PREDICTION OF MEAN SKIN TEMPERATURE AS AN INDEX OF HUMAN RESPONSE TO THE THERMAL ENVIRONMENT

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ABSTRACT

In this paper, the steady state thermal conditions of body exercising in a hot environment is evaluated, in which the thermal equilibrium of human body seems to be attained in less than one hour. An assumption, that the regulatory thermal sweating rate is a linear function of the deviation of mean skin temperature from that of thermal neutrality, is tested and proved to be acceptable. Applying this assumption to the heat balance equation of the human body, the mean skin temperature is expressed explicitly as a function of four environmental factors (air temperature, air velocity, humidity and radiation) plus two human factors (clothing insulation, and metabolic rate).

In cool environment, however, it takes more than several hours to reach thermal equilibrium, that requires the time dependent evaluation of thermal conditions of subjects who stay in a room whose temperature is lower than that of thermal neutrality. In this paper, the mean skin temperature of subjects in a non-steady state who transfer from a room of thermal neutrality to one of lower temperature is also estimated.

INTRODUCTION

The greatest challenge facing us today is how to live in harmony with our environment on earth. The built environment, thermal environment in this paper, will be changed in such a way that, of necessity, people will have to adjust to it. To create an improved environment - easy for the earth and acceptable for the people, it will be essential that people-environment relationship be understood so that we can make better design decisions in planning future alteration of ourselves and our thermal environment.

In order to examine and improve our indoor climate, it would be desirable if the physiological values of people could be expressed explicitly as a function of environmental factors. Since the sensation given from the thermal environment do not correspond directly to the thermal condition of body, that could mislead us.

In a hot environment, steady state evaluation is important, because warm blood reaches the extremities of the body the thermal equilibrium of the body is attained in less than one hour as indicated in studies[5,7]. In a cool environment, however, vasoconstriction occurs, and the temperature of the skin layer and body extremities falls, which makes the period needed to reach thermal equilibrium longer. This requires time-dependent evaluation of the thermal conditions of subjects.

The early well known studies for thermal environment have provided scales for a perspective on the direction of the environment. However, few scales could estimate physiological values directly. In addition, for a cool environment, it seems that the responses of subjects in transient conditions have been treated as those in steady state, where the time dependent evaluation of thermal conditions of subjects will be required.

This paper predicts the mean skin temperature representing the steady state thermal condition of subjects exercising in a hot environment as a function of both factors of the environment and human body. A model - the Predicted Mean Skin Temperature (PMST) model - will be applied which has been developed by the authors[1)] and proved to be applicable for sedentary condition by assuming a linear relationship between the mean skin temperature and sweating rate in the heat balance equation. As discussed in the same paper[1)], in steady state the core and skin temperatures are interdependent, therefore, the thermal condition of human body can be represented by either the skin or core temperature alone. It has been proved[1)] that the results obtained by the new model PMST for sedentary condition in a hot environment achieve the same goal as those given by the Two-Node-Model (TNM) by Gagge et.al[2)] because TNM predicts the steady state thermal condition of human body. Simplicity of PMST will be most important for practical purposes.

In this paper, we also try to predict the mean skin temperature of the human body in a transient condition, when people move into a room the temperature of which is lower than that of thermal neutrality. A simple empirical equation is applied for predicting the mean skin temperature. It has been derived from data obtained through experiments using human subjects. The equation has two exponential terms, each of which includes a so-called "time constant" which relates to the time period required to attain a steady state. The relationship between mean skin temperature and room temperature is represented as a function of clothing and exposure time, from which we could evaluate the thermal condition of the subjects in the room.

HEAT BALANCE EQUATION IN HOT ENVIRONMENT

The heat balance equation of the human body in a steady state is:

$$M - W = M(1 - \eta) = H$$

$$= C_{res} + E_{res} + E_{diff} + E_{swe} + E_{swt} + R + C \quad [\mathrm{W/m^2}] \tag{1}$$

where a term of heat loss by regulatory thermal sweating (E_{swt}) is added to that given by Fanger[3)]. Among the terms appearing in the Equation(1), four factors, E_{diff}, E_{swt}, R and C, are functions of mean skin temperature. They are:

$$R + C = k_{rc} (T_{sk} - T_o) \quad (2)$$

$$E_{diff} = 3.05(1 - w_{sw})(P_{sk} - P_a) \quad (3)$$
[1]

