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## Control of Thermal Sweating and Comfort Sensation of Man

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### Abstract

A comfort diagram is proposed as an index of comfort sensation and for the evaluation of the thermal environment based on a rational heat balance equation. The four main channels of heat exchange are considered from an engineering viewpoint. For radiation heat loss, by extending Gebhart's absorption factor and applying it to the space between the human body and the surrounding walls, a new coefficient of radiant heat transfer is derived. A convective heat transfer coefficient for the human body is also derived based on the heat and mass transfer theory. For the evaporation heat loss from the skin surface, a new model is proposed, i. e., a model is based on that the evaporation heat loss would be inversely proportional to the wettedness and that wettedness would vary even on an equal thermal sensation line. The characteristics of the proposed model were verified by comparing calculated values with physiological data observed in the experiments and the indices given by earlier workers. Lines of comfort sensation can be drawn based on the heat balance equation derived and a control rule of perspiration. The proposed comfort index is prepared for some relevant combinations of variables concerned, namely, clothing insulation, metabolic rate and air movement.

### 1. Introduction

Ambient air temperature alone is not an adequate indication for evaluating environmental warmth. Radiant temperature, humidity, wind and so forth are also important factors of the environmental side which exert a great influence on the thermal sensation. Many attempts have been made by biological engineers and physiologists to establish thermal criteria, i. e., evaluation of levels of thermal sensations. However, the complexity of thermal environments has prevented the establishment of an exact quantitative thermal sensation index in terms of both environmental and physiological parameters.

By applying the heat and mass transfer theory, an analysis of thermal comfort sensation in a steady state is carried out from an engineering angle and a comfort

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diagram is proposed. The proposed index is used to predict thermal comfort sensation from the integrated evaluation of environmental and physiological variables, i. e., ambient air temperature, radiant temperature, humidity, air movement, clothing and metabolic rate.

## 2. Nomenclature

- M : metabolic rate, Kcal/m<sup>2</sup>h  
H<sub>r</sub> : radiation heat loss, Kcal/m<sup>2</sup>h  
H<sub>c</sub> : convection heat loss, Kcal/m<sup>2</sup>h  
H<sub>e</sub> : evaporation heat loss from skin surface, Kcal/m<sup>2</sup>h  
H<sub>n</sub> : respiration heat loss, Kcal/m<sup>2</sup>h  
Q<sub>r</sub> : heat released by radiation exchange, Kcal/h  
A<sub>s</sub> : effective skin area which relates to heat exchange (effective skin area for the radiation, convection and evaporation heat loss is assumed to be equal to the whole body surface area respectively in the present study), m<sup>2</sup>  
S<sub>i</sub> : surface area of surrounding wall, m<sup>2</sup>  
w : wettedness, N. D.  
G : quantity of insensible perspiration and sweat secretion (at comfortable conditions, insensible perspiration alone), g/m<sup>2</sup>h  
L : latent heat, Kcal/g  
h<sub>r</sub> : linear radiation exchange coefficient in man (= ε<sub>s</sub>σk), Kcal/m<sup>2</sup>h °C  
h<sub>c</sub> : convective heat transfer coefficient in man, Kcal/m<sup>2</sup>h °C  
h : heat transfer coefficient in man (= h<sub>r</sub> + h<sub>c</sub>), Kcal/m<sup>2</sup>h °C  
ε<sub>s</sub> : emissivity of man, N. D.  
ε<sub>i</sub> : emissivity of wall, N. D.  
σ : Stefan-Boltzmann constant, Kcal/m<sup>2</sup>h K<sup>4</sup>  
k : temperature factor on radiation exchange, K<sup>3</sup>  
κ : modified Lewis relation, °C/(g/kg)  
b<sub>is</sub> : absorption factor from wall to man, N. D.  
b<sub>si</sub> : absorption factor from man to wall, N. D.  
T<sub>s</sub> : mean skin temperature, °C  
T<sub>r</sub> : mean radiant temperature, °C  
T<sub>a</sub> : ambient air temperature, °C  
V : air movement, m/s  
X<sub>ss</sub> : saturated humidity ratio for boundary layer at skin surface, g/kg  
X<sub>a</sub> : humidity ratio in ambient air, g/kg  
ψ<sub>a</sub> : percentage humidity, %  
I : clo unit (1 clo = 0.18m<sup>2</sup>h °C/Kcal), N. D.  
η : moisture permeability coefficient, N. D.

