
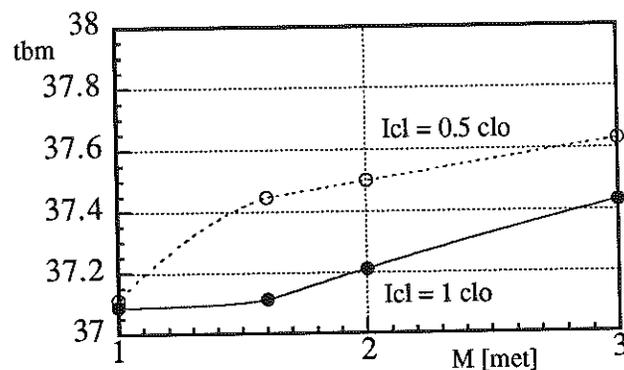
Chapter 8

Individual Influences on the Thermal Perception

8.1 Introduction

No single environment is judged satisfactory by everybody, even if all humans are wearing the same clothing and performing the same activity. As already described in chapter 2.6 there is no ambient condition with less than 5% of the individuals voting 'dissatisfied'. This is due to individual peculiarities in connection with age, adaption and sex, but also influenced by individual tolerances with regard to draft, vertical air temperature differences and asymmetric thermal radiation.

8.2 The Influence of Age

Since the metabolism decreases slightly with age, it could be stated that comfort conditions based on experiments with young and healthy subjects cannot be used for other age groups. However several studies /1, 2/ revealed, that thermal environments preferred by older people do not differ from those

preferred by younger people and that the lower metabolism is compensated by lower evaporative heat loss. However this does not mean they are equally sensitive when exposed to cold or heat. In practice the ambient temperature in homes of elder people is higher, which can be explained by the lower activity since elderly people are sedentary for a greater part of the time.

8.3   The Influence of Adaption

The general opinion is that people can acclimatize themselves by exposure to hot or cold surroundings so that they prefer other thermal environments. However experiments with subjects acclimatized to different world climate zones /1, 2/ revealed only slight differences in preferred ambient temperatures and the other environmental parameters, which indicates that people cannot adapt to preferring warmer or colder environments. However in uncomfortable warm or cold environments, there is an influence of adaption with regard to a heat stress tolerance, since people used to working and living in warm and humid climates can more easily accept and maintain a higher work performance in hot environments than people used to colder climates.

8.4 The Influence of Sex

Experiments by Fanger /1/ show, that men and women prefer almost the same thermal environments. Women's skin temperature and evapo-rative heat loss are slightly lower than those for men, and this balances the somewhat lower metabolism of women. The reason that women often prefer higher ambient temperatures than men is explained by the lighter clothing normally worn by women.

8.5 Other Influencing Environmental Factors

One of the important other influencing factors is draft, which causes an undesired local cooling of the human body. This can be a serious problem in ventilated buildings and many other surroundings. When people sense draught this results in a demand for higher air tempera-tures or stopping the source of the draft. Experiments have revealed, that fluctuating airflow is perceived as more uncomfortable than a constant flow and that especially the head and neck region are very sensitive.

Usually in buildings the air temperature increases with height above the floor; if the gradient is sufficiently large, local cold discomfort can occur at the feet, although the body as a whole is thermally neutral. If however the air temperature at head level is lower than that at ankle level due to for example floor heating and else cold surrounding surfaces, this is not judged as uncomfortable as low temperatures at the ankles.

Asymmetric or nonuniform thermal radiation is usually caused by cold windows, uninsulated walls or cold or warm surfaces in general. Although the mean radiant temperature is taken into account in the presented human model, the asymmetric cases can cause an error, since for instance people are more sensitive to the asymmetry caused by an overhead warm surface than by a vertical cold surface, which has been revealed in experiments /2/.

8.6 Influence of Clothing Asymmetry

Several experiments have been made /7/, whether not only the total amount of clothing insulation is important, but also its distribution over the body surface and whether this has an influence on the preferred ambient temperature. The experiments showed that this asymmetry has no significant influence on thermal perception, so that the standard thermal insulation value Icl obtained for example on a thermal manikin is also valid for very non-uniform distribution over the body.

Chapter 9

Conclusion

The two computer programs given in the present study provide an excellent tool for investigations of the human thermal response to all environmental influences as well as changes in activity and clothing insulation. The HUMAN interactive program provides the possibility of a quick simulation of the human thermal response independent from other considerations like for example the thermal building behavior. Its output represents a very detailed information about all physiological, thermal and comfort quantities.

The 'human thermal response and comfort vote'-component for the modal transient simulation program TRNSYS provides a variety of new simulation possibilities for example in the area of comfort index controlled air-conditioning or for more accurate assessments of the thermal load on buildings due to metabolic heat production and sweat evaporation. This can be very useful for special buildings like for instance sport halls or churches, where the heating could be adjusted in this way, that just at the end of the service a comfort vote of cool is reached - and then the

visitors leave anyway. Finally it opens a whole new field for simulations of more complete systems human - environment.