This is rewritten as:

$$E_{diff} = 3.05(1- E_{sw}/E_{max})(P_{sk} - P_a)$$

$$= 3.05 (k_{sk1}T_{sk} + k_{sk2} - P_a) - 3.05E_{sw} /(L_r\, h_c\, F_{pcl})$$

$$= k_{d1} \{T_{sk} + (k_{sk2} - P_a)/k_{sk1}\} - k_{d2}\, E_{sw} \quad (4)$$
[1, 3]

The heat loss by regulatory thermal sweating E_{swt} which is assumed in our model to have linear relation to the mean skin temperature, is expressed as follows:

$$E_{swt} = k_{sw} (T_{sk} - T_{skh}) \quad (5)$$

The value of T_{skh}, for male subjects, is assumed to be equal to that of thermal neutrality, which is given as follows:

$$T_{sko} = 34.1 - 0.0275\{ M(1 -\eta) - 58 \} \quad (6)$$
[3]

For female subjects, however, the temperature T_{skh} seems to be higher than that of thermal neutrality. In order to identify the value, further studies will be needed.

The value of E_{swe}, heat loss by sweating due to exercise, is given by Fanger[3] as follows,

$$E_{swe} = 0.42\{ M(1 - \eta) - 58 \} \quad (7)$$

The sweating rates themselves are expressed as follows:

$$m_{swe} = 0.63\{M(1 - \eta) - 58\} \quad (8)$$

$$m_{swt} = k_{mt} (T_{sk} - T_{skh}) \quad (9)$$

$$k_{sw} = 0.67\, k_{mt} \quad (10)$$

Then, the sweat rate msw is expressed as follows:

$$T_{sk}\ \ T_{skh} \ : \qquad m_{sw} = m_{swe} = 0.63\{M(1 - \eta) - 58\} \quad (11)$$

$$T_{sk} > T_{skh} \ : \qquad m_{sw} = m_{swe} + k_{mt} (T_{sk} - T_{skh}) \quad (12)$$

Figure 1 shows the relation between sweating rate m_{sw} (= m_{swt} + m_{swe}) and mean skin temperature T_{sk} for the subjects exercising[4-7]. In order to examine the relation between regulatory thermal sweating m_{swt} and mean skin temperature, these data, for male subjects (T_{skh} =T_{sko}), are rearranged as shown in Figure 2, as m_{swt} (= m_{sw} - m_{swe}) against to T_{sk} - T_{sko} , they are roughly classified into three groups as follows:

Line A : $m_{swt} = 50 (T_{sk} - T_{sko})$ (13)corresponds to Stolwijk's data

Line B : $m_{swt} = 100 (T_{sk} - T_{sko})$ (14) Lind's data

Line C : $m_{swt} = 120 (T_{sk} - T_{sko})$ (15) Robinson's data

The gradient of line A, k_{mt} = 50 was roughly estimated and found to be comparable to the gradient for sedentary subjects as reported in previous paper[1]. The gradients of line B and C, larger than that of line A, are for the mine-rescue subjects [4] and subjects well acclimatized to work in heat[6] respectively. From these results, it is our opinion that the value of k_{mt} seems to depend on the level of heat acclimatization of the subjects. The data in Figure 1 are plotted again in Figures 3, 4 and 5, and compared with lines given by Equation(11) and (12) with gradients found in Figure 2 and expressed in Equations (13)~(15). Considering the complexity of the phenomenon, they would seem to provide good evidence for the PMST model, except the data for 390 W/m^2. We will have to reexamine the condition of subject at higher activity.

The value of k_{mt} = 50 (k_{sw} = 33) could be used for an average person in any activity.

PREDICTED MEAN SKIN TEMPERATURE AND WETTEDNESS

Applying the terms described above into Equation(1), we obtained the following Mean Skin Temperatures for the two stages of human response:

[T_{sk} T_{skh} : Vascular Control, E_{swt} = 0]

$$T_{sk} = [H - \{E_{re} + C_{re} + k_{d1} (k_{sk2} - P_a)/k_{sk1} + (1 - k_{d2})E_{swe} - k_{rc} T_o\}]/(k_{rc} + k_{d1}) \quad (16)$$

[$T_{sk} > T_{skh}$: Control by Sweating]

$$T_{sk} = [H - \{E_{re} + C_{re} + k_{d1} (k_{sk2} - P_a)/k_{sk1} + (1 - k_{d2})(E_{swe} - k_{sw} T_{skh}) - k_{rc} T_o\}] /\{k_{rc} + k_{d1} +(1 - k_{d2}) k_{sw}\} \quad (17)$$

Skin wettedness, $(E_{swe} + E_{swt})/E_{max}$, is calculated by using these two mean skin temperatures.

