#4591

A DYNAMIC MODEL FOR ESTIMATING THERMAL COMFORT

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Introduction

The main focus of this paper is to establish a dynamic model taking into account both the metabolism transients and the environment transients. By means of this model, a new index (connected with the rate of heat storage) will be used to predict the thermal transient comfort.

Heat is transferred from the skin to the environment by convection, radiation, and evaporation. When man is in a steady state, the rate of heat storage is equal to zero. When man is in a neutral condition, the thermoregulatory system would not have to work. Thermal comfort equation, see Fanger (1970), deals with this situation. But a person is seldom in a steady state or in a neutral condition, man often experiences thermal transients in his daily life, including the rate of metabolic heat production and environment transients. Compared with steady state thermal comfort equation, these are the following factors for transient conditions.

- o From one type of activity to another, the metabolic heat production will vary. Because of thermoregulation (shivering, vasodilating or vasoconstricting), the metabolic heat production is not constant even for the same type of activity.
- o The sweat secretion is not in the narrow limits.
- o The rate of heat storage is not equal to zero.

It is worth mentioning that the rate of heat storage is particular for thermal transient condition, it could be an important item for predicting thermal transient comfort.

There are two kinds of thermal transients : one is due to changes in activity etc. (metabolic rate) and the other is due to thermal environment transient. People cannot sustain the same level of activity for a long period of time, specially involving heavy work. Studying this kind of transient is important in order for people to work at their optimal comfort and therefore remain healthy. For the thermal transient environment, there are several cases involving people's daily routines at both their workplace and home environment

- o stepwise change - entering or leaving a building or moving among rooms where the temperature is different
- o ramp or drift change - the gradual temperature increment or decrement experienced at the start /stop of air conditioning in the morning and evening
- o swing change - the fluctuation of the temperature caused by feedback control, and so on.

The studying of thermal transient comfort is significant for energy saving, and also for providing an acceptable thermal environment for the buildings occupants. For instance, in the summer a building could be precooled at night with outside air or with refrigeration when power rates are usually lower and when the coefficient of performance is usually higher. In the winter, it could be heated by heat storage devices which provide high temperatures at the beginning of the working day and lower temperatures later on. And for passive solar houses, the use of auxiliary energy can be regulated to keep the indoor thermal conditions acceptable.

Thermal comfort involves a large number of variables. The physiological nature of variables; and also the subjective nature of individual's perception of thermal comfort (which can be influenced by the nonthermal aspects) makes this field of study difficult to quantify.

Historical review

Reviewing the literature of thermal comfort over the last three decades, it can be seen that many scientific disciplines have been involved in research. For thermal transients, the research work can be separated into two sections: the simulation of human response to the environment (thermoregulatory model) and the experimental study.

Three breakthroughs are recognized in the research of thermoregulatory models. The first is the application of heat transfer to a biological problem, see Pennes (1948), and the attempt to model the whole body, see Mache and Hatch (1947). The second is the inclusion of control functions into a model by Crosbie et al (1963). In their model, see Fig. 1, Crosbie et al assumed the heat flow from the core to the skin to be unidirectional. This one-dimensional model is divided into three layers: the core (viscera, skeleton, etc.) which is the source of basal metabolism; the muscle layer which is the source of increased metabolism caused by exercising or shivering; and skin.

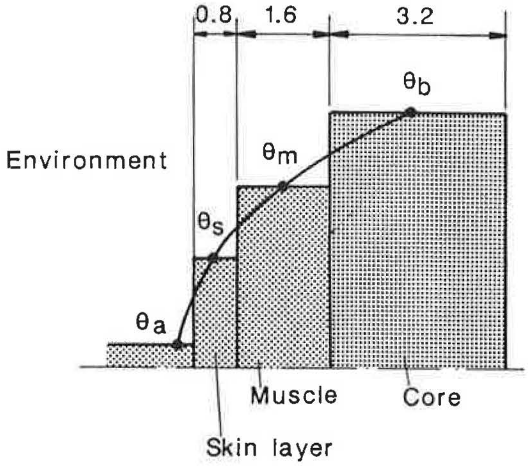

Fig.1. Three-layer model of Crosbie, Hardy and Fessenden (1963).

Assuming that the regulated temperature is the average body temperature and that the temperature regulation involves three basic types of control mode (proportional control, rate control, on-off control), the simulator is able to predict steady state values of skin and deep body temperature, metabolic rate, and evaporative heat loss. If the time constants for various thermal changes are introduced, the simulator can also predict the dynamic responses to sudden shifts in environmental temperature. The third is the publication of a much improved controller by Stolwijk and Hardy (1966), enabling a wide application of the model. In this model, the body is represented by the six segments: head, trunk, arms, hands, legs and feet. Each of the six segments is divided into four concentric layers. Thus, with the central blood compartment, there are a total of 25 compartments. A schematic representation of one segment is given in Fig. 2, showing the interrelations between the four concentric layers. The subscript I refers to the segment, I=1 being the head, I=2 the trunk, I=3 the arms, I=4 being the hands, I=5 the legs and I=6 the feet. The subscript N is used to indicate the individual compartments, such that N=4*I-3 always identifies the core layer of segment I, with N=4*I-2 representing the muscle layer, N=4*I-1 the subcutaneous fat layer and N=4*I is the skin compartment of segment. The central blood compartment is represented by N=25

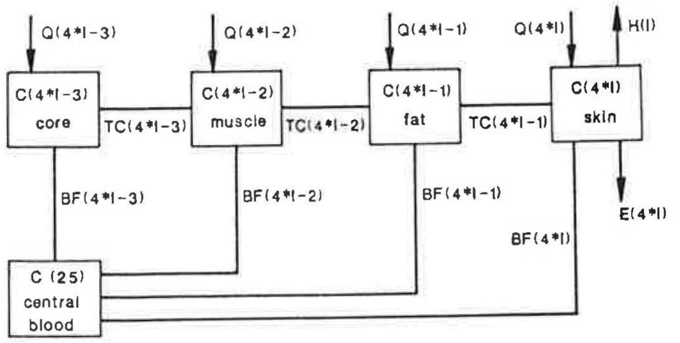

Fig. 2. Schematic diagram of the four compartments of segment I.

Q() total metabolic heat production
C() heat capacitance of compartment
TC() thermal conductance between adjacent layers
BF() total effective blood flow
H() total environmental heat transfer coefficient for segment I
E() total evaporative heat loss.

The input for the controller is represented by the signals, coming from 25 compartments. For each compartment, the distribution of different tissue types, their volume, heat capacitance, basal metabolic rate, and thermal conductance are determined. The local heat transfer coefficients are used in the model. Stolwijk model has been a source of inspiration to other investigators. Gordon (1977) expanded Stolwijk's model from 6 to 14 segments and from 4 to 11 layers, See Fig. 3.

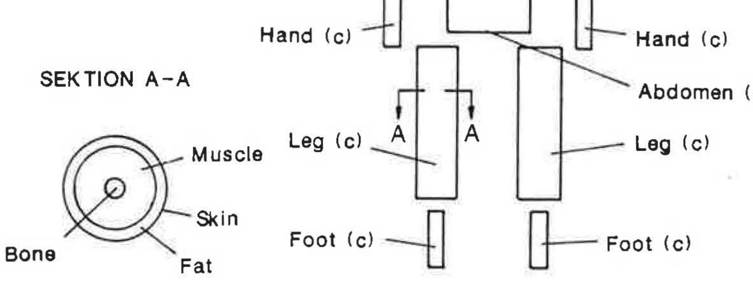

Fig. 3. Model of Gordon, Roemer and Horvath (1977) consisting of 10 cylinders(*c*), 2 cylindrical segments (*cs*) and 2 spherical segments (*ss*).

Wissler's model (1982) is also an expansion of Stolwijk's model to 15 segments and 15 layers. Shou (1987) improved the controllers from Stolwijk's model, and so on.

The thermoregulatory functions are not very clear so far, therefore there are many uncertain factors which limit its usage. And the local heat transfer coefficients are very simplified. Although some parameters, for instance mean skin temperature and sweat secretion were predicted in these models, they still have not been connected to the judgement of thermal comfort.

Gagge et al (1971, 1986) developed another infuential model, it was quite similar to Stolwijk's model. Gagge simplified the model down to just core and shell compartments, connected to a simple controller, with the aim of developing a useful tool for comfort calculations. In this model, the thermal index for steady state was used. Mean skin temperature, mean heat transfer coefficient were used. But for different body segments, the total heat capacitance, skin temperature and so on are different, see Fig. 4 from Peterson (1980), so the dynamic characteristics are different. One core and one shell are probably not enough for dynamic situations.

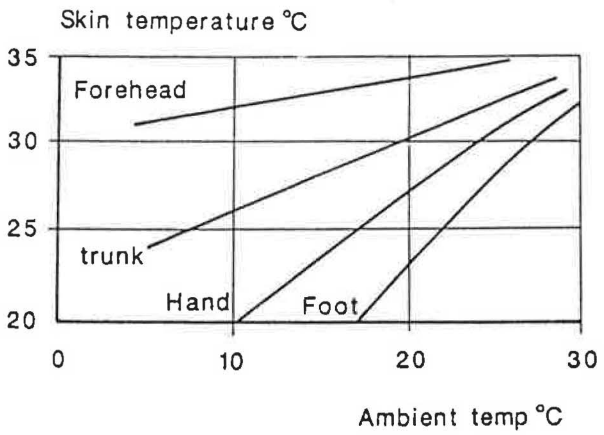

Fig. 4. Skin temperature as a function of ambient temperature.

At the same time, experimental studies were being developed. As mentioned above, it was possible to distinguish several sorts of environmental variations on which experimentation has taken place.

- o stepwise change
  When the human beings move from hot outdoor environments into an air-conditioned space (or vice versa). These studies have been performed by Gagge et al (1967). In this type of experiment, they exposed nude subjects alternately to cold and neutral environments and also from hot to neutral environments. The changing thermal sensation was found to be correlated with the actual skin temperature and sweat rate in the same way as under steady state conditions. But when these transients were reversed, i.e. proceeding from a cold or hot to a neutral environment, they felt almost immediately comfortable, even though their skin temperature had not yet reached the steady state level considered comfortable.

- o ramp or drift change - a gradual temperature increment or decrement.
  Wyon et al (1971) studied this situation. Slow steady one-directional temperature changes of 0,±0,5,±1 and ±1,5°C/h were done by Griffiths (1974). Berglund et al (1978) performed a similar experiment. Two kinds of experiments were designed by Ohno (1987). The first is for conditions ranging from thermal discomfort to neutral and the second is for the reverse, with ramp change for both conditions.

- o swing change or cyclic change of the temperature.
  Sprague et al (1970), Rohles et al (1980) also did some experiments in this field.