Appendix 1

The Fortran Codes for Human, Type57, Loop and Index

```
c----------------------------------------------------------------------
c----------TRNSYS Deck Replacement/ Main Routine `HUMAN.FOR'------------
c----------------------------------------------------------------------
c Calls the subroutines TYPE57,LOOP,INDEX as TRNSYS would do; however it
c is easier to handle and provides more complete body state outputs.
c For use in TRNSYS only the subroutines TYPE57 (with activated
c 'call TYPECK' line), LOOP and INDEX have to be linked.

      PROGRAM HUMAN

      dimension xin(8),out(9),par(11),info(10)
      common/store/nstore,iav,s(5000)

      real lr,icl,mb,mbtv,mode
      common/general/act,we,vel,clo,ata,evefo,icl,ta,rh,pa,tr,chco,mode
      common/body/rt,evef,wk,chc,chr,lr,mb,facl,chclo,tcl,Adu
      common/cloop/ eres,cres,dry,regsw,ersw,alpha,edif,pwet,drip,tsk,
     *  tcr,rhsk,tbm,skbf,esk,rm,emax,stroke,store
      common/cindex/pmv,mbtv,ppd

c*********************----Parameters:---*******************************
c-----2:Adu[m2 skinarea], 3:mb[kg body],  4:evefo[0<>1,evaporation effi-
c-----ciency override], 5:[0<>1,efficiency of mass transfer of clothing]
c-----6:chco[W/m2K,override conv.heat trans.coeff.]
c-----initial values:  7:tski[C], 8:tcri[C],  9:alphai[0<>1,mskin/mbody]
c-----10:skbfi[l/m2h,skinbloodflow],    11:eski[W/m2,evap.heat loss skin]
c-----par(1)...'mode' from input

      par(2)=1.8
      par(3)=70.
      par(4)=0.
      Par(5)=0.45
      par(6)=0.
      par(7)=33.7
      par(8)=36.8
      par(9)=0.1
      par(10)=6.3
      par(11)=7.3
c*********************************************************************
      write(*,*)
      write(*,*)'----------------------------------------------------'
      write(*,*)'---------------Program Human.for--------------------'
      write(*,*)'----------------------------------------------------'

 10   write(*,*)'---Inputs:---'
```

```
      write(*,*)  '(Rem.: if time-input<0 then end)'
      info(7)=-1
      info(3)=8
      info(4)=11
      write(*,*)
      write(*,*)  'time(h), step(h), mode(0=steady), Ta(C), Tr(C),
     *act(met)'
      read(*,*) hrs, step, par(1),xin(1),xin(2),xin(3)
      if (hrs.le.0.) goto 200
      write(*,*)' Icl(clo), rh(0<rh<1), vel(m/s), we(0<we<1), Pamb(atm)'
      read(*,*) xin(4), xin(5), xin(6), xin(7), xin(8)
      write(*,*)
      write(*,*)  'calculation mode =',par(1)

      do 100 time=step,hrs,step

          call type57(time,xin,out,t,dtdt,par,info)

          info(7)=info(7)+1
c------------------------------------------------------------------------
c-----Output section
c------------------------------------------------------------------------
      write(*,*)'------------------------------------------------------',
     *'---------------------'
      write(*,'(9a8)') 'PMV:','MBTV:','PPD:','Qsens:','Qlat:',
     *   'Tsk: ','Tcr: ','Tcl: ','Alpha:'
      write(*,'(9f8.3)') out(1),out(2),out(3),out(4),out(5),
     *   out(6),out(7),out(8),out(9)
      write(*,'(9a8)')'-3<>3','-3<>3','  %  ',' W  ',' W  ',' C  ',
     *   ' C  ',' C  ','%msk '
      write(*,*)


      write(*,*) '-------Output additional to TRNSYS:-------',
     *   '---------------'
      if (par(1).lt.0.01) then
          tim=0.0
      else
          tim=time*60.
      endif
              write(*,'(7a8)')'Time','Eres','Edif','Esk ','Cres',
     *   'Dry ','Store'
      write(*,'(7f8.3)') tim,eres,edif,esk,cres,dry,store
      write(*,'(7a8)') 'min ','W/m2 ','W/m2 ','W/m2 ',
     *  'W/m2 ','W/m2 '
      write(*,*)

      write(*,'(7a8)')'Tbm','Ersw','pwet','Emax','hrad','drip',
     *   'skbf'
      write(*,'(7f8.3)') tbm,ersw,pwet,emax,chr,drip,skbf
      write(*,'(7a8)')'C  ','W/m2 ','0<>1 ','W/m2 ','W/m2K',
     *   'g/m2h','1/m2h'
      write(*,*)

      write(*,'(7a8)')'Icl ','rh ','Tr ','Ta ','Work','hconv','Met'
      write(*,'(7f8.3)')clo, rh,tr,ta,wk,chc,rm
      write(*,'(7a8)')'clo ','0<>1 ','C  ','C  ','W/m2 ','W/m2K',
     *   'W/m2 '
```

```
      write(*,*)'----------------------------------------------------',
   *'------------------------'

100   continue

      goto 10

200    continue

      end




********************************************************************

c------------------------------------------------------------------------
c-----Main Subroutine for 2node human response model `TYPE57.FOR'------
c------------------------------------------------------------------------
c Calculates the general ambient parameters, organizes calculation mode
c as well as input-/output-/initial value transfer.


      SUBROUTINE TYPE57(time,xin,out,t,dtdt,par,info)

      real lr,icl,mbtv,mb,mode
      dimension xin(8),out(9),par(11),info(10)

      common/store/nstore,iav,s(5000)

      common/general/act,we,vel,clo,ata,evefo,icl,ta,rh,pa,tr,chco,mode
      common/body/rt,eveff,wk,chc,chr,lr,mb,facl,chclo,tcl,Adu
      common/cloop/ eres,cres,dry,regsw,ersw,alpha,edif,pwet,drip,tsk,
   * tcr,rhsk,tbm,skbf,esk,rm,emax,stroke,store
      common/cindex/pmv,mbtv,ppd

      ta =xin(1)
      tr =xin(2)
      act=xin(3)
      clo=xin(4)
      rh =xin(5)
      vel=xin(6)
      we =xin(7)
      ata=xin(8)

      mode  =par(1)
      Adu   =par(2)
      mb    =par(3)
      evefo =par(4)
      icl   =par(5)
      chco  =par(6)

      if(info(7).eq.(-1))then
c-----for first run - initial values for body regulation loop
      tsk  =par(7)
      tcr  =par(8)
      alpha=par(9)
```

```
            skbf =par(10)
            esk  =par(11)
            timold=0.
            stroke=0.
            rm=act*58.2
            wk=we*rm

         else
c-----else takeover of previous values for body regulation loop
            j=info(10)
            tsk  =s(j)
            tcr  =s(j+1)
            alpha=s(j+2)
            skbf =s(j+3)
            esk  =s(j+4)
            rm   =s(j+5)
            timold=s(j+6)
         endif


c-------------------------------------------------------------------
c-----calculation of initial and general variables
c-------------------------------------------------------------------
         pa=rh*exp(16.6536-4030.183/(ta+235.))