### 3. Radiation heat loss

The rate of radiation heat exchange between a human body and its surrounding wall surfaces is given as follows [1], by applying and developing Gebhart's absorption factor [2] which deals with reciprocal radiation exchange.

$$\begin{aligned} Q_r &= \varepsilon_s \sigma (T_s + 273)^4 A_s - \sum b_{is} \varepsilon_i \sigma (T_i + 273)^4 S_i \\ &= \varepsilon_s \sigma k (\sum b_{si} T_s - \sum b_{si} T_i) A_s \\ &= h_r (T_s - \sum b_{si} T_i) A_s \end{aligned} \quad (1)$$

$$H_r = \frac{Q_r}{A_s} = h_r (T_s - T_r) \quad (2)$$

Although the effective surface area for radiation exchange may vary with the posture and clothing worn, in the present work the whole body surface area is applied as an approximation. Since the temperature factor  $k$  in Eq (1) can be treated as a constant and the skin of a human body and garment surface would have an emissivity close to that of a black body. A term  $\varepsilon_s \sigma k$  can be assumed as a constant value in a temperature range of our daily life. The linear radiation exchange coefficient for an unclothed man is now defined by

$$h_r = \varepsilon_s \sigma k = 5.14 \text{ Kcal/m}^2\text{h } ^\circ\text{C}$$

The value substituted,

$$\varepsilon_s = 0.95 \text{ N. D.}$$

$$\sigma = 4.88 \times 10^{-8} \text{ Kcal/m}^2\text{h K}^4$$

$$k = 1.11 \times 10^8 \text{ K}^3$$

Since the surface temperature of clothing worn is less than that of skin, the coefficient value under clothed conditions was also examined. The radiation coefficient

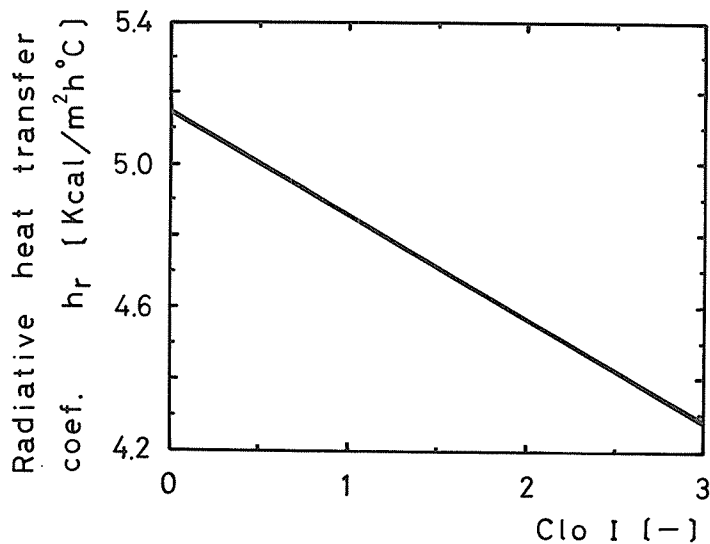


Fig. 1 Relation between radiative heat transfer coefficients and clo value [3]

resulted in a value of 4.8 to 5.0 Kcal/m<sup>2</sup>h °C corresponding to 1.0 to 0.5 clo [3].