There are other cases for transient conditions, for instance, the radiant transient, see Berglund et al (1982), the metabolic rate transient, see Stolwijk (1971). The main efforts of work have been directed to set up regression equations that enable the prediction of thermal sensation and comfort during the thermal transients.

These regression equations differ from each other by considering just one or two of the thermal variables. Therefore it is necessary to establish a dynamic model, involving all the thermal variables to in trying to predict thermal transient comfort.

Mathematical model of body temperature regulation

A human has a built in self-adaptive ability. By means of shivering, sweating and vasodilating or vasoconstricting, he can adjust his body temperature and sweat secretion. Body temperature regulation can be assumed as a negative controlling system, it is presented below

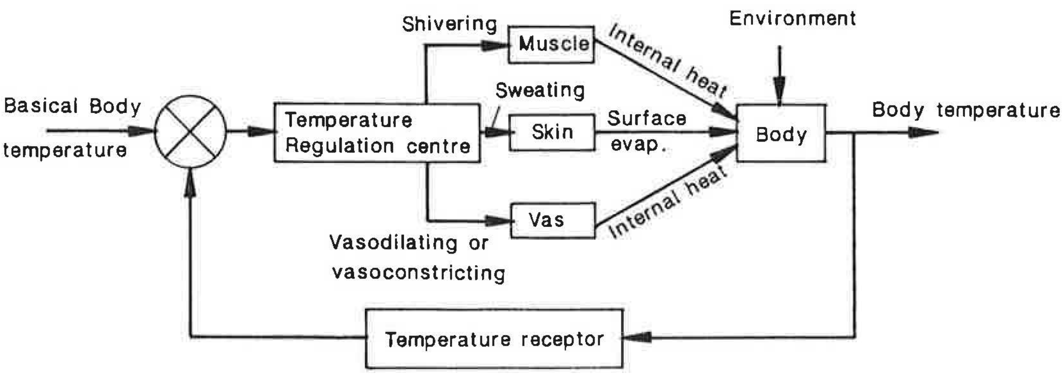

Fig. 5. A feedback controlling system of body temperature regulation.

Physical model

The human body can be separated into six body segments, i.e, head, trunk, arms, hands, legs and feet. See Fig. 6. Every segment just has one layer.

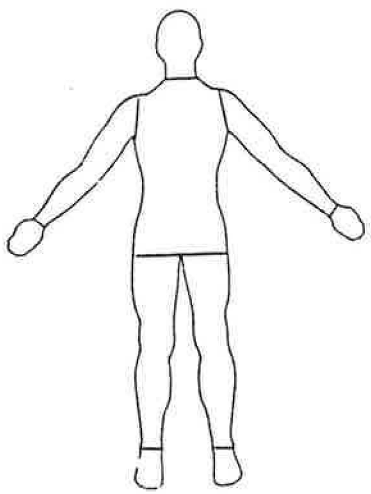

Fig. 6. A physical model of human body.

Mathematical model

The human thermoregulatory system is a very complex biology system. For this model, the following assumptions were made

- o The core temperature or the centre of the body temperature remains constant (Approximately, it is equal to 37,5 °C). Normally, changes in the core temperature are not desirable.
- o Every segment just has one layer. One of the reasons is that each the tissues (skeleton, viscera, muscle, fat, skin) almost has the same specific heat capacity.
- o Metabolic heat production impresses on the body at the beginning of activities.
- o Metabolic heat production includes all the internal heat production. Therefore Fig. 5 can be simplified below

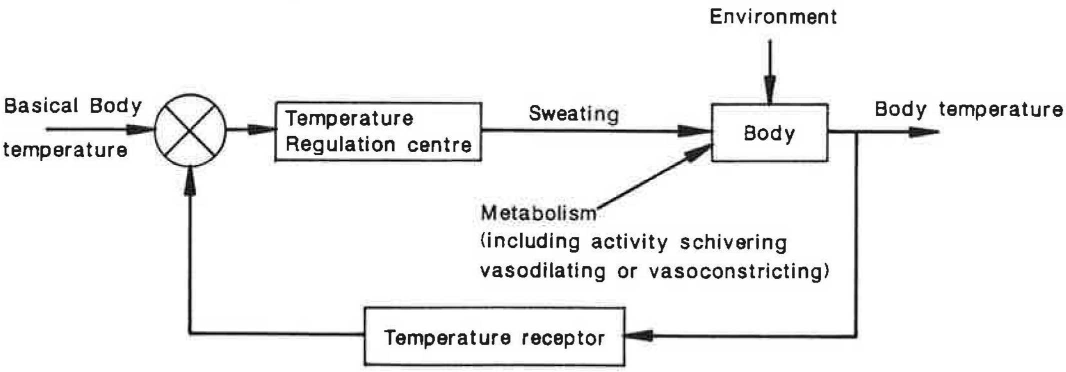

Fig. 7. A simplified feedback controlling system of body temperature regulation.

- The heat loss by respiration comes from the trunk core.

According to the energy conservation law, an equation exists for every segment:

$$P_{\tau,i}\, d\tau = Q_{c\tau,i}\, d\tau + Q_{r\tau,i}\, d\tau + E_{\tau,i}\, d\tau + C_i\, d\left(\frac{\theta_{s\tau,i}+\theta_c}{2}\right) \qquad (1)$$

where

P_τ	is the internal heat production,W
$Q_{c\tau}$	is the heat loss by convection, W
$Q_{r\tau}$	is the heat loss by radiation, W
E_τ	is the heat loss by evaporation, W
C_i	is the heat capacitance, Ws/°C
$\theta_{s\tau}$	is the mean segment skin temperature, °C
θ_c	is the core temperature,°C
τ	is the time, s

subscribt i refers to segment i .

Assuming the core temperature is equal to a constant, then equation(1) becomes

$$\frac{d\theta_{s\tau,i}}{d\tau} = \frac{P_{\tau,i} - Q_{c\tau,i} - Q_{r\tau,i} - E_{\tau,i}}{0{,}5C_i} \qquad (2)$$

Heat loss by respiration

Heat and water vapor are transferred to inspired air by convection and evaporation from the mucosal lining of the respiratory tract. Therefore, breathing results in a latent heat loss and a dry heat loss from the body. The latent respiration heat loss could approximately be given by Fanger (1970)

$$P_{re} = 0{,}0023 \cdot M \cdot (44 - p_a / 133{,}32) \qquad (3)$$

where

M	is the metabolic rate, W
p_a	is the partial pressure of water vapor in inspired air (ambient air), Pa

The dry respiration heat loss could be:

$$L = 0{,}0014 \cdot M \cdot (34 - \theta_a) \qquad (4)$$

where

θ_a	is the ambient air temperature, °C

So the total respiration heat loss is

$$P_r = P_{re} + L = 0{,}0023M \cdot (44 - p_a/133{,}32) + 0{,}0014M(34 - \theta_a) \qquad (5)$$

There are other calculations for respiration heat. But compared with other kinds of heat losses, i.e. convective heat loss, radiative heat loss and evaporative heat loss, heat loss by respiration represents a minimal amount. For pratical purposes, equation (5) is taken for this model.

Heat loss by convection

The convective heat loss from the skin surface of the nude body is given by:

$$Q_{c\tau,i} = \alpha_{c,i} \cdot A_i \cdot (\theta_{s\tau,i} - \theta_a) \qquad (6)$$

where

A_i	is the segment surface area, m^2
α_c	is the convective heat transfer coefficient, $W/m^2 \cdot °C$

The surface area is a function of a person's height and weight. The classic DuBois formula is used here:

$$A = 0{,}202 \cdot W^{0{,}425} \cdot H^{0{,}725} \qquad (7)$$

where

W	is the total mass of human, kg
H	is the height of human body, m

The ratio of surface for every segment, see Stolwijk (1971), is presented in Table 1.

Table 1. Ratio of surface area, $A_{ri,}$ for every segment

i	Body segment	A_{ri} ,%
1	Head	8,3
2	Trunk	32,3
3	Arms	13,5
4	Hands	5,6
5	Legs	31,9
6	Feet	8,4

So

$$A_i = A \cdot A_{ri} \qquad (8)$$

For convective heat transfer coefficient,

$$\alpha_{cfree} = A \cdot \Delta\theta_{s\text{-}a}{}^{m_1} \qquad (9)$$

$$\alpha_{cforced} = B \cdot V^{m_2} \qquad (10)$$

α_{cfree} is the free convective heat transfer coefficient, $W/m^2 \cdot °C$

$\alpha_{cforced}$ is the forced convective heat transfer coefficient, $W/m^2 \cdot °C$

The coefficients A, B and exponents m_1, m_2 in equations (9) and (10) are given in Table 2 and Table 3.

Table 2 Data for free convection (Wang 1990a)

i	Body segment	*A*	m_1
1	Head	1,26	0,27
2	Trunk	2,30	0,29
3	Arms	2,70	0,27
4	Hands	3,08	0,16
5	Legs	1,87	0,20
6	Feet	3,08	0,16

Table 3 Data for forced convection (Wang 1990b, 1990c)

i	Body segment	*B*	m_2
1	Head	10,82	0,55
2	Trunk	15,73	0,52
3	Arms	15,23	0,62
4	Hands	12,92	0,55
5	Legs	18,68	0,45
6	Feet	12,92	0,55

Equation (9) is for low air velocity (air velocity <0,15m/s), when there is no forced convection. While equation (10) is for situations where there is forced convection. Normally, free convection and forced convection are mixed together. For this combined situation, the convective heat transfer coefficient could be obtained from Wang (1990b, 1990c).

$$\alpha_c = \sqrt{(A \cdot \Delta\theta_{s\text{-}a}{}^{m_1})^2 + (B \cdot V^{m_2})^2} \qquad (11)$$

Heat loss by radiation

The radiative heat loss can be calculated from

$$Q_{r\tau,i} = \sigma \cdot \varepsilon \cdot \phi \cdot A_i . ((\theta_{s\tau,i}+273)^4 - (\theta_w+273)^4) \quad (12)$$

where

ε is the emissivity of the surrounding surface
σ is Stefan-Boltzmann constant, $5{,}67 \cdot 10^{-8}$ $W/m^2 \cdot K^4$
θ_w is the surrounding wall temperature, °C
ϕ is the effective radiant factor

Heat loss by evaporation

There are two sources of evaporation from the skin, one is water vapor diffusion, the other is sweating.

The water vapor diffusion is one of the insensible perspirations, see Fanger (1970), it is given by

$$E_{d,i} = 3{,}08 \cdot 10^{-3} \cdot A_i \cdot (p_{s,i} - p_a) \qquad (13)$$

where

p_s is the saturated vapor pressure at skin temperature, Pa
p_a is the partial water vapor pressure in ambient air, Pa
A_i is the segment skin area, m^2

Sweating seems to be interrelated with local temperature and mean skin temperature, see Stolwijk (1971). given in Fig. 8.