         facl=1.+0.25*clo
         lr=16.5
         if(ata.gt.0.) lr=16.5/ata

c------Calculation of clothing insulation (W/m2K):
         chclo=1.e5
         if (clo.gt.0.) chclo=1./(0.155*clo)

c------Calculation of evaporative efficiency:
         if(vel.le.0.) vel=1E-3
         if(clo.le.0.)then
            eveff=0.38*vel**(-0.29)
            icl=1.
         else
            eveff=0.59*vel**(-0.08)
         endif
         if (evefo.gt.0.) eveff=evefo

c------Calculation of convective heat transfer coefficients:
         chca=0.
c        walking in still air:
         if(ata.le.0.) ata=1.E-3
         if (act.gt.0.85) chca=5.66*((act-0.85)*ata)**0.39
c        room air movement:
         chcv=8.6*(vel*ata)**0.53
         chc=max(chca,chcv)
         if(chc.lt.(3.*ata)**0.53) chc=(3.*ata)**0.53
c        override by input
         if(chco.gt.0.) chc=chco

c------initial estimations:
         chr=4.7
         tcl=(chclo*tsk+facl*(chc*ta+chr*tr))/(chclo+facl*(chc+chr))
```

```
c-------------------------------------------------------------------
c------either transient(mode<>0) or steady state(mode=0) calculation
c-------------------------------------------------------------------
      if (mode.ne.0.)then
          t=(time-timold)*60.
          do 100 l=1,int(t+0.5)
          call loop
 100      continue
      else
          do 200 n=1,1440
          call loop
            if(abs(store).le.0.1) goto 300
 200      continue
          write(*,*)'No steady state within 24h-iteration reached'
      endif

 300      continue
      call index

c-----Assignment of space in TRNSYS S-array (doesn't affect 'Human'-use)
      if (info(7).eq.(-1)) then
          info(10)=7
          ni=info(3)
          np=info(4)
*erase asterix for TRNSYS-use in 1.column of 'call':
*         call typeck(1,info,ni,np,0)
      endif

      i=info(10)

      s(i)  =tsk
      s(i+1)=tcr
      s(i+2)=alpha
      s(i+3)=skbf
      s(i+4)=esk
      s(i+5)=rm
      s(i+6)=time

      qsens=(dry+cres)*Adu
      qlat =(esk+eres)*Adu
      out(1)=pmv
      out(2)=mbtv
      out(3)=ppd
      out(4)=qsens
      out(5)=qlat
      out(6)=tsk
      out(7)=tcr
      out(8)=tcl
      out(9)=alpha*100.

      if(stroke.eq.1.) then
        Write(*,*)'Heatstroke occurred due to core temperature',
     *' >42.0C; now act=1.0met!!'
        stroke=0.
      endif

      if(tcr.lt.31.) write(*,*)'Lethal danger due to core tem',
```

```
*'perature below 31C'

      return
      end
```

```
c  ----------------------------------------------------------------
c  Simulation of Body Temperature Regulation "LOOP.FOR"
c  ----------------------------------------------------------------
c Performs minute by minute temperature regulation using physiological
c data from previous time step and current environmental conditions.
c Variables in common block LOOP are computed in this routine.
c  ----------------------------------------------------------------

      SUBROUTINE LOOP

      real lr,icl,mbtv,mb,mode
      common/general/act,we,vel,clo,ata,evefo,icl,ta,rh,pa,tr,chco,mode
      common/body/rt,eveff,wk,chc,chr,lr,mb,facl,chclo,tcl,Adu
      common/cloop/eres,cres,dry,regsw,ersw,alpha,edif,pwet,drip,tsk,
     *  tcr,rhsk,tbm,skbf,esk,rm,emax,stroke,store
      common/cindex/pmv,mbtv,ppd

c-----Dry heat balance: iterative solution for tcl and chr
 20   tclold=tcl
      chr=4.*0.72*5.67e-8*((tcl+tr)/2+273.15)**3
      tcl=(chclo*tsk+facl*(chc*ta+chr*tr))/(chclo+facl*(chc+chr))
      if(abs(tcl-tclold).gt.0.01) goto 20

c-----Heat flow from clothing surface to environment
      dry=facl*(chc*(tcl-ta)+chr*(tcl-tr))

c-----Dry and latent respiratory heat losses according to Fanger
      eres=0.0173*rm*(5.8662-pa)
      cres=0.0014*rm*(34.-ta)*ata

c-----Heat flows to skin and core (W/m2)
      hfsk=(tcr-tsk)*(5.28+1.163*skbf)-dry-esk
      hfcr=rm-(tcr-tsk)*(5.28+1.163*skbf)-cres-eres-wk

c-----Thermal capacities:
c-----58.2 W.min/(kg.K). Therm. capacities (TCCR, TCSK) in W.min/K
      tccr=58.2*(1.-alpha)*mb
      tcsk=58.2*alpha*mb

c-----Temperature changes [K/min]:
      dtsk=(hfsk*Adu)/tcsk
      dtcr=(hfcr*Adu)/tccr
      tsk=tsk+dtsk
      tcr=tcr+dtcr
```

```
c-------------------------------------------------------------------
c-----Definition of control signals for physiological temperature
c-----regulation.
c-------------------------------------------------------------------
c-----TTCR, TTSK, and TTBM are standard set points for core, skin and
c-----average body temperatures corresponding to physiol. neutrality
c-----Typical values for TTCR, and TTSK are 36.8, and 33.7
c-----bsn is the stand. ratio of skin mass to total body mass, bsn=0.1
c-----ALPHA is the actual ratio of skin mass to total body mass
c-----Constants for vasodilation :      cdil = 200 kg/(m2.hr.K)
c-----               vasoconstriction : cstr = 0.1 dimensionless
c-----               reg. sweating  :    csw = 170 g/(m2.hr)
c-----               shivering:         cshiv = 19.4 dimensionless
c-----6.3 kg/(m2.hr) is normal skin blood flow in the absence
c-----of any thermoregulatory vascular control;
c-----max. skin blood flow :          skbfm = 90 kg/(m2.hr)
c-----maximum sweating rate :.        regswm = 500 g/m2.hr
c-------------------------------------------------------------------
c-----Physiological setpoints and parameters:
      ttsk   =33.7
      ttcr   =36.8
      csw    =170.
      cstr   =0.5
      cdil   =200.
      bsn    =0.1
      skbfm  =90.
      rgswm  =500.
      cshiv  =19.4

c-----Calculation of vascular control signals:
      if(tsk.gt.ttsk) then
         warms=tsk-ttsk
         colds=0.
      else
         colds=ttsk-tsk
         warms=0.
      endif

      if(tcr.gt.ttcr) then
         warmc=tcr-ttcr
         coldc=0.
      else
         coldc=ttcr-tcr
         warmc=0.
      endif

      ttbm=bsn*ttsk+(1.-bsn)*ttcr
      tbm=alpha*tsk+(1.-alpha)*tcr
      if(tbm.gt.ttbm) then
         warmb=tbm-ttbm
         coldb=0.
      else
         coldb=ttbm-tbm
         warmb=0.
      endif
```

```
c---------------------------------------------------------------------
c-----Physiological temperature regulation