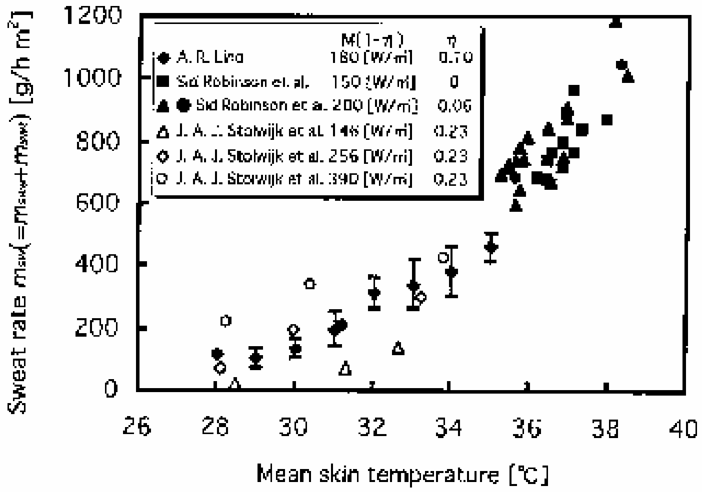


Figure 1. Relations between sweating rate in exercise (m_{sw}) and mean skin temperature (T_{sk})

Lind : treadmill , Robinson 150 W /m² : treadmill (level),Robinson 194 W /m² : treadmill (2.5% grade), Stolwijk : ergometer

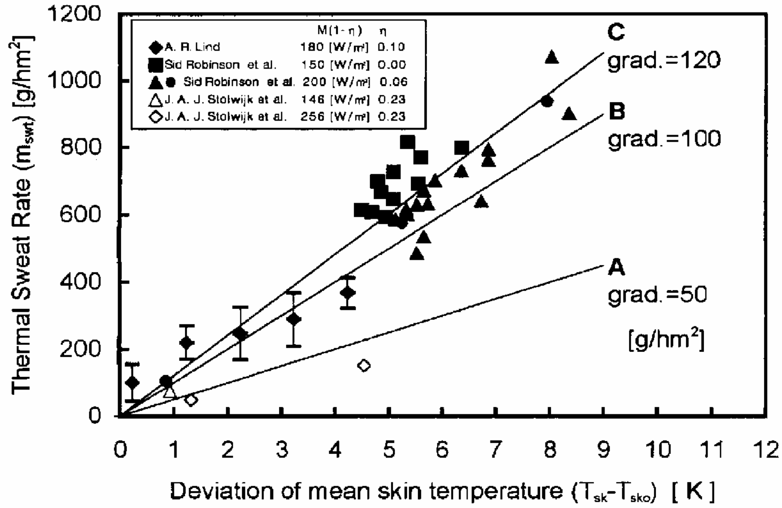


Figure 2. Thermal sweating rate vs. Deviation of mean skin temperature from that of thermal neutrality (T_{sko})

Subjects : mines-rescue (Lind), well acclimatized to work in heat (Robinson), no description (Stolwijk)

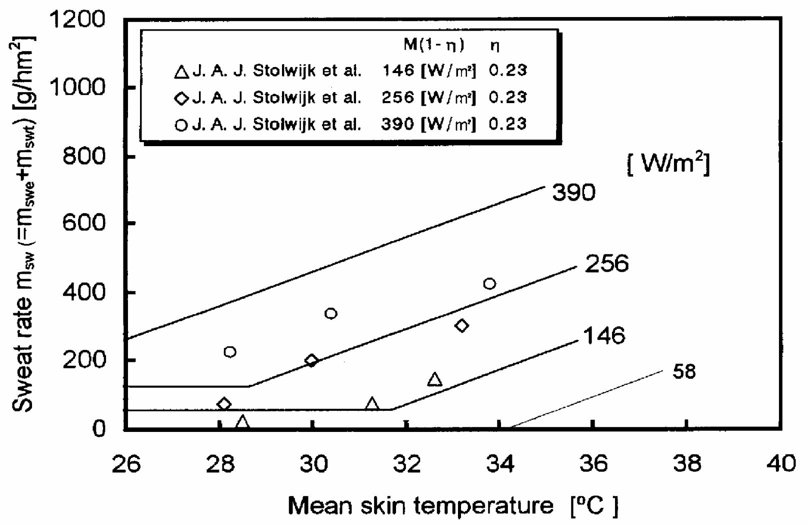


Figure 3. Relations between sweating rate in exercise (m_{sw}) and mean skin temperature (T_{sk}) - ergometer