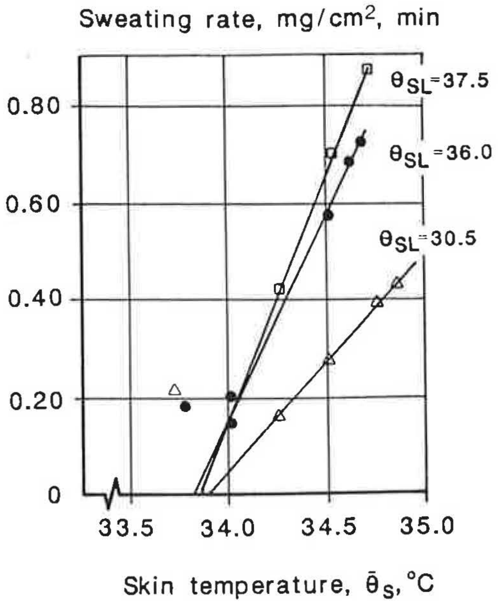

Fig. 8. Linearity of local sweating response with average skin temperature, at constant internal temperature.

From this Figure, the three correlation equations are gained

while θ_{sl} =30,5°C

$$E_{sw,i} = C_{ei} \cdot 192{,}3 \cdot A_i \cdot (\overline{\theta_s} - 33{,}89) \quad (14)$$

while θ_{sl} =36°C

$$E_{sw,i} = C_{ei} \cdot 369{,}5 \cdot A_i \cdot (\overline{\theta_s} - 33{,}76) \quad (15)$$

while θ_{sl} =37°C

$$E_{sw,i} = C_{ei} \cdot 452{,}4 \cdot A_i \cdot (\overline{\theta_s} - 33{,}84) \quad (16)$$

where

C_{ei} is the evaporative ratio of the total sweat, see Table 4.

Table 4. Evaporative ratio of the total sweat

i	Body segment	C_{ei}
1	Head	0,30
2	Trunk	0,20
3	Arms	0,15
4	Hands	0,15
5	Legs	0,15
6	Feet	0,15

Using interplation, the heat loss by sweating $E_{sw,i}$ can be calculated. So the total evaporative heat loss is

$$E_{\tau,i} = E_{d,i} + E_{sw,i} \quad (17)$$

The maximum evaporative heat loss from a totally wet skin surface is proportional to the water vapor pressure difference from the skin surface to the ambient air. The maximum evaporative capacity of wet skin, see Lewis (1922), Cena (1981), can be written as

$$E_{max} = 1{,}65 \cdot 10^{-2} \cdot \alpha_{ci} \cdot A_i \cdot (P_{s,i} - P_a) \quad (18)$$

if $E_{\tau,i} > E_{max}$, then $E_{\tau,i} = E_{max}$

Internal heat production

The energy released by the oxidation processes in the human body per unit time is so-called metabolic rate M

$$P/A = M/A \cdot (1-\eta) \quad (19)$$

where

- P is the total internal heat production, W
- M is the metabolic rate, W
- A is the DuBois area, m^2
- η is the external mechanical efficiency.

Metabolic rate is a function of the environment, a person's activities, age, sex, condition of health, etc. For an average body, metabolic rate is a function of the environment and a person's activities. See Fig. 9.

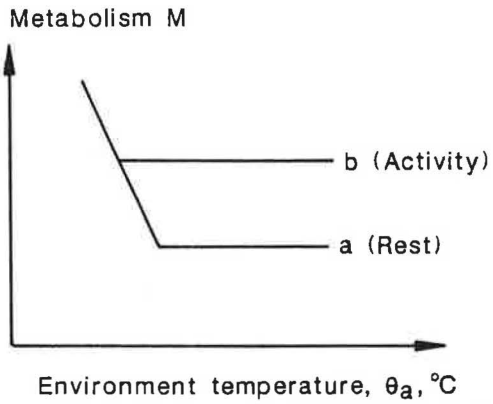

Fig. 9. Response of metabolic heat production M to environment temperature, see Cena et al (1981).

temperature can be used to predict this situation. Stolwijk's (1971) results, see table 6, can be used to calculate this metabolic increasing rate ΔM

Table 6. Metabolic rate changing with mean skin temperature, re-arranged from Stolwijk (1971).

$\overline{\theta_s}$,°C	M/A , W/m^2
30,02	39,4
29,76	40,6
29,56	46,6
29,40	56,0
29,27	65,1
29,17	74,1
29,09	78,6
29,03	80,2

By using multiple linear regression method, ΔM is easily calculated.

$$M/A = M_0/A + \Delta M/A = 39{,}4 + 46{,}788 \cdot (29{,}9 - \overline{\theta_s}) \qquad (20)$$

The correlation coefficient,r = 0,93, so the ΔM is given as

$$\Delta M/A = 46{,}788 \cdot (29{,}9 - \overline{\theta_s}) \qquad (21)$$

if $\overline{\theta_s} > 29{,}9$ then $\Delta M/A = 0$

The metabolic rate can be given as

$$M = M_0 + \Delta M \qquad (22)$$

For every segment, the internal heat production is

$$P_{\tau,i} = M \cdot (1-\eta) \cdot w_i \qquad (23)$$

where w_i is the distribution coefficient for metabolism

$i = 1, 3$ to 6

for trunk

$$P_{\tau,2} = M \cdot (1-\eta) \cdot w_2 - P_r \qquad (24)$$

According to the partly known knowledge about the distribution of metabolic rate and the experience, the distribution coefficient HM_i is given below

Table 7. Distribution coefficient for metabolic rate.

Body segment	w_i
Head	0,105
Trunk	0,446
Arms	0,110
Hands	0,040
Legs	0,269
Feet	0,030

Therefore the internal heat production for different body segment can be calculated.

The rate of heat storage

The rate of heat storage is important for the dynamic situations, it is probably an imporatnt index for the thermal transients. From the heat balance equation (2), heat storage Q_s could be calculated as

$$Q_s = P - Q_c - Q_r - E \qquad (25)$$

From the equation (2), we gain

$$Q_s = 0{,}5 \sum_{i=1}^{6} C_i \cdot \frac{d\theta_{s\tau,i}}{d\tau} \qquad (26)$$

where C_i is the heat capacitance for segment, W·s/°C

It can be obtained from

$$C_i = w_{i,j} \cdot W \cdot c_j \cdot 4186{,}8 \qquad (27)$$

where

W	is the total mass of human body, kg
c_j	is the specific heat capacity for " j " tissue, kcal/kg·°C
$w_{i,j}$	is the weight ratio of segment i and tissue j.

The specific heat capacities for different tissues j (Stolwijk 1971) and the weight ratios for different segments, which are recalculated from Stolwijk (1971), are presented in Table 8 and Table 9.

Table 8 Specific heat capacities for different tissues, from Stolwijk (1971).

j	Tissue	c_j, kcal/kg·°C
1	Skeleton	0,5
2	Viscera	0,9
3	Muscle	0,9
4	Fat	0,6
5	Skin	0,9

Table 9. Weight ratios for different segments ,% (recalculated from Stolwijk 1971)

Segment	Skeleton	Viscera	Muscle	Fat	Skin
Head	1,64	2,41	0,50	0,50	0,36
Trunk	3,80	15,9	24,1	9,50	1,82
Arms	2,03	1,00	4,53	1,30	0,65
Hands	0,30	0,04	0,09	0,20	0,26
Legs	6,75	2,58	13,7	3,20	1,61
Feet	0,50	0,08	0,09	0,30	0,32

So far, all the items in equation (2) have been discussed, calculation now can be made for a nude person.

Clothing influence

Transfer of dry heat between the skin and the outer surface of the clothed body is quite complicated, involving interval convection and radiation process in the intervering air space, and the conduction through the cloth itself. To simplify calculations, Gagge et al (1941) introduced a term I_{cl} as a dimensionless expression for the total thermal resistance from the skin to the outer surface of the clothed body I_{cl} is defined by

$$I_{cl} = R_{cl} \,/\, 0{,}18 \quad \text{(clo)} \qquad (28)$$

where is the total thermal resistance, in $m^2 \cdot °C/W$.

Because the processes of heat and mass transfer are much more complicated during the nonstationary state, the clothing here is considered to be in the heat and mass balance. According to the report of heat and mass transfer, see Nishi et al (1976), the resistance factors to the heat transfer and to the evaporation are given as

$$F_{cl,i} = (1{,}0+0{,}15 I_{cl,i})/(1{,}0+0{,}155\alpha_{tot} \cdot I_{cl,i}) \qquad (29)$$

$$F_{pcl,i} = (1{,}0+0{,}15 I_{cl,i})/(1{,}0+0{,}143\alpha_c I_{cl,i}) \qquad (30)$$

Numerical Model

Equation (3) can be rewritten into following form

$$\frac{d\theta_{s\tau,i}}{d\tau} = f_i(\theta_{s\tau,1}, \theta_{s\tau,2}, \cdots, \theta_{s\tau,6}) \qquad (31)$$

$$\theta_{s\tau,i} = C_i = \text{Const}, \ \tau = 0 \qquad (32)$$

where

i = 1 to 6

f_i () is independent of the time.

This belongs to the normal differential equations group. By means of Roung-Kutta method, it can be easily solved. Roung-Kutta method for this problem is presented below

$$\theta_{sn+1,i} = \theta_{sn,i} + \frac{h}{6} \cdot (K_{1,i} + 2K_{2,i} + 2K_{3,i} + K_{4,i}) \qquad (33)$$

$$K_{1,i} = f_i(\theta_{sn,1}, \theta_{sn,2}, \cdots, \theta_{sn,6}) \qquad (34)$$

$$K_{2,i} = f_i(\theta_{sn,1} + \frac{h}{2}K_{1,1}, \theta_{sn,2} + \frac{h}{2}K_{1,2}, \cdots, \theta_{sn,6} + \frac{h}{2}K_{1,6}) \qquad (35)$$

$$K_{3,i} = f_i(\theta_{sn,1} + \frac{h}{2}K_{2,1}, \theta_{sn,2} + \frac{h}{2}K_{2,2}, \cdots, \theta_{sn,6} + \frac{h}{2}K_{2,6}) \qquad (36)$$

$$K_{4,i} = f_i(\theta_{sn,1} + hK_{3,1}, \theta_{sn,2} + hK_{3,2}, \cdots, \theta_{sn,6} + hK_{3,6}) \qquad (37)$$

where

i =1 to 6
h is the time step, s

Using step-by-step method, equation (33) is solved.

Computer program

In order to gain the temperature response, there are several kinds of data needed for input

- o the coefficient of distribution, for instance, the distribution coefficient for metabolic rate, weight ratios for different segments, etc.
- o physical conditions (the height and weight) of human body
- o activities level
- o ambient conditions

  The ambient air temperature, the surrounding temperature, the air velocity and air relative humidity should be input.
- o the initial segment skin temperature
  The following initial temperatures are taken as default values.