c---------------------------------------------------------------------
c-----Control of skin blood flow
      dilat=cdil*warmc
      stric=cstr*colds
      skbf=(6.3+dilat)/(1.+stric)

c-----skbf is never below 0.5 kg/(m2.hr) nor above skbfm
      if(skbf.lt.0.5) skbf=0.5
      if(skbf.gt.skbfm) skbf=skbfm

c-----Ratio of skin-core masses changes with skbf
      alpha=0.04178+0.7455/(skbf+0.5854)

c-----Control of regulatory sweating.[regsw in gr./m2.hr]
      regsw=csw*warmb*exp(warms/10.7)
      if(regsw.gt.rgswm) regsw=rgswm
      ersw=0.68*regsw

c-----Adjustment of metabolic heat due to shivering
      rmsh=cshiv*colds*coldc
c       Limitation of shivering to 200 W/m2
      if(rmsh.gt.200.) rmsh=200.
      rm=act*58.2+rmsh

c-----Heatstroke occurs for tcr>42C,then rm=58.2;act=1
      if(tcr.gt.42.)then
          rm=58.2
          wk=0.
          act=1.
          stroke=1.
      endif


c---------------------------------------------------------------------
c-----Evaluation of heat transfer by evaporation at skin surface.
c-----(rt is total vapor resistance of clothing + air layer)
c---------------------------------------------------------------------
      rt=(1./lr)*(1./(facl*chc)+1./(chclo*icl))
      pssk=exp(16.6536-4030.183/(tsk+235.))
      emax=(1./rt)*(pssk-pa)
      prsw=ersw/emax

c-----0.06 is pdif for nonsweating skin
      pdif=(1.-prsw)*0.06
      edif=pdif*emax
      esk=ersw+edif
      pwet=esk/emax

c-----Beginning of dripping (Fraction of sweat not evaporated)
      if((pwet.ge.eveff).and.(emax.ge.0.)) then
          pwet=eveff
          prsw=(eveff-0.06)/0.94
          ersw=prsw*emax
          pdif=(1.-prsw)*0.06
          edif=pdif*emax
          esk=ersw+edif
```

```
          endif

c-----When emax<0 condensation on skin occurs
          if(emax.lt.0.) then
              pdif=0.
              edif=0.
              esk=emax
              pwet=eveff
              prsw=eveff
              ersw=0.
          endif

c-----drip = unevaporated sweat in air
          drip=(regsw*0.68-prsw*emax)/0.68
          if(drip.lt.0.) drip=0.

c-----store is used as loop-stop criterium in type57 for 'steady' mode
          store=rm-wk-eres-cres-dry-esk

          return
          end
```

```
====================================================================
********************************************************************


c--------------------------------------------------------------------
c-----Comfort Indices PMV and MBTV --- Subroutine`Index.for'
c--------------------------------------------------------------------

          SUBROUTINE INDEX

          real mbtv,num,load,mneg,mpos,lr,icl,mb,mode
          common/general/act,we,vel,clo,ata,evefo,icl,ta,rh,pa,tr,chco,mode
          common/body/ rt,eveff,wk,chc,chr,lr,mb,facl,chclo,tcl,Adu
          common/cloop/eres,cres,dry,regsw,ersw,alpha,edif,pwet,drip,tsk,
        * tcr,rhsk,tbm,skbf,esk,rm,emax,stroke,store
          common/cindex/pmv,mbtv,ppd

c--------------------------------------------------------------------
c-----Calculation of Fangers Predicted Mean Vote PMV
c--------------------------------------------------------------------
c-----Fangers faclf surface factor:
          if(clo.le.0.5) faclf=1.+0.2*clo
          if(clo.gt.0.5) faclf=1.05+0.1*clo

  30      continue
c-----Fangers convective heat trans. coeff.:
          conv=0.
          if((tclf-ta).gt.0.) conv=2.38*(tclf-ta)**(0.25)
          wind=0.
          if(vel.gt.0.) wind=12.1*sqrt(vel)
          chcf=max(conv,wind)
          if(chcf.eq.0.) chcf=1E-6
```

```
c-----Fangers tclf at comfort condition by Newton iteration:
      tclf=tcl
      rn=act*58.2
      if (clo.eq.0.) clo=1E-6
      num=(35.7-0.0275*(rn-wk)-tclf)/(0.155*clo*faclf*chcf)-3.954E-8
     * *((tclf+273.15)**4-(ta+273.15)**4)/chcf+ta-tclf
      den=1./(0.155*clo*faclf*chcf)+15.82E-8/chcf*(tclf+273.15)**3+1.
      if(den.ne.0.) tclf=tclf+num/den
      if(den.eq.0.) tclf=tclf+0.1
        if (abs(tclf-tclfo).le.0.01) goto 50
        tclfo=tclf
      goto 30
 50      continue

c-----Fangers dry heat loss:
      dryf=1.163*3.4E-8*faclf*((tclf+273.15)**4-(tr+273.15)**4)+faclf*
     * chcf*(tclf-ta)

c-----Fangers diffusive heat loss ediffg:
      ediffg=3.05*(5.733-0.00699*rn-pa)

c-----Fangers evaporative skin heat loss at comfort condition:
      ecomf=(rn-wk-58.2)*0.42
      if(ecomf.lt.0.) ecomf=0.

c-----Fangers respiration heat exchange:
      eresf=.0173*rn*(5.8662-pa)
      cresf=.0014*rn*(34.-ta)*ata

c-----Predicted Mean Vote PMV calculated as a function of the heat
c-----transfer load exceeding ecomf of skin:
      load=rn-wk-ediffg-ecomf-eresf-cresf-dryf
      pmv=(0.303*exp(-0.036*act*58.2)+0.028)*load
      if(pmv.gt.3.) pmv=3.
      if(pmv.lt.(-3)) pmv=-3.

c--------------------------------------------------------------------
c-----Calculation of the Mean Body Temperature Vote MBTV
c--------------------------------------------------------------------
c----- This is an approximation for PMV especially for transient deve-
c----- lopments,whereas PMV is defined only for stationary body states.
c----- It is based on correlations between PMV and the mean body temp.
c----- tbm. The highest accuracy +/-0.07 is given in the interval
c----- 0.5<MBTV <+0.5; else +/-0.1

      actn=act-wk/58.2
      point=-0.45-0.25*clo*(actn-1.)
      mpos=41.2-54.21*actn+31.48*actn**2-8.29*actn**3+0.83*actn**4-0.6*
     * clo
      mneg=6.77-11.33*actn+8.32*actn**2-2.64*actn**3+0.31*actn**4-0.6*
     * clo

c-----tbm=36.5 is the setpoint mean body temp. of the Gagge model
      if(tbm.lt.36.5) mbtv=point-mneg*(36.5-tbm)
      if(tbm.ge.36.5) mbtv=point+mpos*(tbm-36.5)
      if(mbtv.gt.3.) mbtv=3.
      if(mbtv.lt.(-3.)) mbtv=-3.
```

```
c-----------------------------------------------------------------
c------Calculation of PPD..Predicted Percentage Dissatisfied
c-----------------------------------------------------------------
c-----Calculation with PMV for steady state mode, else with mbtv
      if(abs(mode).lt.0.01) then
          vote=pmv
      else
          vote=mbtv
      endif
      ppd=100.-95.*exp(-0.03353*vote**4-0.2179*vote**2)

      return

      end
```