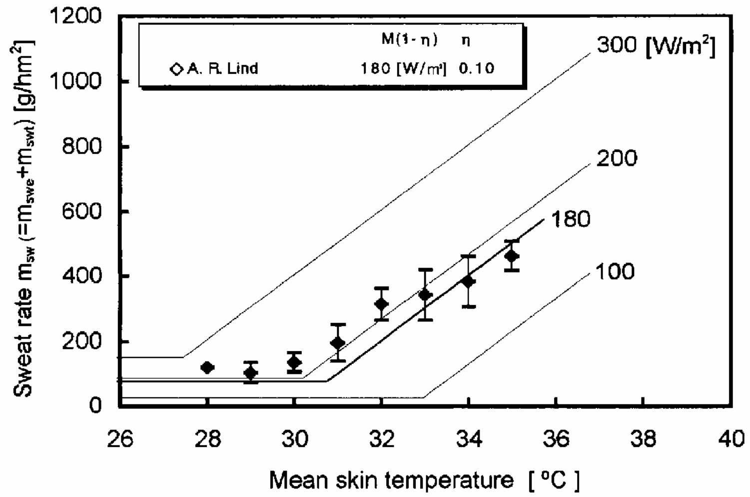


Figure 4. Relations between sweating rate in exercise (m_{sw}) and mean skin temperature (T_{sk}) - treadmill 5% grade

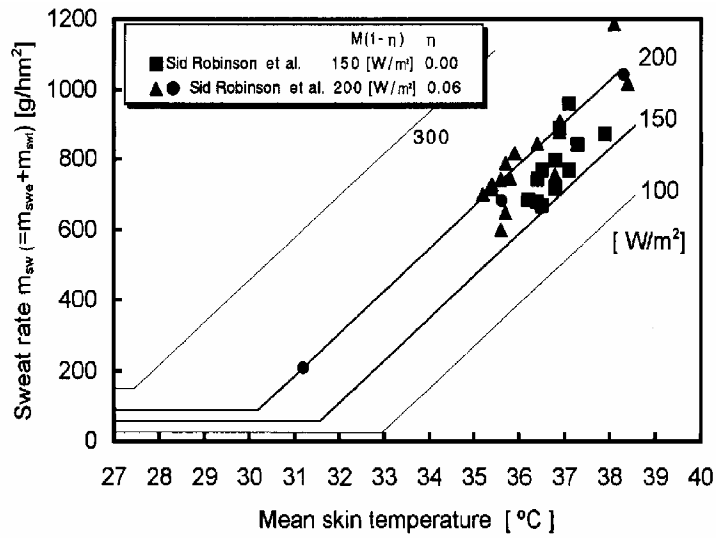


Figure 5. Relations between sweating rate in exercise (m_{sw}) and mean skin temperature (T_{sk})150 W/m^2 treadmill (level), 194 W/m^2 -treadmill (2.5% grade)

RELATIONSHIP BETWEEN PMST AND PMV

Fanger's PMV is defined in terms of thermal load (L), which is measured as the difference between metabolic heat production in a comfortable environment and virtual heat loss (gain) when the mean skin temperature is maintained in a comfortable state (thermal neutrality):

$$PMV = \alpha L \quad (18)$$

Using the new PMST model, the heat load (L) for the body response is as follows:

[Vascular Control, T_{sk} T_{skh}, $E_{swt} = 0$] : $$L = (k_{d1}+k_{rc})(T_{sk} - T_{sko}) \quad (19)$$

[Controlled by Sweating, $T_{sk} > T_{skh}$] :

$$L = k_{sw} (1 - k_{d2}) (T_{sko} - T_{skh}) + \{k_{d1} + k_{rc} + k_{sw} (1 - k_{d2})\}(T_{sk} - T_{sko}) \quad (20)$$

The PMV is obtained by substituting these values into the Equation(18) and found to be affected not only by the Deviation of the Mean Skin Temperature from optimum (DMST = $T_{sk} - T_{sko}$), but also by the value of k_{rc}, which is a function of air velocity and clothing. Figure 6 and 7 demonstrate the difference of characteristics between DMST and PMV. For practical assistance, the rise of the mean skin temperature (DMST) at PMV=+0.5 is presented in Figure 8. It indicates that the values of DMST corresponding to the condition of PMV=+0.5 vary with the thermal resistance of clothing.