Table 10. Initial segment skin temperature

Body segment	Initial skin temp., °C
Head	34,6
Trunk	33,6
Arms	33,3
Hands	35.2
Legs	34,1
Feet	35,0
Mean	34,0

The flow chart of program is illustrated in Fig.10.

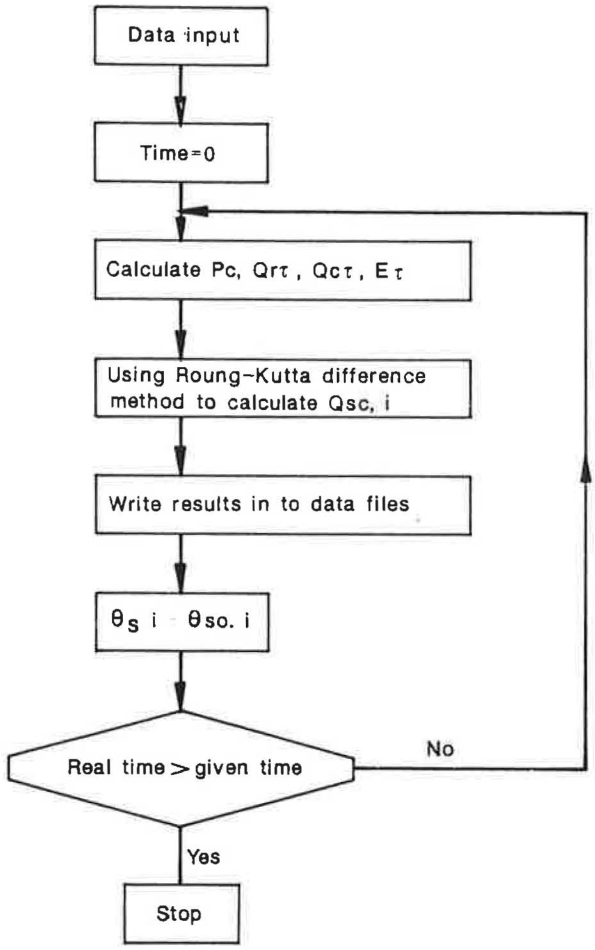

Fig. 10. The flow chart of program

Validation and application of this model are given in Appendix I and Appendix II.

Thermal comfort index during transients

The most important variables which influence the condition of thermal comfort at steady state are

activity level (heat production in the body)
thermal resistance of the clothing (clo value)
air temperature
mean radiant temperature
relative air velocity
water vapour pressure in ambient air.

During the thermal transients, the rate of heat storage is very important. The combination of all the variables mentioned above influence the sensation of human thermal comfort. Because the thermoregulatory model can combine all these variables, reasonably, it can become a usuful tool for predicting thermal comfort. Some people have connected the model with the thermal comfort calculation, see Azer et al (1976), Gagge et al

(1971), Sprague et al (1974). The conventional thermal index (for steady state) was used in these models.

It is considered that the mean skin temperature and sweat secretion at a given activity level are closely connected with the sensation of thermal comfort for steady state, see Gagge (1937), (1967), (1971), (1986), Fanger (1967), (1970), Berglund et al (1986), Humphrey (1967), Gagge (1967), supposed that the rate of change of skin temperature is very important. But when a human is exposed to a hot climate, the mean skin temperature does not change very much, instead the sweat secretion changes dramatically. The rate of heat storage probably reflects the dynamic situation much better than the change rate of mean skin temperature.

The dynamic thermal sensation, see Peterson (1986), is assumed as

$$U = U_0 + \Delta U \qquad (38)$$

where

U_0 is the thermal sensation under steady state.
ΔU is the dynamic item.

$$\Delta U = f(Q_s) \qquad (39)$$

where

Q_s is the rate of heat storage, W/m^2

Griffiths (1974) experimental data (re-arranged by Peterson (1986)) is used here.

For this experiment, slow steady one-directional temperature changes of 0, -0,5, -1 and -1,5°/h were considered. The wall temperature is always equal to air temperature. Lightly clothed sedentary subjects (metabolic rate P/A= 65 W/m^2) were tested. The clo values for different segments were evaluated below

Table 11. The evaluating clo value

Body segment	Clo value
Head	0,6
Trunk	0,9
Arms	0,9
Hands	0
Legs	0,88
Feet	0,60

The air velocity is equal to 0,1 m/s, and relative humidity RH = 50%. Environment of 23°C is considered as the initial condition. Using the physiological model here, the initial segment skin temperatures are calculated and given in Table 12.

Table 12 Initial segment skin temperatures

Body segment	Skin temperature, °C
Head	34,1
Trunk	34,2
Arms	34,4
Hands	27,6
Legs	33,3
Feet	26,7
Mean	32,7

Thermal sensations during steady state were a function of the deviation of the measured mean skin temperature ($\overline{\theta_{sk}}$) from the predicted mean skin temperature for comfort ($\overline{\theta_{skc}}$) as defined by Fanger (1972), represented by:

Thermal sensation

$$U_0 = 4{,}4 + 0{,}41 \cdot (\overline{\theta_{sk}} - \overline{\theta_{skc}}) \qquad (40)$$

where

$$\overline{\theta_{skc}} = 35{,}7 - 0{,}0276(P/A) \qquad (41)$$

P / A is the measured internal heat production per unit surface area, W/m^2.

For U and U_0, the 7-points scale is used

U (or U_0)

1	much too cool
2	too cool
3	comfortably cool
4	comfortable neither cool or warm
5	comfortably warm
6	too warm
7	much warm

The experimental results are illustrated in Fig. 11.

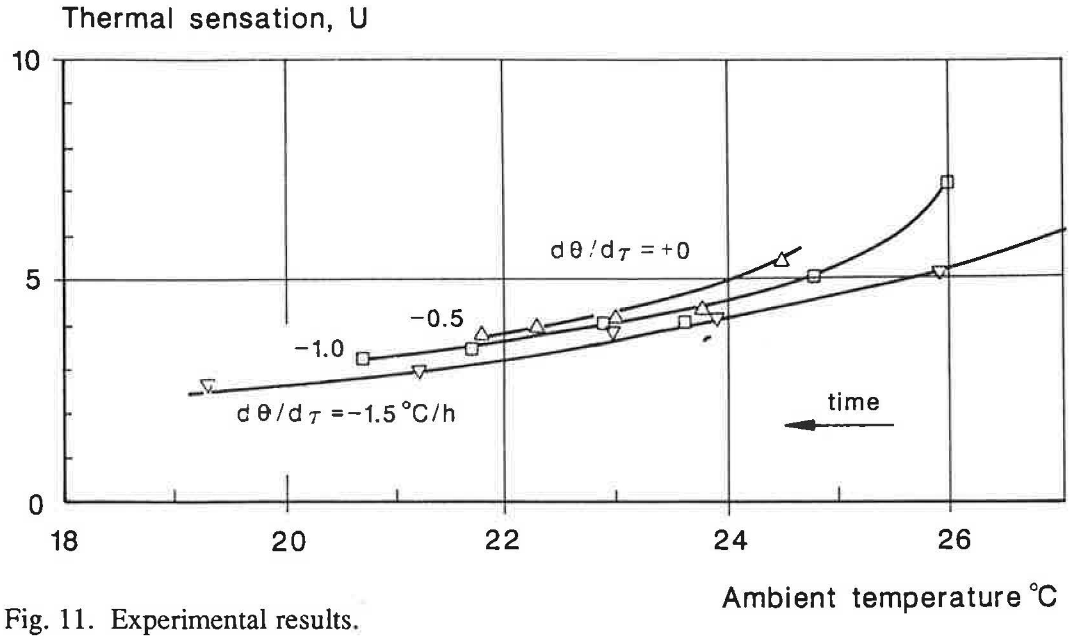

Fig. 11. Experimental results.

For different ramp change rates, the thermal sensations are different, even if the other conditions are the same. Figures 12 to 14 compare the experimental results with those predicted results by equation (40). The mean skin temperature is calculated by author's physiological model.

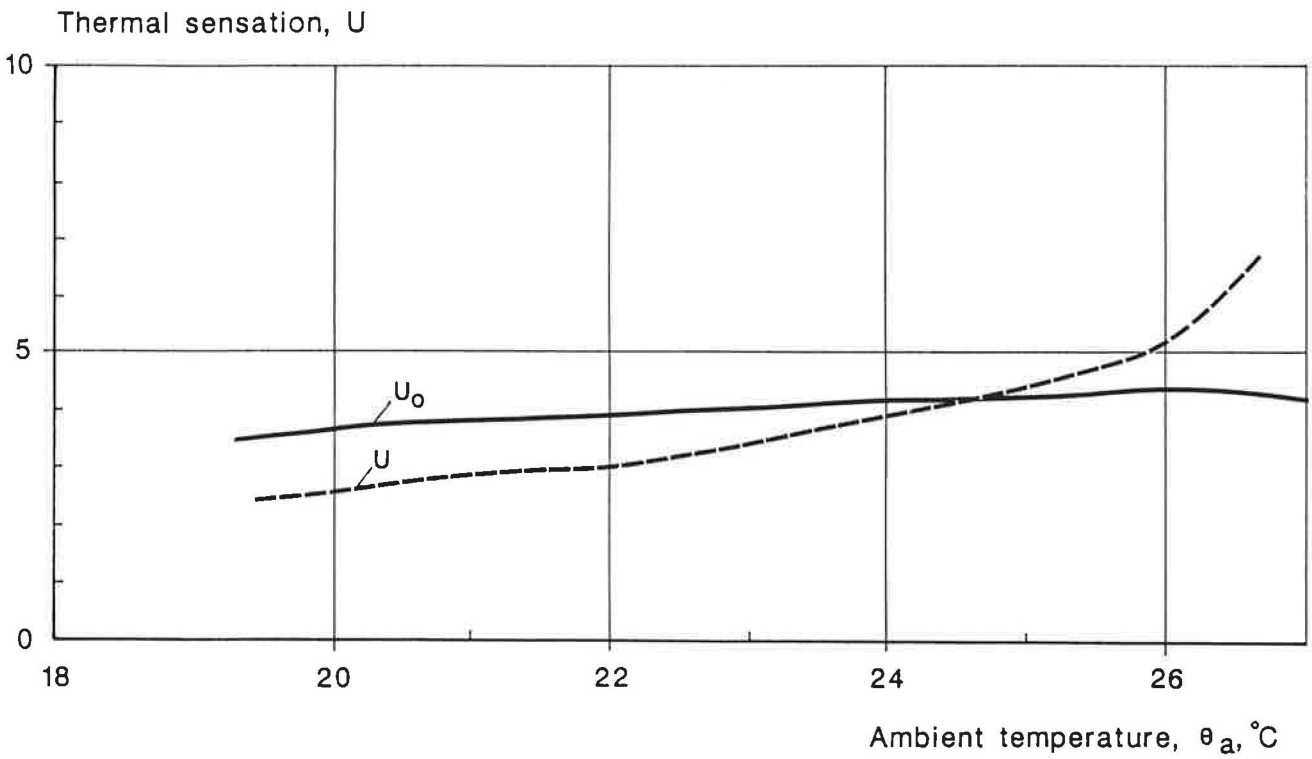

Fig. 12. Thermal sensation comparison
The ramp change rate = -1,5 °C/h.