Appendix 2

Input/ Output of the Interactive Simulation Program HUMAN:

```
RAIMUND> run human


--------------------------------------------------
----------------Program Human.for--------------------
--------------------------------------------------
---Inputs:---
(Rem.: if time-input<0 then end)

time(h), step(h), mode(0=steady), Ta(C), Tr(C), act(met)
1,1,1,25,25,1

 Icl(clo), rh(0<rh<1), vel(m/s), we(0<we<1), Pamb(atm)
1,.6,.2,.01,1


calculation mode =   1.000
-------------------------------------------------------------------
   PMV:    MBTV:     PPD:  Qsens:   Qlat:    Tsk:     Tcr:    Tcl:   Alpha:
  0.341   0.407    8.449  66.711  36.954  34.232   36.833  28.601   9.691
  -3<>3   -3<>3      %       W       W       C        C       C      %msk

-------Output additional to TRNSYS:---------------------
   Time    Eres    Edif    Esk     Cres    Dry     Store
 60.000   3.993   5.474  16.537   0.733  36.328   0.027
   min    W/m2    W/m2    W/m2    W/m2    W/m2    W/m2

    Tbm    Ersw    pwet    Emax    hrad    drip    skbf
 36.581  11.063   0.162 102.294   4.407   0.000  12.938
    C     W/m2    0<>1    W/m2    W/m2K   g/m2h   1/m2h

    Icl     rh      Tr      Ta     Work   hconv    Met
  1.000   0.600  25.000  25.000   0.582   3.665  58.200
   clo    0<>1     C       C      W/m2    W/m2K   W/m2
-------------------------------------------------------------------
```

Appendix 3

The TRNSYS Deck for the Basic Human Model Simulation

```
                TRNSYS - A TRANSIENT SIMULATION PROGRAM
        FROM THE SOLAR ENERGY LAB AT THE UNIVERSITY OF WISCONSIN
                      VERSION  13.1    LATE 1990

*------------------------------------------------------------------
 Simulation  0  2  0.5
*------------------------------------------------------------------

*if times are changed, don't forget to change printtimes too!

 Assign trnsys.out          6
 Width        72

 Constants 8
 ta=25  tr=25  act=1  Icl=1  rh=0.9  vel=0.2  we=0.01  Pamb=1


*------------------------------------------------------------------
 Unit 1  Type 57            Human
*------------------------------------------------------------------
      Parameters  11
      1.0    1.8  70.0   0.0    0.45 0.0    33.7  36.8  0.1
      6.3    7.3
*     mode  Adu  mbody  evefo  icl  chco  Tski  Tcri  Alphai
*     skbfi  eski
*     For mode=0 in each step iteration until steady state
*     evefo is override for evaporation efficiency of clothing
*     chco is override for conv. heat transfer coefficient
*     The index i means initial value for body loop

      Inputs  8
      ta      tr    act    icl    rh    vel     we     pamb
      24.0    24.0  1.0    1.0    0.5   0.2     0.01   1.0


*------------------------------------------------------------------
 Unit 2  Type 25            Printer
*------------------------------------------------------------------
      Parameters  4
      0.5    0.0    2.0  -6
*     step   begin  end  fileunit

 format
 (9(f8.3))
```

```
Inputs  9
1,1   1,2   1,3   1,4   1,5   1,6   1,7   1,8   1,9
PMV   MBTV  PPD   Qsens Qlat  Tsk   Tcr   Tcl   alpha
```

```
END
```
_____

Appendix 4

The TRNSYS deck and results for a human model simulation with forcing functions for ambient temperature, metabolism and clothing insulation.