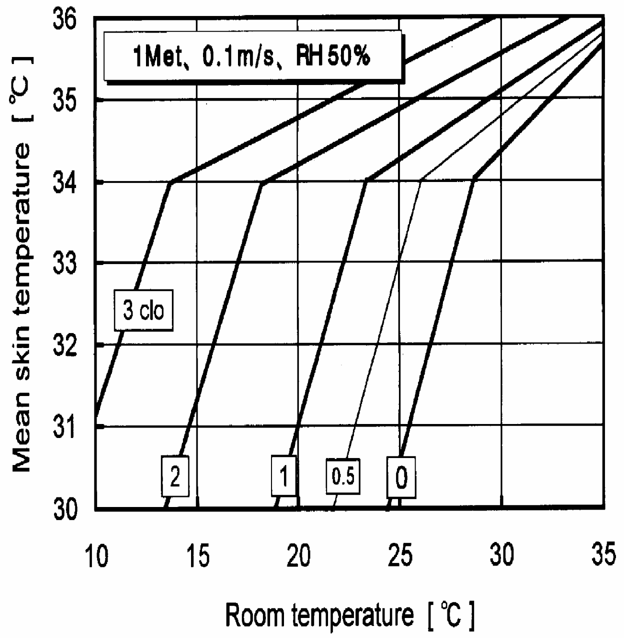


Figure 6. Steady state mean skin temperature vs. room temperature

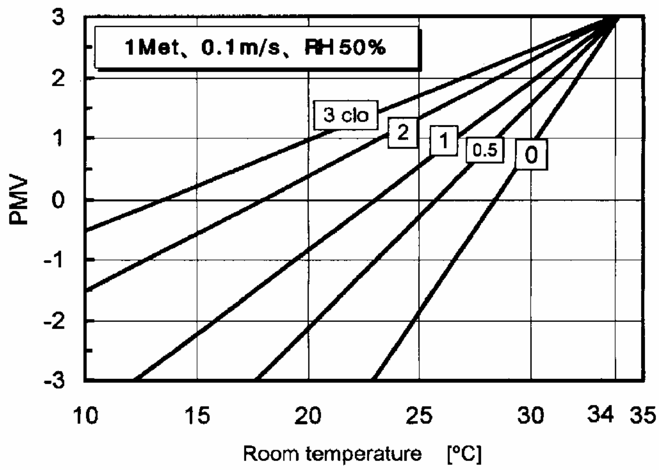


Figure 7. PMV vs. room temperature

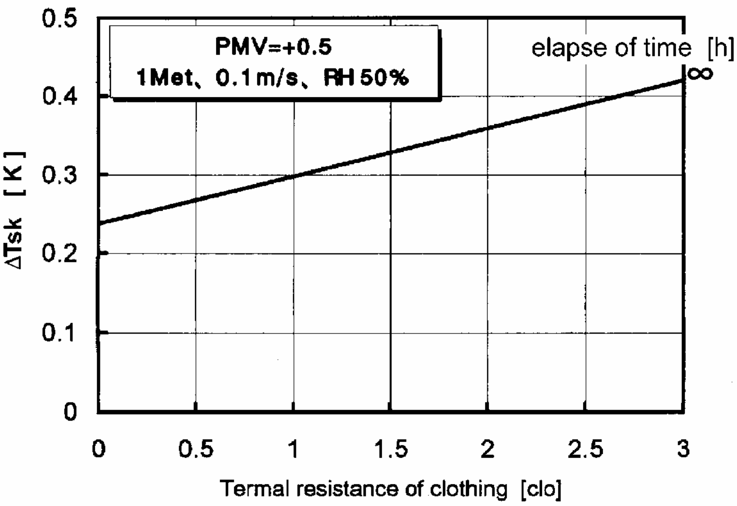


Figure 8. Rise of mean skin temperature (ΔTsk) at a temperature of PMV=+0.5

COMPARISON BETWEEN PMST AND TNM (Two-Node-Model)

Figure 9 represents the sweating rate against mean skin temperature calculated from the PMST and TNM by Gagge et. al, the two models of PMST and TNM would appear to give different solutions for the conditions of subjects in exercise. As far as this result is concerned, the primary reason of the difference seems to come from the term of m_{swe}, which seems to be zero in TNM (Figure 10).