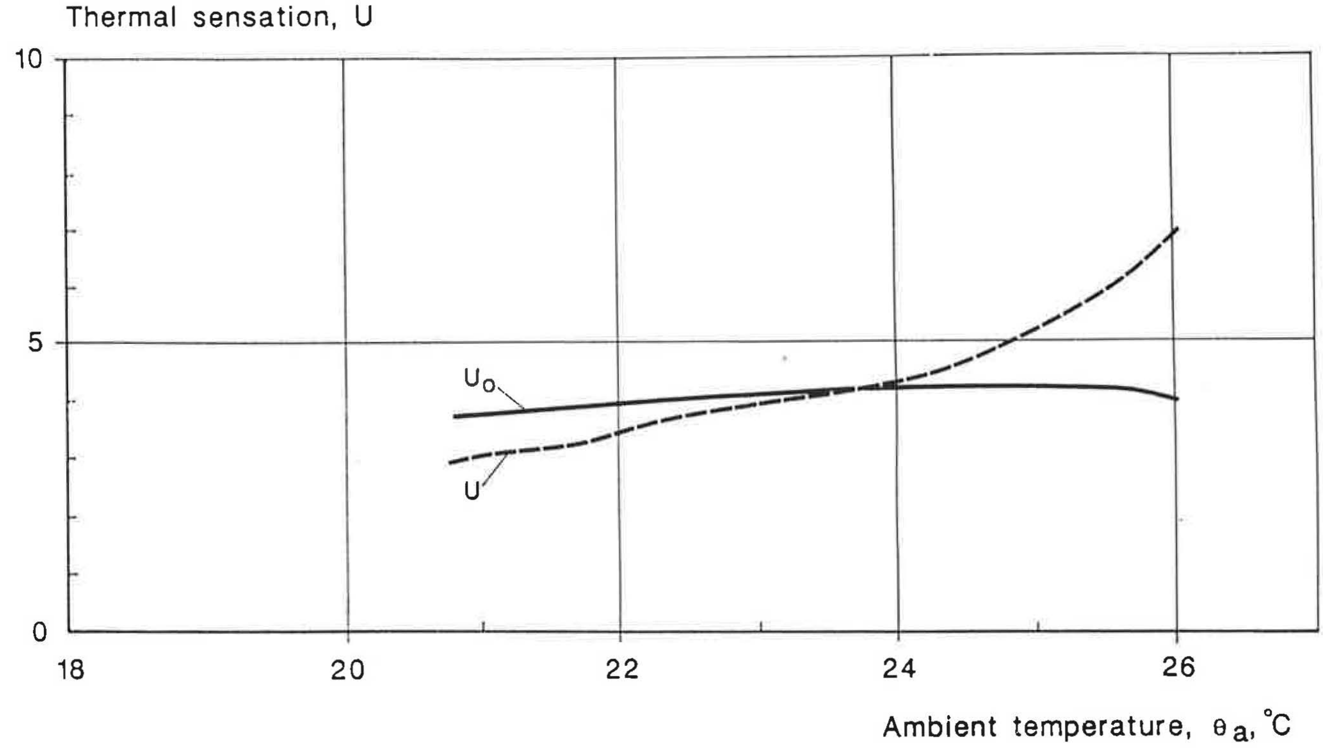

Fig. 13. Thermal sensation comparison
The ramp change rate = -1,0 °C/h.

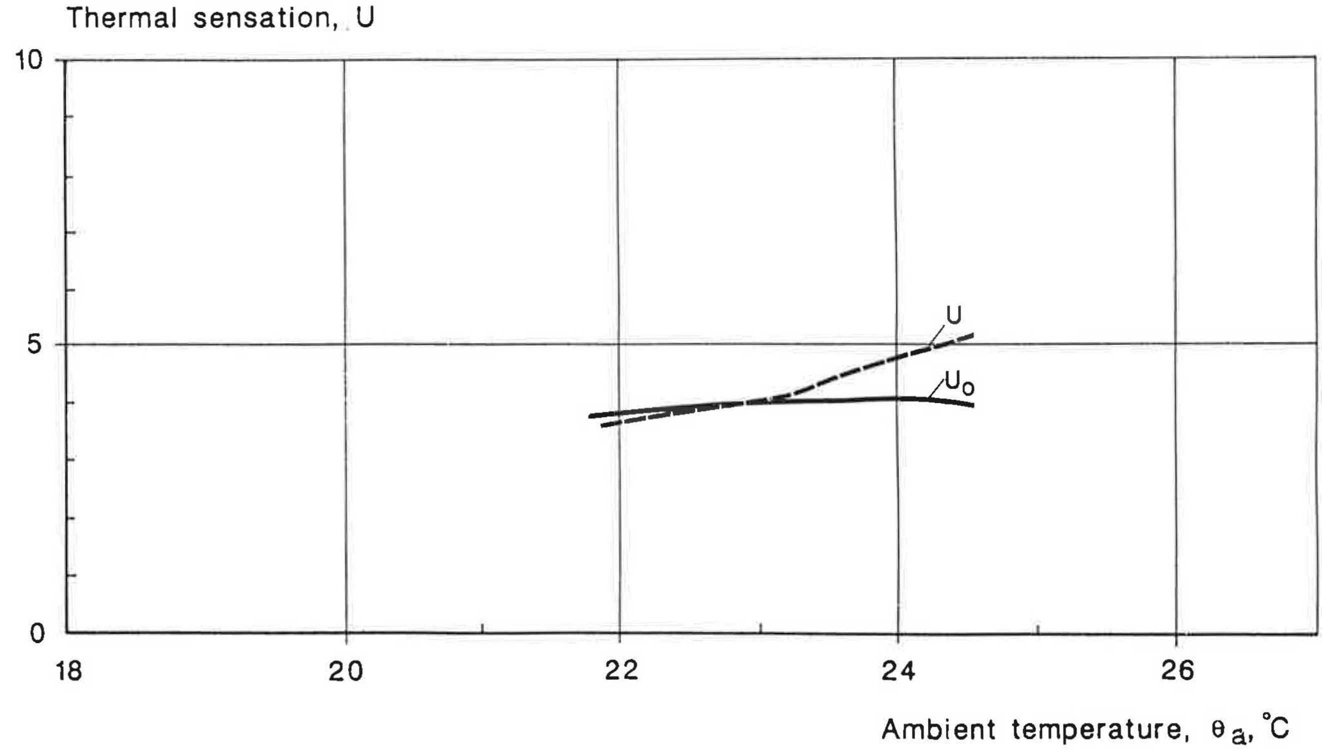

Fig. 14. Thermal sensation comparison
The ramp change rate = -0,5 °C/h.

Figures 12 to 14 further prove that it can create serious errors using a conventional steady state thermal sensation equation for predicting the thermal transient comfort. When all the data are put together, the relationship between heat storage rate and thermal sensation is illustrated in Fig. 15.

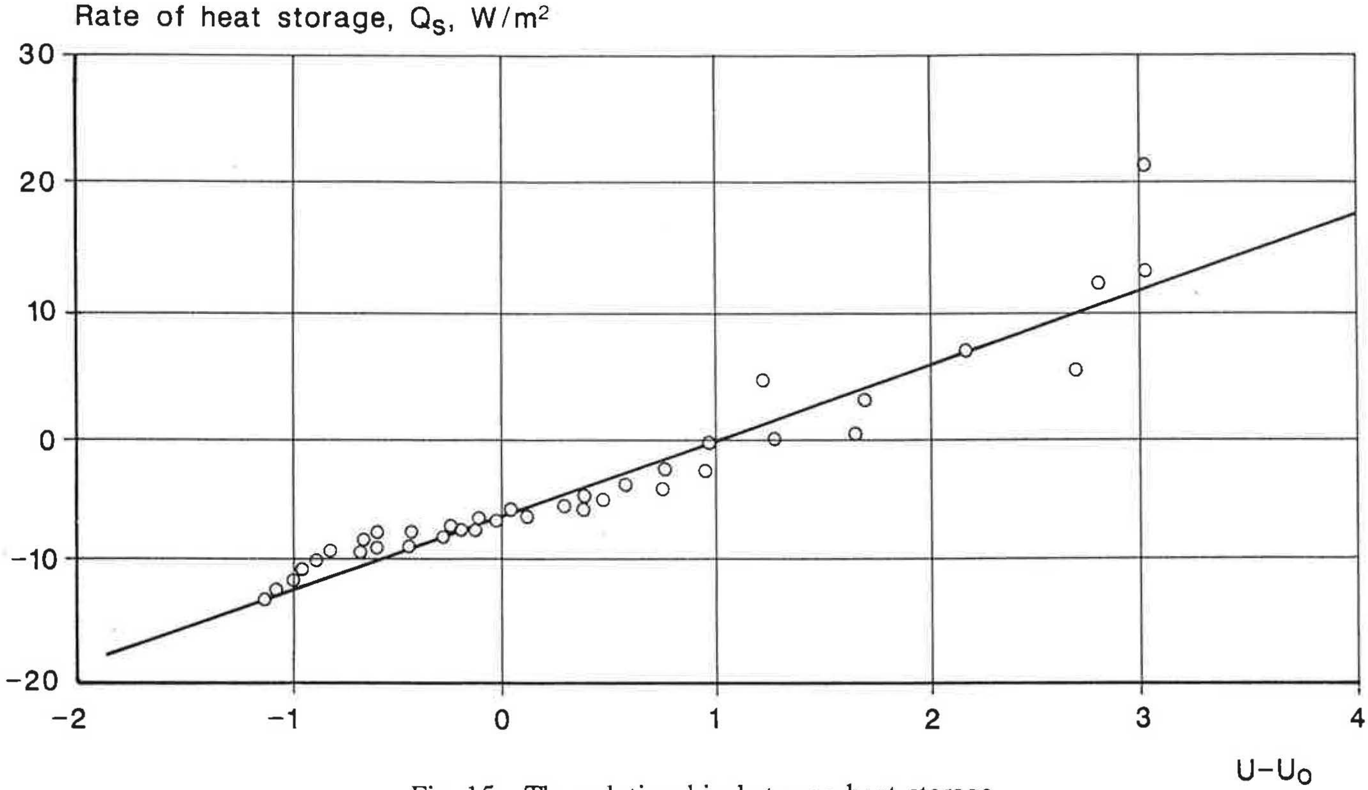

Fig. 15. The relationship between heat storage rate and thermal sensation.