Moreover,  $T_r = \Sigma b_{si} T_i$  derived theoretically in Eq (2) expresses a kind of mean radiant temperature and is defined by a weighted mean of the temperatures of the surrounding surface with an absorption factor which includes angle factor. In order to differentiate the mean radiant temperature weighted by an angle factor or by area ratio and to avoid confusion brought about by the difference in averaging, a new mean radiant temperature  $T_{r'} = \Sigma b_{si} T_i$  will be referred to as "environmental radiant temperature" [4].

#### 4. Convection heat loss

The heat loss by convection from the skin surface to the ambient air can be written by the following equation.

$$H_c = h_c (T_s - T_a) \quad (3)$$

The convective heat transfer coefficient in Eq (3) takes widely varying values affected by the velocity of air flow, physical properties, and the shape and size of a human body. Eq (4), a mean convection coefficient for a man, which considers both natural and forced convection at the same time, was theoretically derived by the author [1]. Effective convection area is assumed to be equal to a whole body surface area as the same as in the case of radiation exchange. As a result of being investigated from various aspects, the equation which calculates the convection coefficient for an unclothed and a clothed man was proposed as follows [3].

$$h_c = \sqrt[3]{270V^2 + 23} \quad (4)$$

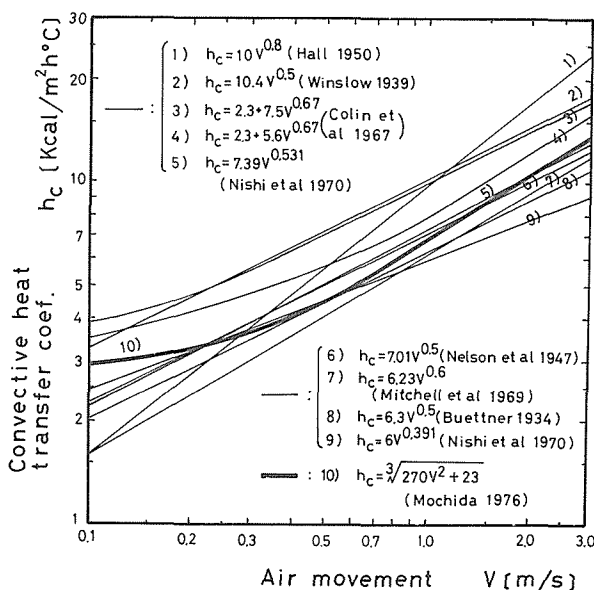


Fig. 2 Convective heat transfer coefficients for human body [1]

### 5. Evaporative heat loss from skin surface

In the present study evaporative heat loss means the insensible heat loss and that by sweat secretion from skin surface and the discussion is limited within a range where no sweat dripping occurs in the heat and no shivering takes place in the cold.

The outline of wettedness which takes different value on the line of an equal skin temperature is described briefly [5].

The general equation of evaporative heat loss is expressed using wettedness proposed by Gagge et al [6] as follows.

$$H_e = G \cdot L = \kappa h_c (X_{ss} - X_a) W \quad (5)$$

Drawn by using heat balance equation Eq (7)' containing Eq (5), an equal skin temperature line with constant wettedness shows a straight line as shown in Fig. 3. In this case the evaporative heat loss in the hot environment where the humidity is absolutely zero amounts to 238 Kcal/m<sup>2</sup>h and this value is approximately the quintuple of the metabolic rate, as is evident from Fig. 3. However, the two following facts, the experimental report that evaporative heat loss while sedentary in the shade in a desert [7] is almost twice the quantity of the metabolic rate and Givoni's experimental data [8], which only give a few examples, in the hot circumstances shown in Fig. 3, suggest that an equal thermal sensation line might not change linearly but would draw a curve, as is extrapolated in broken lines in Fig. 3. From analyses of Givoni's data, the following three items became evident [5] :

On the line of equal thermal sensation,

1. wettedness is not constant but takes varying values.