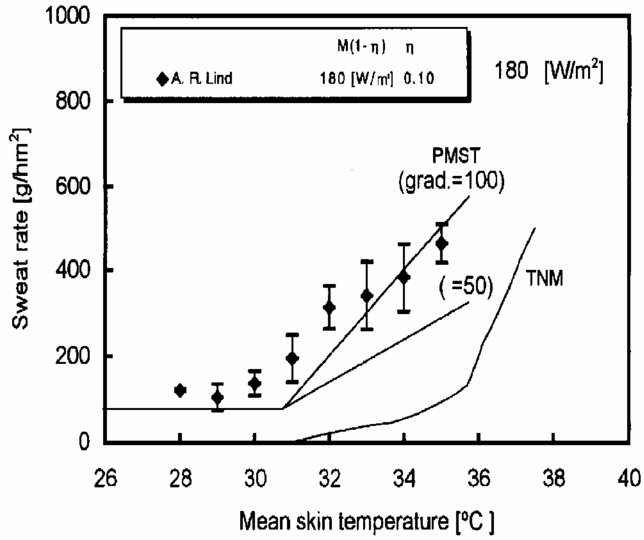
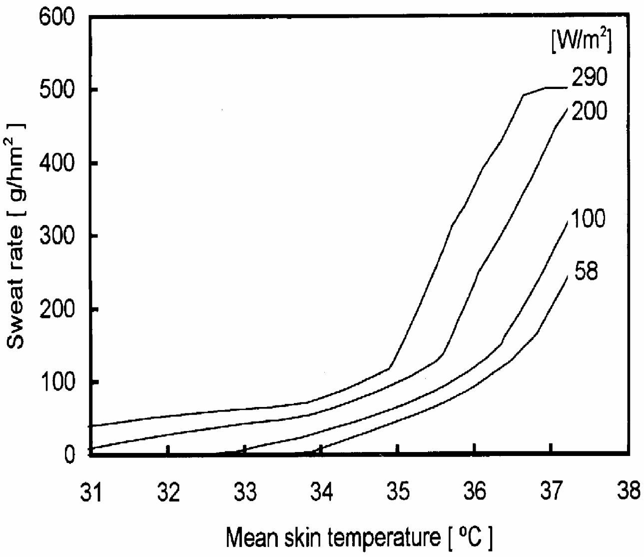


Figure 9. Comparison of predictions on sweat rate obtained from PMST and TNM



Figuer10. Sweat rate obtained from Two-Node-Model by Gagge et al.

TRANSITIONAL MEAN SKIN TEMPERATURE OF SEDENTARY SUBJECTS IN A COOL ENVIRONMENT

The following empirical equation was applied for predicting mean skin temperature:

$$T_{sk}\,(t) = T_{sk}\,() + \{\, T_{sk}\,(0) - T_{sk}\,()\}\{k_1 \exp(-t\,/t_1) + k_2 \exp(-t\,/t_2)\} \quad (21)$$

The mean skin temperature at a steady state T_{sk} () was estimated by Equation(16). The time constant t_2 (> t_1) was estimated by using the following equation derived from Equation (21) applicable for tt_1.

$$\{\, T_{sk}\,(t - 1) - T_{sk}\,()\}/\{\, T_{sk}\,(0) - T_{sk}\,()\} = \exp\{-(t - 1)/t_2\} \quad (t\ \ 1) \quad (22)$$

A series of experiments[9)] was conducted with 13 male subjects whose clothing was about 1.3 clo in a climate chamber with still air. Relative humidity was about 55%. From regression analysis on the data shown in Figure 11 obtained from these experiments[9)], the following equation was obtained and the value of t_2 was found to be 4.0 [h]:

$$\{\, T_{sk}\,(t - 1) - T_{sk}\,()\}/\{\, T_{sk}\,(0) - T_{sk}\,()\}\ (\phi) = \exp\{-(t - 1)/4.0\} \quad (t\ \ 1) \quad (23)$$