Using multiple linear regression, the following equation is obtained

$$U = U_0 + Q_s/5{,}13 + 1{,}04 \qquad (42)$$

The correlation coefficient (r) is 0,92.

In equation (40), U_0 is predicted by the measured mean skin temperature, usually skin surface temperatures were measured from the chest, front arm, thigh and leg, which were used to yield mean skin temperature according to weight, such as 0,34 for the chest, 0,15 for front arm, 0,33 for thigh and 0,18 for leg, see Ohno et al (1987). Because the temperatures of these four segments have higher values, the measured mean skin temperature weighted by this method is obviously higher than the mean skin temperature predicted by the model weighted by segment surface area ratios. This is one of the reasons why the equation (42) has one item more. We can rewrite equation (42) as

$$U = U_0' + Q_s/5{,}135 \qquad (43)$$

$$U_0' = U_0 + 1{,}04$$
$$= 4{,}4 + 0{,}41(\overline{\theta_s} - 33{,}16 - 0{,}0276(P/A)) \qquad (44)$$

where

$\overline{\theta_s}$ is the mean skin temperature predicted by physiological model.

Using this new correlation equation, the thermal transient comfort can be predicted.

Conclusions and discussion

This paper has dealt with all the heat transfer items

- o convective heat tranfer
- o radiative heat transfer
- o evaporative heat transfer.

The simple thermoregulation is considered in this paper

- o internal heat production
- o sweat secretion

The model is used to simulate different thermal conditions, see appendix I and II, the good results are given.

But the more physiological data are needed to improve the model, and more experiments are needed to prove the new thermal sensation equation

Appendix I Validation of thermoregulatory model

In order to validate the author's model, the calculations are made to compare with experimental results.

Steady state conditions

The calculating conditions are given in Table I-1.

Table I-1. The calculating conditions.

Condition	M/A, W/m^2	v, m/s	θ_a, °C	θ_w, °C	RH, %
1	55	0,15	20	20	35
2	55	0,15	30	30	35

The results are given in Table I-2

Table I-2 Segment skin temperature during rest.

Body segment	Condition1	Condition 2
Head	34,0	34,1
Trunk	30,2	34,0
Arms	28,3	33,5
Hands	27,4	33,0
Legs	27,2	33,2
Feet	23,5	31,1
Mean	28,6	33,3

Compared with Peterson (1980) experimental results, see Fig.8, The simulating results are quite acceptable.

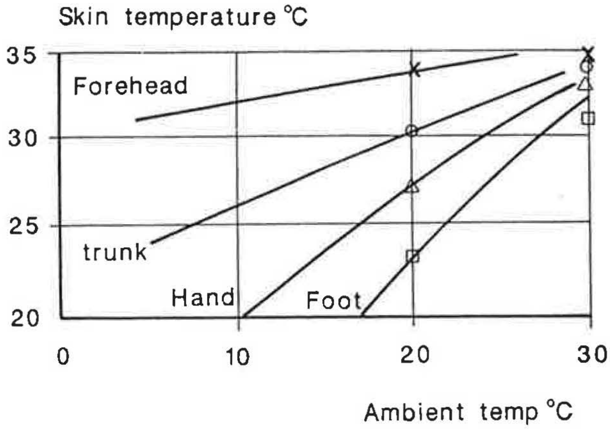

Fig. I-1. Skin temperature as a function of ambient temperature.
×--Head skin temp o--Trunk skin temp.
Δ--Hand skin temp. □--Feet skin temp.

Nonstationary conditions

Stolwijk's (1971) conditions are calculated here for validating the dynamic properties of the model. Two cases are considered here. The first is: the nude subject spends 30 minutes at thermally neutral temperature of 30 °C; 120 minutes at ambient temperature of 48°C; and 60 minutes recovery in 30°C environment. The second case is: the same subject spends 60 minutes at ambient temperature of 43°C; and 120 minutes at ambient temperature of 18°C; and 30 minutes in 43°C environment.

In both cases, the subject is at rest, and the initial segment skin temperatures are the same as those presented in Table 10. The other ambient conditions are presented below:
relative humidity RH = 30%
air velocity v = 0,1 m/s
the surrounding temperature is equal to the air temperature.

The comparison of results are presented in Fig I -2 and Fig.I - 3.

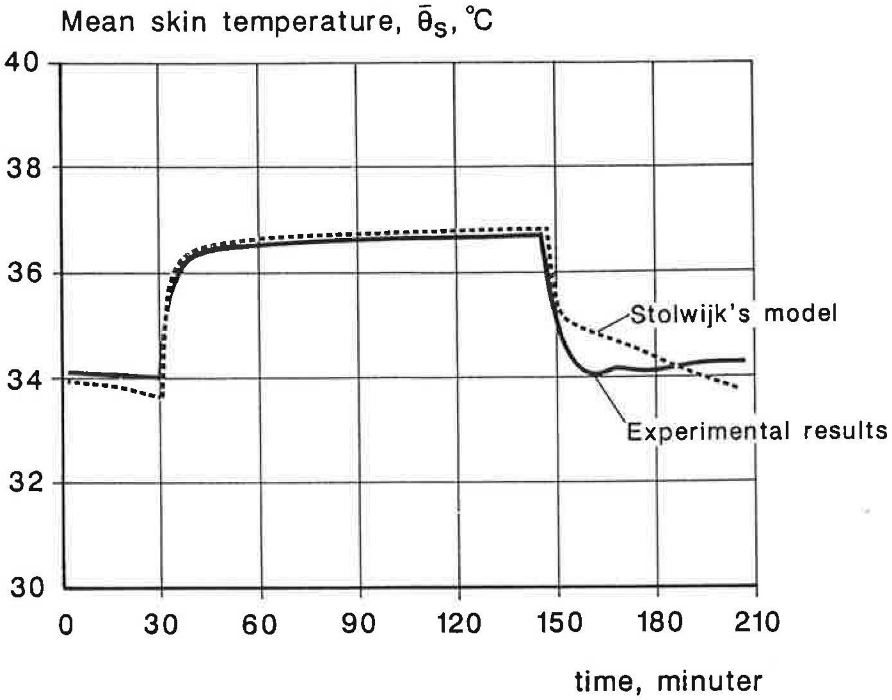

Fig. I - 2a. Stolwijk's (1971) results.

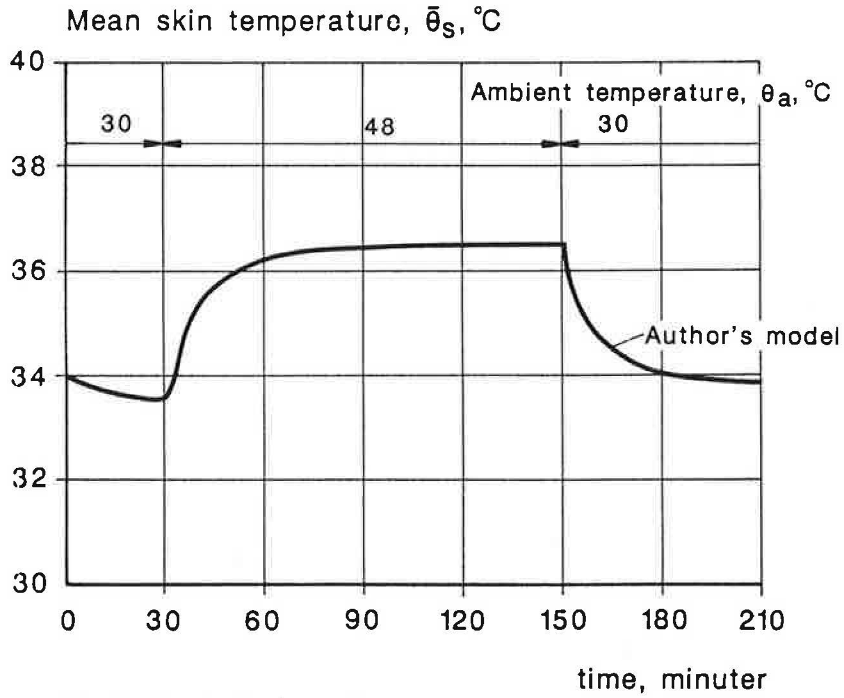

Fig. I - 2b Author's results.

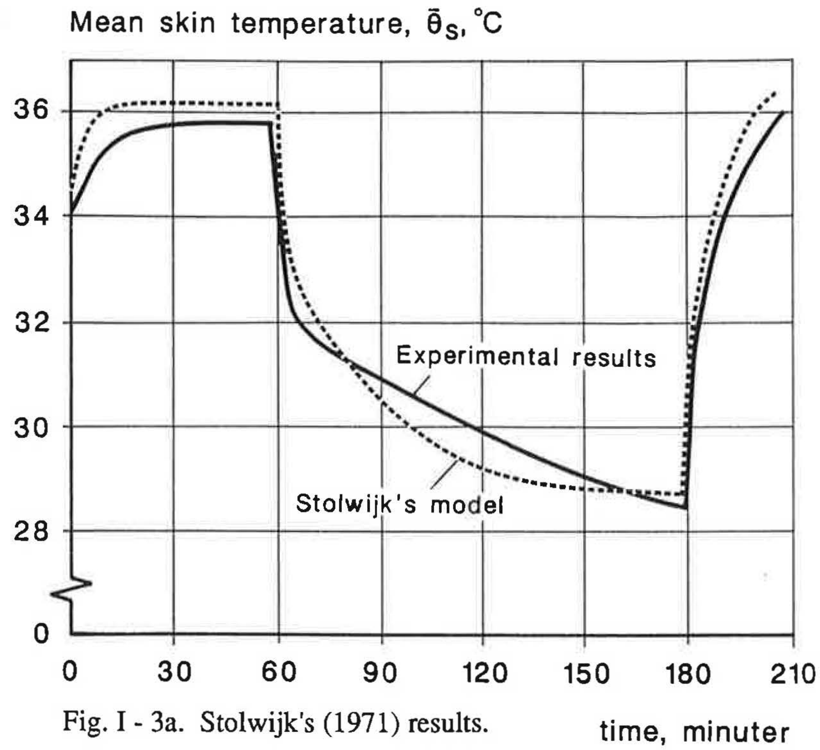

Fig. I - 3a. Stolwijk's (1971) results.