_____


```
               TRNSYS - A TRANSIENT SIMULATION PROGRAM
         FROM THE SOLAR ENERGY LAB AT THE UNIVERSITY OF WISCONSIN
                      VERSION 13.1   LATE 1990


*-------------------------------------------------------------------

  SIMULATION         0.000E+00    6.000E+00    2.500E-01
*-------------------------------------------------------------------
*if times are changed, don't forget to change them in printer and
*forcingfunctions too !!!

  ASSIGN  HUMAN.OUT             6

  WIDTH    72

  CONSTANTS  4
       RH    = 9.000E-01      VEL   = 2.000E-01
       WE    = 1.000E-02      PAMB  = 1.000E+00


*-------------------------------------------------------------------

  UNIT  1     TYPE 57     Human
*-------------------------------------------------------------------
       PARAMETERS  11
       1.000E+00   1.800E+00   7.000E+01   0.000E+00   4.500E-01
       0.000E+00   3.370E+01   3.680E+01   1.000E-01   6.300E+00
       7.300E+00
*      mode Adu  mbody  evefo  icl  chco  Tski  Tcri  Alphai
*      skbfi  eski

*      For mode=0 in each step iteration until steady state
*      evefo is override for evaporation efficiency of clothing
*      chco is override for conv. heat transfer coefficient
*      The index i means initial value for body loop

       INPUTS   8
```

```
         3,1              3,1              5,1              4,1              RH
         VEL              WE               PAMB
         2.500E+01        2.500E+01        1.000E+00        5.000E-01        5.000E-01
         2.000E-01        1.000E-02        1.000E+00
*        Ta      Tr     Act    Icl    rh
*        vel     we     pamb


*------------------------------------------------------------------------

 UNIT  2      TYPE 25       Printer
*------------------------------------------------------------------------
         PARAMETERS   4
         2.500E-01        0.000E+00        6.000E+00       -6.000E+00
*        step  begin   end   fileunit

         FORMAT
          (9(f8.3))

         INPUTS   9
         1,1              1,2              1,3              1,4              1,5
         1,6              1,7              1,8              1,9
         PMV              MBTV             PPD              QSENS            QLAT
         TSK              TCR              TCL              ALPHA


*------------------------------------------------------------------------

 UNIT  3      TYPE 14       Temperature forcing function
*------------------------------------------------------------------------
         PARAMETERS   12
         0.000E+00        2.500E+01        1.000E+00        2.500E+01        1.000E+00
         1.500E+01        4.000E+00        1.500E+01        4.000E+00        2.500E+01
         6.000E+00        2.500E+01
*(parameters describe timestep and value)


*------------------------------------------------------------------------

 UNIT  4      TYPE 14       Clothing forcing function
*------------------------------------------------------------------------
         PARAMETERS   12
         0.000E+00        5.000E-01        2.000E+00        5.000E-01        2.000E+00
         1.500E+00        5.000E+00        1.500E+00        5.000E+00        5.000E-01
         6.000E+00        5.000E-01


*------------------------------------------------------------------------

 UNIT  5      TYPE 14       Activity forcing function
*------------------------------------------------------------------------
         PARAMETERS   12
         0.000E+00        1.000E+00        3.000E+00        1.000E+00        3.000E+00
         2.000E+00        5.000E+00        2.000E+00        5.000E+00        1.000E+00
         6.000E+00        1.000E+00


*------------------------------------------------------------------------

 END
*------------------------------------------------------------------------
```

```
      TRANSIENT SIMULATION       STARTING AT TIME =   0.000E+00
                                 STOPPING AT TIME =   6.000E+00
                                         TIMESTEP =     1/4
               DIFFERENTIAL EQUATION ERROR TOLERANCE =   1.000E-02
                    ALGEBRAIC CONVERGENCE TOLERANCE =   1.000E-02
      DIFFERENTIAL EQUATIONS SOLVED BY MODIFIED EULER
```

```
                    TIME  =    0.0000
      PMV            MBTV            PPD            QSENS          QLAT
  -3.541E-01     -3.000E+00      9.912E+01      0.000E+00      1.314E+01
      TSK            TCR             TCL            ALPHA
   3.370E+01      3.680E+01       3.003E+01      1.000E+01
```

```
                    TIME  =    0.2500
      PMV            MBTV            PPD            QSENS          QLAT
  -3.541E-01     -4.765E-01      9.742E+00      8.456E+01      1.489E+01
      TSK            TCR             TCL            ALPHA
   3.369E+01      3.682E+01       3.008E+01      1.097E+01
```

```
                    TIME  =    0.5000
      PMV            MBTV            PPD            QSENS          QLAT
  -3.541E-01     -4.529E-01      9.281E+00      8.559E+01      1.626E+01
      TSK            TCR             TCL            ALPHA
   3.379E+01      3.682E+01       3.015E+01      1.073E+01
```

```
                    TIME  =    0.7500
      PMV            MBTV            PPD            QSENS          QLAT
  -3.541E-01     -4.182E-01      8.647E+00      8.585E+01      1.758E+01
      TSK            TCR             TCL            ALPHA
   3.381E+01      3.682E+01       3.016E+01      1.063E+01
```

```
                    TIME  =    1.0000
      PMV            MBTV            PPD            QSENS          QLAT
  -3.541E-01     -4.074E-01      8.460E+00      8.589E+01      1.778E+01
      TSK            TCR             TCL            ALPHA
   3.381E+01      3.682E+01       3.016E+01      1.062E+01
```

```
                    TIME  =    1.2500
      PMV            MBTV            PPD            QSENS          QLAT
  -3.000E+00     -4.058E-01      8.432E+00      8.589E+01      1.781E+01
      TSK            TCR             TCL            ALPHA