Adapting lumped-constant-systems into the human subject, the value of t_2 will be estimated as follows:

$$t_2 = k_c\, c_b\, B/(\, k_{rc}\, A_{Du}) \quad (24)$$

We have 0.38 for the value of k_c by applying values of subjects 1.3 clo, A_{Du} = 1.72 m^2 and B = 62.4 kg. Then we have following expression for t_2.

$$t_2 = 0.37\, B/(\, k_{rc}\, A_{Du}) \quad (25)$$

From this equation, the value of t_2 for the sedentary nude subjects (I_{cl} = 0) of B = 60 kg and A_{Du} = 1.7 m^2 in a still air, is estimated about 1.8 h, which could explain the characteristics of the experimental data[11)]. By applying following equation on the data, the value of k_2 is found to be about 0.88 .

$$k_2 = [\{T_{sk}\,(1) - T_{sk}\,()\,\}/\,\{\, T_{sk}\,(0) - T_{sk}\,()\}]\,/\exp(-1/4.0) \quad (26)$$

As the result, k_1 becomes 0.12. By analyzing data for t < 1 [h] we obtained t_1 = 0.18 [h]. Then the following equation is given for sedentary subjects, assuming t_1 is constant (= 0.18).

$$T_{sk}\,(t) = T_{sk}\,() + \{\, T_{sk}\,(0) - T_{sk}\,()\}\{0.12 \exp(-t\,/0.18) + 0.88 \exp(-t\,/t_2)\} \quad (27)$$

Figure 12 compares values between experimental and predicted results, and seems to show a good correlation. It demonstrates the difference between the mean skin temperature in transient conditions and that at a steady state calculated from Equation(16). For practical purpose, the transitional values of mean skin temperature at the room temperature of PMV=-0.5 are presented in Figure 13, from which it is found that the decrease of mean skin temperature (DMST) at PMV=-0.5 varies with both of the thermal resistance of clothing and elapse of time.

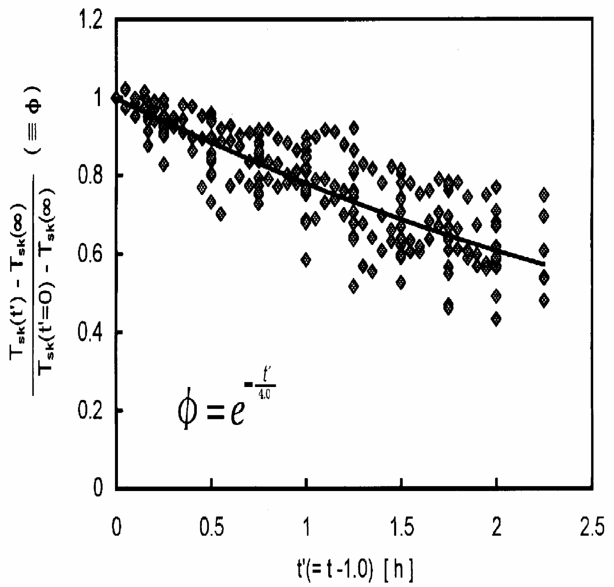


Figure 11. Empirical quation for the mean skin temperature decrease derived from data shown in this figure.

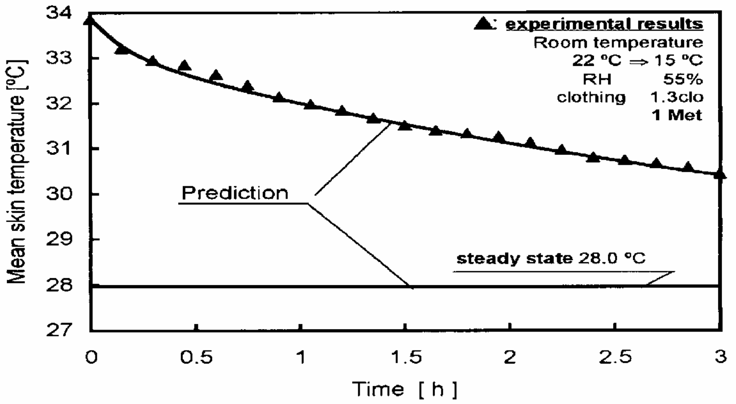


Figure12. Comparison of experimental and predicted mean skin temperatures showing a good correlation, and demonstrating the difference between the mean skin temperature in transient conditions and that at a steady state calculated from Equation(16).