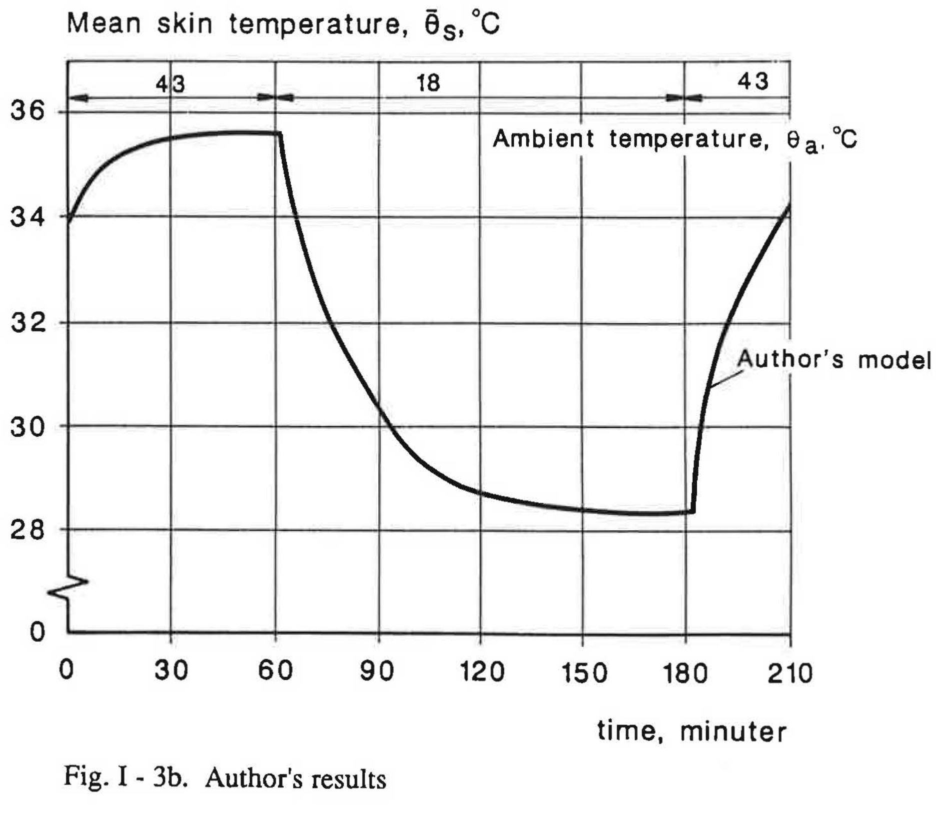

Fig. I - 3b. Author's results

Fig. I - 1 to Fig. I - 3 proved that the author's model can predict the steady state conditions and dynamic characteristics.

Appendix II: Application of model

This model is used to calculate human response in normal passive solare house.

The solar house and the indoor climate used here were described by Loftness et al (1982). The indoor climate is given by the air temperature(and wall temperature) and air humidity (estimated from weather data). Changes in relative air humidity and wall temperature are also considered. As for the air movement in the house, two cases are considered, one at low velocity 0,15m/s, and the other at 0,5 m/s (corresponding to airing). The air and wall temperatures are illustrated in Fig. II - 1.

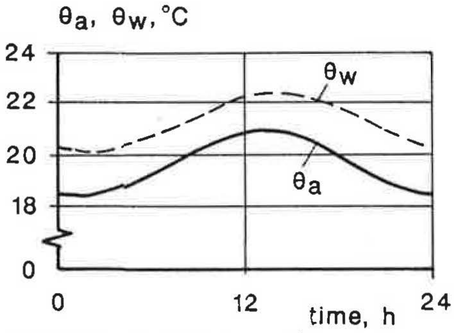

Fig. II-1. Ambient conditions.

Both temperatures are assumed to be periodical functions of time,τ

$$\theta_a = 1,25 \cdot \sin(\tau/4\text{-}105) + 19,75 \qquad \text{(II-1)}$$
$$\theta_w = 1,20 \cdot \sin(\tau/4\text{-}120) + 21,30 \qquad \text{(II-2)}$$

where τ is in mintues.

The clothed human response to the changes in conditions in the solar house can now be estimated by solving the set of differential equations mentioned above. By doing simple physical activity, see Table II-1, the metabolism is changed.

Table II-1. Working activity during one day.

Time,h	Activity	M/A, W/m^2
6.00-7.00	Eating breakfast	65
7.00-13.00	Household work	95
13.00-15.00	Having lunch	65
15.00-18.00	Working	95
18.00-19.00	Resting	65

In Fig. II -1 the mean skin temperature is illustrated as a function of time at constant relative humidity is equal to 35%, and the low air velocity is equal to 0,15 m/s.

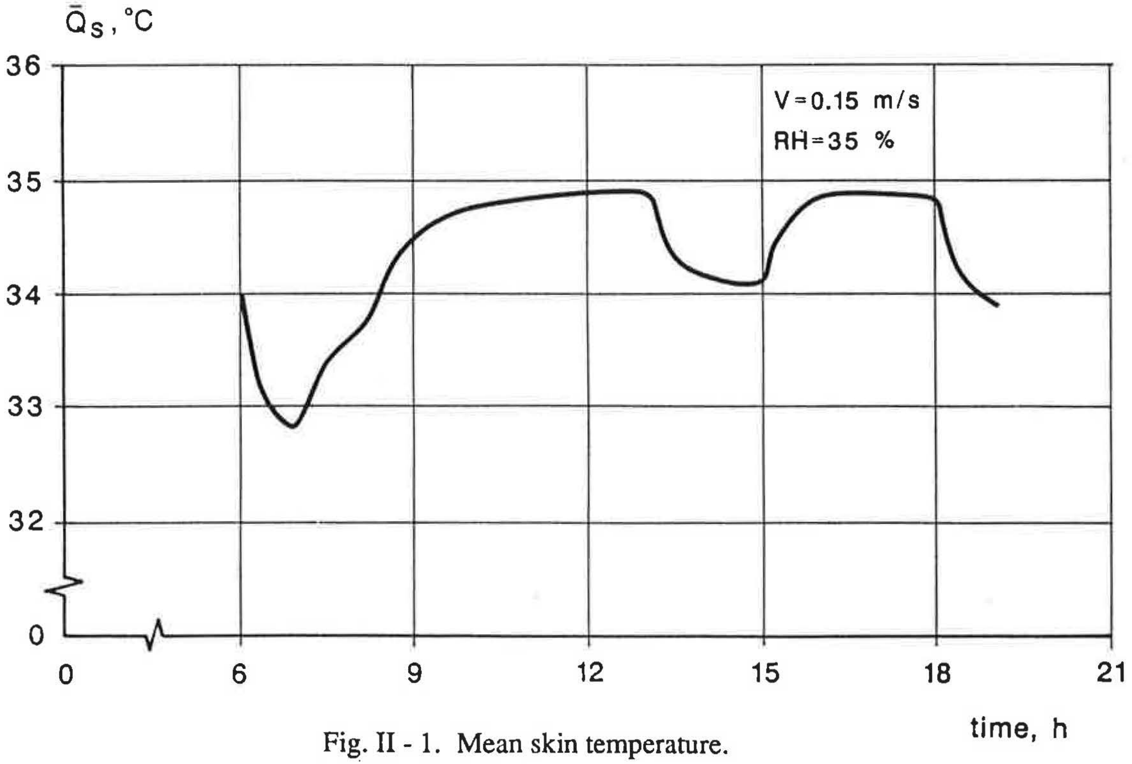

Fig. II - 1. Mean skin temperature.

The curve in Fig.I-1 is obtained for the starting temperatures given in Table (10), and clo values are obtained from Wang (1990d).

The heat losses are illustrated in Fig. II - 2. The calculations show that the heat losses by convection and radiation do not change very much, but as long as sweating occurs, the evaporative heat loss will change considerably.

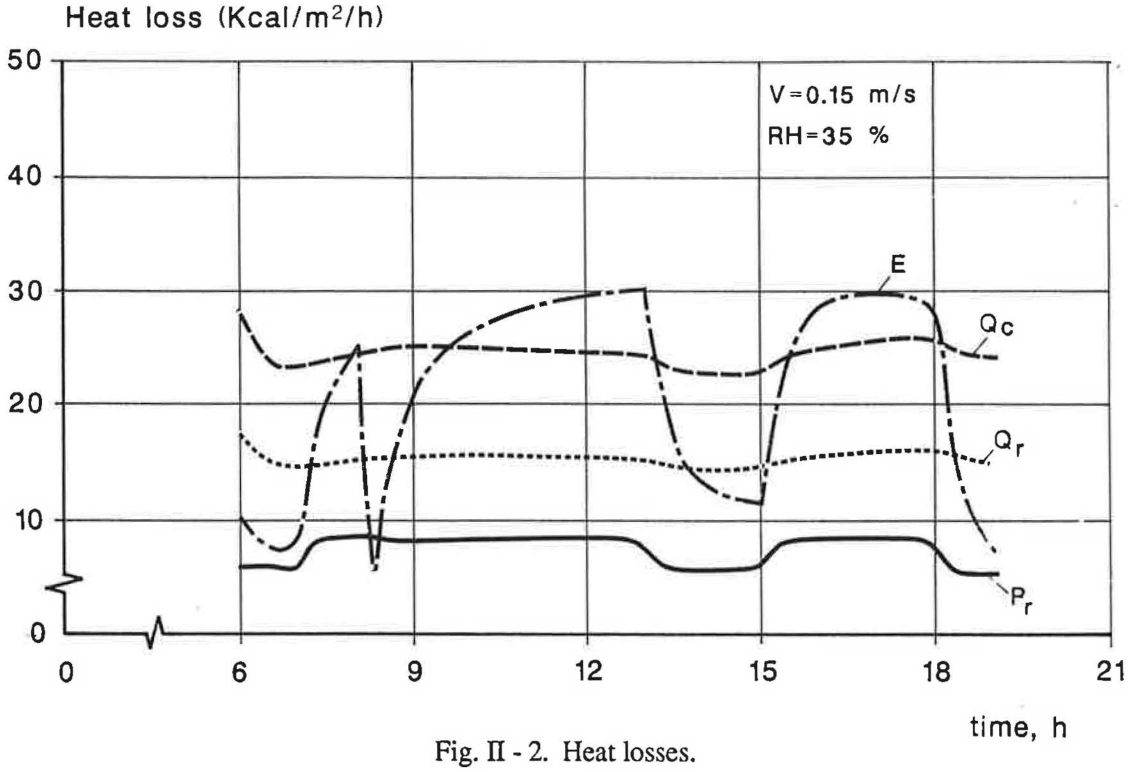

Fig. II - 2. Heat losses.

Influence of airing, variations in relative air humidity and wall temperature are calculated here.

In Figs II - 3, the mean skin temperatures are plotted as functions of time for air velocity up to 0,5m/s(airing), relative humidity up to 90% and wall temperature increased by 5 °C (as compared to equations (II-1) and (II-2)).