   3.381E+01      3.682E+01       2.588E+01      1.061E+01
```

```
                    TIME  =    1.5000
      PMV            MBTV            PPD            QSENS          QLAT
  -3.000E+00     -1.189E+00      3.469E+01      1.596E+02      2.016E+01
      TSK            TCR             TCL            ALPHA
   3.165E+01      3.681E+01       2.498E+01      1.910E+01
```

```
                    TIME  =    1.7500
      PMV            MBTV            PPD            QSENS          QLAT
  -3.000E+00     -1.952E+00      7.455E+01      1.486E+02      1.893E+01
      TSK            TCR             TCL            ALPHA
   3.054E+01      3.680E+01       2.430E+01      2.629E+01
```

```
                    TIME  =    2.0000
      PMV            MBTV            PPD            QSENS          QLAT
```

```
-3.000E+00    -2.621E+00     9.562E+01     1.415E+02     1.818E+01
     TSK           TCR           TCL          ALPHA
  2.980E+01     3.680E+01     2.386E+01     3.155E+01
```

```
                    TIME  =      2.2500
      PMV           MBTV          PPD          QSENS         QLAT
  -1.101E+00    -1.659E+00     5.953E+01     1.364E+02     1.782E+01
     TSK           TCR           TCL          ALPHA
  2.927E+01     3.678E+01     1.888E+01     3.347E+01
```

```
                    TIME  =      2.5000
      PMV           MBTV          PPD          QSENS         QLAT
  -1.100E+00    -1.613E+00     5.705E+01     8.184E+01     1.348E+01
     TSK           TCR           TCL          ALPHA
  2.944E+01     3.676E+01     1.919E+01     3.285E+01
```

```
                    TIME  =      2.7500
      PMV           MBTV          PPD          QSENS         QLAT
  -1.100E+00    -1.564E+00     5.441E+01     8.269E+01     1.357E+01
     TSK           TCR           TCL          ALPHA
  2.959E+01     3.676E+01     1.923E+01     3.231E+01
```

```
                    TIME  =      3.0000
      PMV           MBTV          PPD          QSENS         QLAT
  -1.100E+00    -1.522E+00     5.208E+01     8.341E+01     1.361E+01
     TSK           TCR           TCL          ALPHA
  2.973E+01     3.677E+01     1.927E+01     3.183E+01
```

```
                    TIME  =      3.2500
      PMV           MBTV          PPD          QSENS         QLAT
   5.906E-01    -1.448E+00     4.806E+01     8.402E+01     1.362E+01
     TSK           TCR           TCL          ALPHA
  2.984E+01     3.677E+01     1.836E+01     3.142E+01
```

```
                    TIME  =      3.5000
      PMV           MBTV          PPD          QSENS         QLAT
   5.914E-01    -8.668E-01     2.086E+01     1.017E+02     2.216E+01
     TSK           TCR           TCL          ALPHA
  3.164E+01     3.690E+01     1.893E+01     9.867E+00
```

```
                    TIME  =      3.7500
      PMV           MBTV          PPD          QSENS         QLAT
   5.918E-01     1.354E-01     5.380E+00     1.170E+02     6.676E+01
     TSK           TCR           TCL          ALPHA
  3.409E+01     3.690E+01     1.954E+01     6.982E+00
```

```
                    TIME  =      4.0000
      PMV           MBTV          PPD          QSENS         QLAT
   5.918E-01     4.505E-01     9.235E+00     1.195E+02     8.248E+01
     TSK           TCR           TCL          ALPHA
  3.446E+01     3.693E+01     1.964E+01     6.490E+00
```

```
                    TIME  =      4.2500
      PMV           MBTV          PPD          QSENS         QLAT
   1.829E+00     5.321E-01     1.092E+01     1.200E+02     8.666E+01
```

```
        TSK            TCR            TCL           ALPHA
     3.455E+01      3.694E+01      2.716E+01      6.371E+00




                       TIME  =      4.5000
        PMV            MBTV           PPD           QSENS          QLAT
     1.829E+00      1.452E+00      4.828E+01      6.586E+01      1.032E+02
        TSK            TCR            TCL           ALPHA
     3.574E+01      3.705E+01      2.748E+01      5.492E+00




                       TIME  =      4.7500
        PMV            MBTV           PPD           QSENS          QLAT
     1.829E+00      2.096E+00      8.090E+01      6.866E+01      1.078E+02
        TSK            TCR            TCL           ALPHA
     3.619E+01      3.716E+01      2.759E+01      5.119E+00


                       TIME  =      5.0000
        PMV            MBTV           PPD           QSENS          QLAT
     1.829E+00      2.625E+00      9.570E+01      7.007E+01      1.101E+02
        TSK            TCR            TCL           ALPHA
     3.641E+01      3.727E+01      2.764E+01      5.000E+00


                       TIME  =      5.2500
        PMV            MBTV           PPD           QSENS          QLAT
    -3.561E-01      3.000E+00      9.912E+01      7.063E+01      1.110E+02
        TSK            TCR            TCL           ALPHA
     3.650E+01      3.737E+01      3.165E+01      5.000E+00


                       TIME  =      5.5000
        PMV            MBTV           PPD           QSENS          QLAT
    -3.547E-01      3.000E+00      9.912E+01      9.852E+01      9.123E+01
        TSK            TCR            TCL           ALPHA
     3.502E+01      3.694E+01      3.092E+01      6.266E+00


                       TIME  =      5.7500
        PMV            MBTV           PPD           QSENS          QLAT
    -3.541E-01      3.688E-01      7.832E+00      8.862E+01      3.265E+01
        TSK            TCR            TCL           ALPHA
     3.406E+01      3.684E+01      3.033E+01      9.517E+00


                       TIME  =      6.0000
        PMV            MBTV           PPD           QSENS          QLAT
    -3.541E-01     -2.877E-01      6.719E+00      8.632E+01      2.003E+01
        TSK            TCR            TCL           ALPHA
     3.385E+01      3.682E+01      3.019E+01      1.045E+01




              UNIT   1 WAS CALLED      31 TIMES
                     2                 25
                     3                 26
                     4                 26
                     5                 26
```