CONCLUSIONS

The applicability of a new model (Predicted Mean Skin Temperature PMST) to subjects exercising in hot environment was confirmed by showing that under such conditions a linear relationship exists between thermal regulatory sweating and steady state mean skin temperature. As a result, the steady state mean skin temperature has been successfully predicted as a function of four environmental factors (air temperature, humidity, air velocity and radiation) and two human factors (clothing and metabolic heat production).

The relationships between PMST and PMV (by Fanger), and PMST and TNM (by Gagge et al.) have been presented.

In addition, an equation for predicting mean skin temperature of people in transient conditions who move into a room of low temperature, has been derived as a function of room temperature, clothing, and elapse of time.

ACKNOWLEDGMENTS

Our appreciation is expressed to Prof.Y.Nishi for providing us with the program for the Two-Node-Model. The authors are indebted to Messes. T.Takeuchi, T.Yamazaki and M.Maki for preparing this paper.

NOMENCLATURE

A_{Du} = DuBois surface area of human body [m^2], B = weight of human body [kg], C = heat loss by convection [W/m^2], c_b = specific heat of human body (= 0.97) [J/kgK], C_{res} = dry heat loss by respiration [W/m2], E_{diff} = heat loss by vapor diffusion through the skin [W/ m^2], E_{max} = maximum evaporative heat loss (= L_r h_c (P_{sk}- P_a) F_{pcl}) [W/ m^2], E_{res} = latent heat loss by respiration [W/m^2], E_{swe} = heat loss by sweating due to exercise [W/ m^2], E_{swt} = heat loss by regulatory thermal sweating [W/ m^2], f_{cl} = ratio of surface area of clothed body to that of nude body [-], f_{eff} = effective radiation area factor [-], F_{pcl} = permeation efficiency factor for vapor evaporated from skin surface through clothing to the air [-], H = metabolic heat production [W/ m^2], h_c = convective heat transfer coefficient [W/(K m^2)], h_r = radiative heat transfer coefficient [W/(K m^2)], I_{cl} = clothing insulation [clo], k_1 = empirical coefficient [-], k_2 = empirical coefficient [-], k_c = change rate of the mean body temperature corresponds to a unit change of mean skin temperature. [-], k_{d1} =3.05k_{sk1}, k_{d2} =3.05/(L_r h_c F_{pcl}), k_{mt} =factor on regulatory sweating [g/(h m^{2}K)], k_{rc} = f_{cl} /{0.155I_{cl} + 1/(f_{eff} h_r + h_c)} [W/(m^{2}K)], k_{sw} = factor on evaporative heat loss by regulatory sweating [W/(m^{2}K)], k_{sk1} = see P_{sk}, k_{sk2}

= see P_{sk}, L_r = Lewis relation [K/kPa], M = metabolic energy production [W/ m^2], m_{sw} (= m_{swt} + m_{swe}) sweating rate [g/(h m^2)], m_{swe} =sweating rate due to exercise [g/(h m^2)], m_{swt} = regulatory thermal sweating rate [g/(h m^2)], P_a = vapor pressure of the air [kPa], P_{sk} = saturated vapor pressure at mean skin temperature (P_{sk} = $k_{sk1}T_{sk}$ + k_{sk2}) [kPa], R = heat loss by radiation [W/ m^2],R_{cl} = thermal resistance of clothing [m^{2}K/W], R_s = thermal resistance of clothing surface [m^{2}K/W], t = time of exposure [h], t_1 = time constant [h], t_2 = time constant [h], T_o = operative temperature [], T_{sk} = mean skin temperature [], T_{sk} () = mean skin temperature at steady state (t =) [], T_{sk} (0) = mean skin temperature at the beginning of exposure (t = 0) [], T_{sk} (t) = mean skin temperature at exposure time t [h], T_{skh} = critical mean skin temperature where the regulatory sweating begins [], T_{sko} = mean skin temperature in thermal neutrality [], W = work accomplished [W/ m^2], w_{sw} = wetted area ratio defined by (E_{swe} +E_{swt})/E_{max} [-], a = sensitivity coefficient as a function of metabolic heat production in PMV by Fanger [m^2/W], η = W/M [-].

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