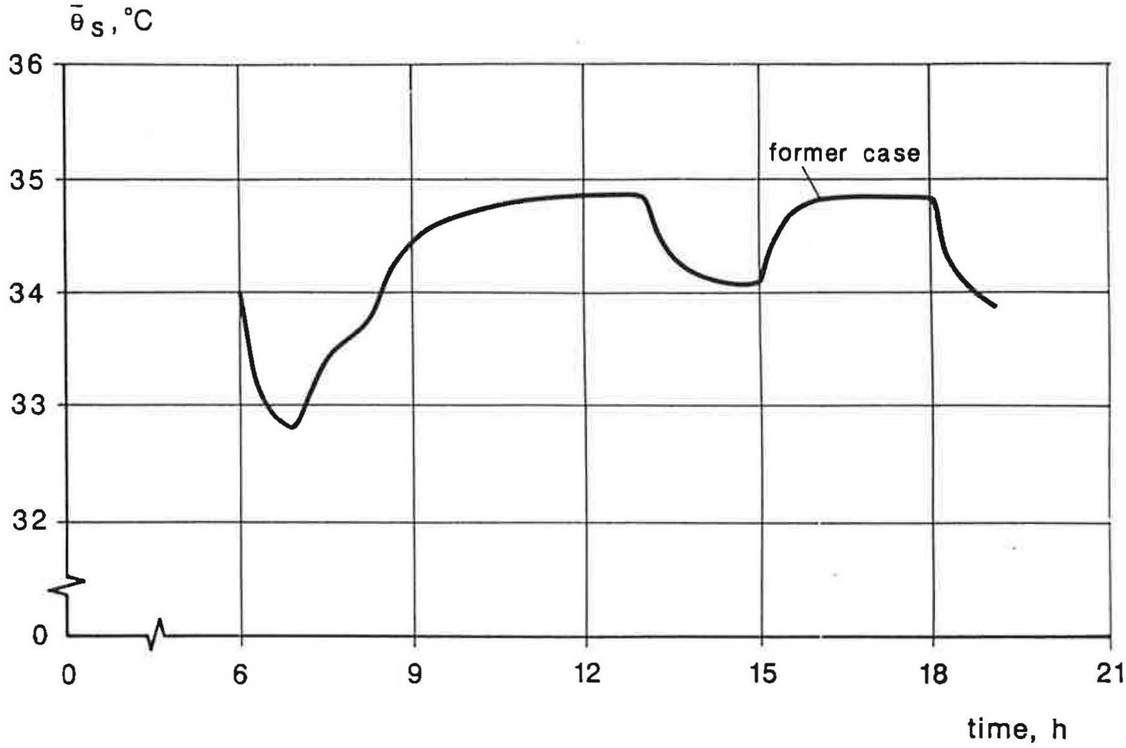

Fig. II - 3a. Mean skin in the condition mean above.

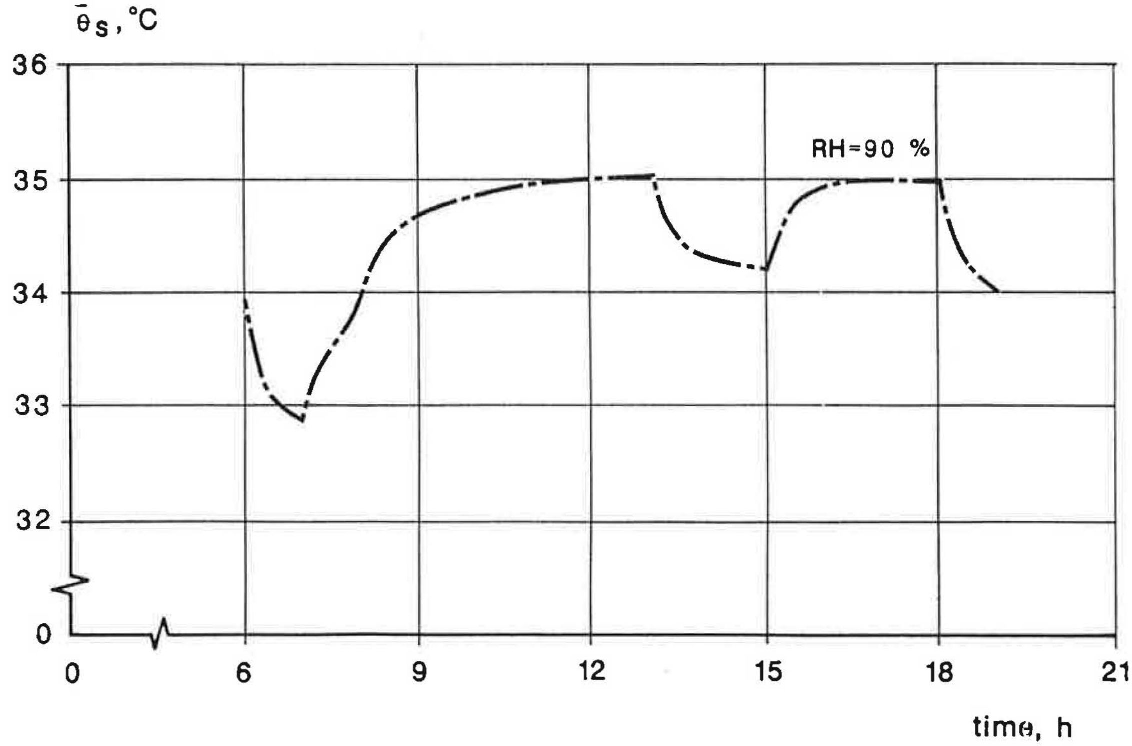

Fig. II - 3b. Mean skin temperature for relative humudity up to 90%.

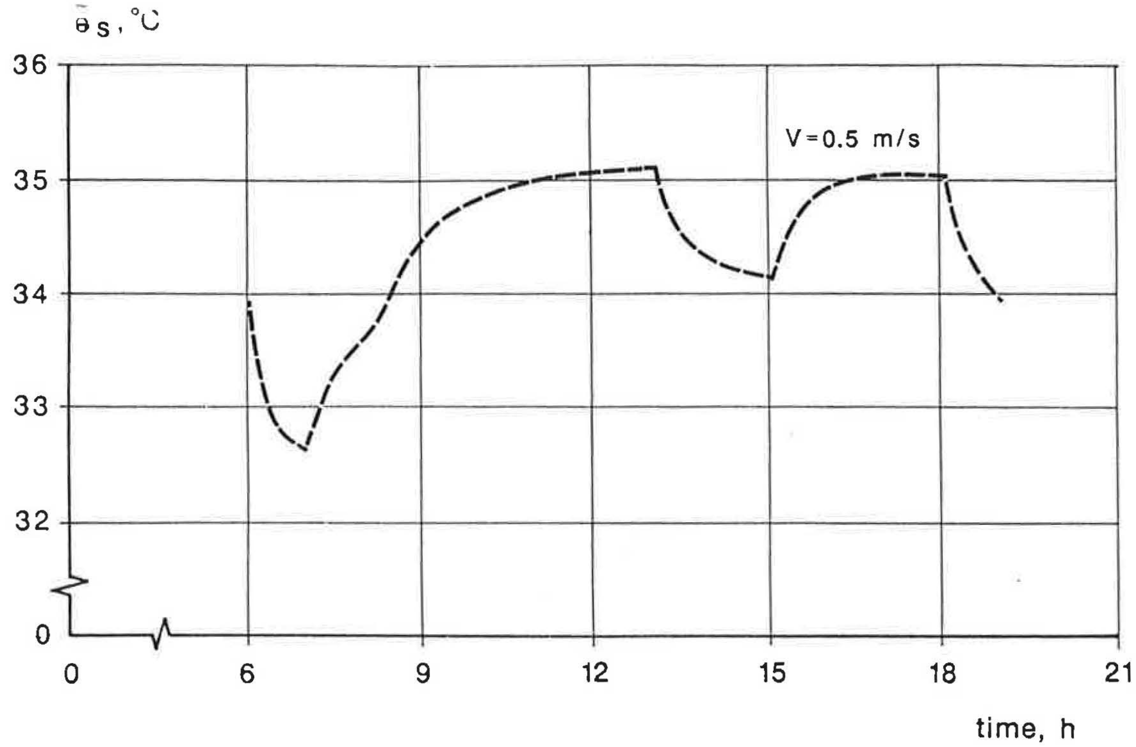

Fig. II - 3c. Mean skin temperature for air velocity up to 0,5 m/s.

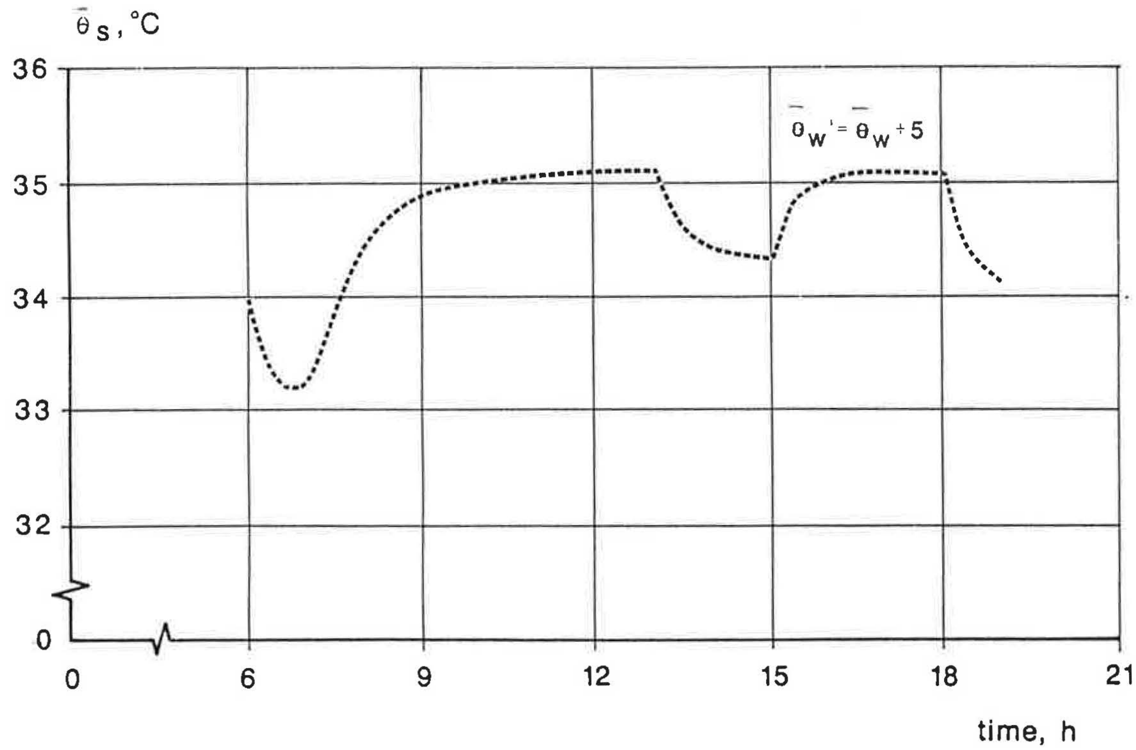

Fig. II - 3d. Mean skin temperature for wall temperature increased by 5 °C (as compared to equation (II-2)).

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