Nomenclature

Symbol	Unit	Description
A_{cl}	m2	Clothing surface area
act	met	Activity/Metabolism (1met = 58.2 W/m2)
A_{Du}	m2	Dubois body surface area
alpha	-	Ratio of skin mass to body mass
alphai	-	Initial alpha
ata	bar	Ambient air pressure
bsn	-	Standard alpha ratio
C	W/m2	Convective skin heat loss
cdil	kg/m2hK	Vasodilation constant
chc	W/m2K	Convective heat transfer coefficient
chco	W/m2K	Override input value for chc
chclo	W/m2K	Heat conductivity of clothing
clo	clo	Intrinsic clothing insulation Icl
coldcr	C	Cold signal from core
coldsk	C	Cold signal from skin
C_{res}	W/m2	Respiration sensible heat loss
cshiv	-	Shivering constant
cstr	-	Vasoconstriction constant
csw	g/m2h	Sweating constant
dilat	-	Vasodilation

drip	g/m2h	Amount of unevaporated sweat
Dry	W/m2	Total sensible heat loss
E_{diff}	W/m2	Evaporative skin heat loss by diffusion
E_{max}	W/m2	Evaporative heat loss potential
E_{res}	W/m2	Evaporative respiration heat loss
E_{rsw}	W/m2	Evaporative heat loss by regulative sweating
E_{sk}	W/m2	Total evaporative skin heat loss
Eski	W/m2	Initial E_{sk}
E_{sw}	W/m2	Sweat evaporation heat loss
eveff	-	Evaporation efficiency of clothing
evefo	-	Override input value for eveff
fcl	-	Clothing area increasing factor
facl	-	Clothing area increasing factor in program
h	W/m2K	Total heat transfer coefficient
h_e	W/m2Pa	Evaporative heat transfer coefficient
h_c	W/m2K	Convective heat transfer coefficient
hfcr	W/m2	Heat flow to core compartment
hfsk	W/m2	Heat flow to skin compartment
h_r	W/m2K	Radiative heat transfer coefficient
icl	-	Effectiveness of clothing mass transfer
I_{cl}	clo	Intrinsic clothing insulation
I_t	clo	Total clothing insulation (air layer included)
K	W/m2K	Heat conductance of human tissue
K_{cl}	W/m2	Heat flow through clothing layer

L	W/m^2	Thermal load on the body
LR	K/kPa	Lewis relation factor (standard LR = 16.5)
M	met; W/m^2	Metabolism rate (1 met = 58.2 W/m^2)
m	kg	Body mass
mb	kg	Body mass in program
m$_{bl}$	kg/m^{2}h	Skin blood flow
MBTV	-	Comfort Mean Body Temperature Vote
m$_{rsw}$	g/hm^2	Amount of secreted regulative sweat
mneg		Slope in cold zone of MBTV function
mode	-	Calculation mode (0 =steady state mode)
mpos	-	Slope in warm zone of MBTV function
Mshiv	W/m^2	Heat generated by shivering
p$_a$	bar	Ambient air pressure
pdif	-	Proportion of skin wet with diffusive sweat
PMV	-	Predicted Mean Vote for comfort [-3 to +3]
PPD	%	Predicted Percentage Dissatisfied
p$_{sk,s}$	kPa	Saturated vapor pressure at skin
pssk	kPa	Saturated vapor pressure at skin in program
pwet	-	Total proportion of skin wet with sweat
Q$_{comb}$	W/m^2	Total heat flow through clothing

Q_{cr-sk}	W/m²	Heat flow from core to skin compartment
Q_{lat}	W/m²	Total latent heat loss
Q_{sens}	W/m²	Total sensible heat loss (=Dry)
R	W/m²	Radiative skin heat loss
$R_{e,cl}$	m²Pa/W	Intrinsic evaporative clothing resistance
$R_{e,t}$	m²Pa/W	Total evaporative clothing resistance
regsw	g/hm²	Amount of secreted regulative sweat
rgswm	g/hm²	Maximal rate of regsw
rh	-	Relative air humidity [0 - 1]
rm	W/m²	Actual metabolic rate (including shivering)
rt	m²Pa/W	Total evaporative clothing resistance
S_{cr}	W/m²	Heat flow to core compartment (=hfcr)
skbf	kg/m²h	Skin blood flow
skbfi	kg/m²h	Initial skbf
skbfm	kg/m²h	Maximal skbf (standard skbfm = 90)
S_{sk}	W/m²	Heat flow to skin compartment (=hfsk)
step	hours	Timestep of data output
store	W/m²	Total heat imbalance of body
stric	-	Vasoconstriction constant
stroke	-	Heat stroke indicator variable
t_a	C	Ambient dry bulb temperature
t_{bm}	C	Mean body temperature
t_{cl}	C	Clothing surface temperature
t_{cr}	C	Core temperature

tcri	C	Initial t_{cr}
time	hours	Simulation time
timestep	hours	Timestep of data output
t_o	C	Operative (combined) ambient temperature
t_r	C	Mean radiative ambient temperature
t_{sk}	C	Mean skin temperature
tski	C	Initial t_{sk}
ttbm	C	Set point for mean body temperature
ttcr	C	Set point for core temperature
ttsk	C	Set point for mean skin temperature
V	kg/h	Respiration air ventilation
vel	m/s	Ambient relative air velocity
W	W/m^2	Effective work
w	-	Total proportion of skin wet with sweat
warmb	C	Warm signal from the whole body
warmcr	C	Warm signal from core
warmsk	C	Warm signal from skin
we	-	Work efficiency as proportion of M
wk	W/m^2	Effective work in program
x_a	kgw/kgair	Humidity ratio of ambient air
x_{ex}	kgw/kgair	Humidity ratio of expired air

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