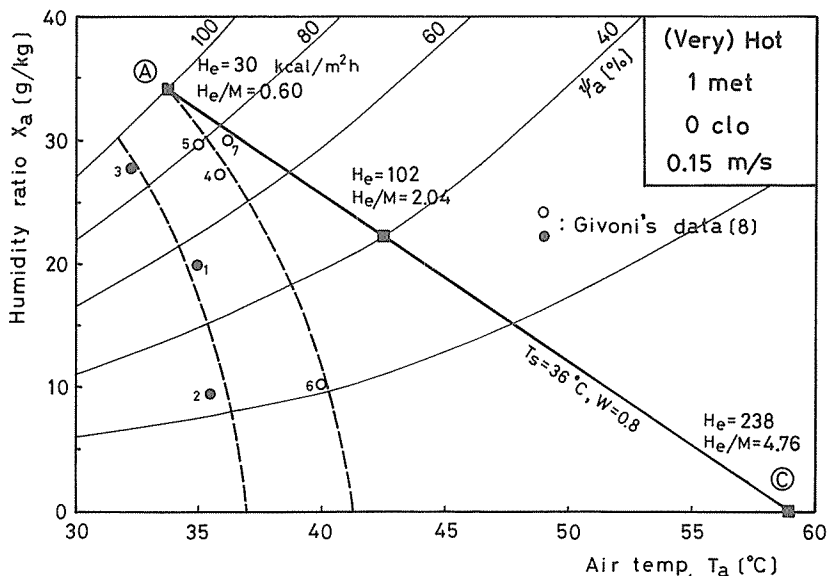


Fig.3 Equal thermal sensation line at hot environment and evaporative heat loss [5]

2. evaporative heat loss is inversely proportional to wettedness.
3. the value of wettedness in a low range of humidity is smaller than that in a high range.

With these considerations above in mind, we set forth a relation between the quantity of evaporation and wettedness shown in Fig. 4 as a temporary standard and term this relation “control rule of perspiration” in the present study. In Fig. 5 theoretical results calculated by using both the control rule of evaporation (Fig. 4) and heat balance equation Eq (7)’ almost coincides with the experimental values observed by

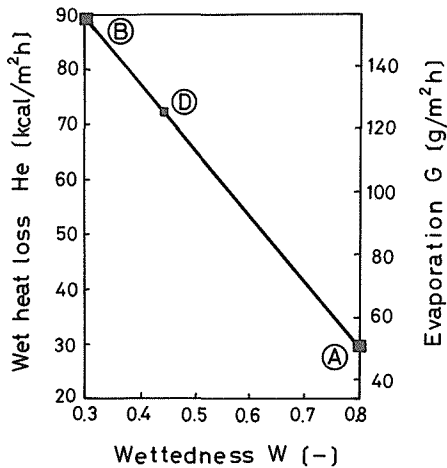


Fig. 4 Control rule of perspiration in hot condition—relation between wettedness and evaporation [5]

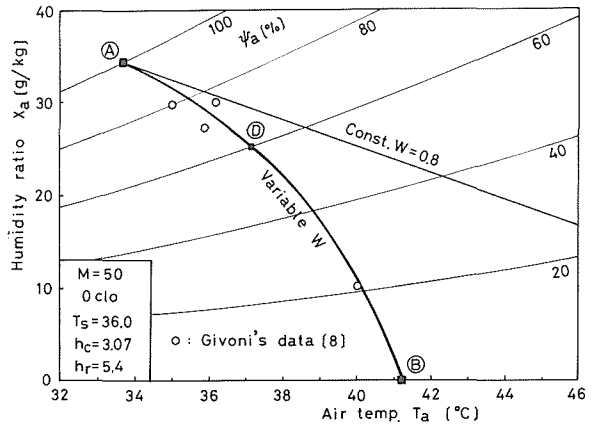


Fig. 5 Calculated lines of equal skin temperature 36.0°C—comparison of the lines by constant wettedness and by variable wettedness based on the present model [5]

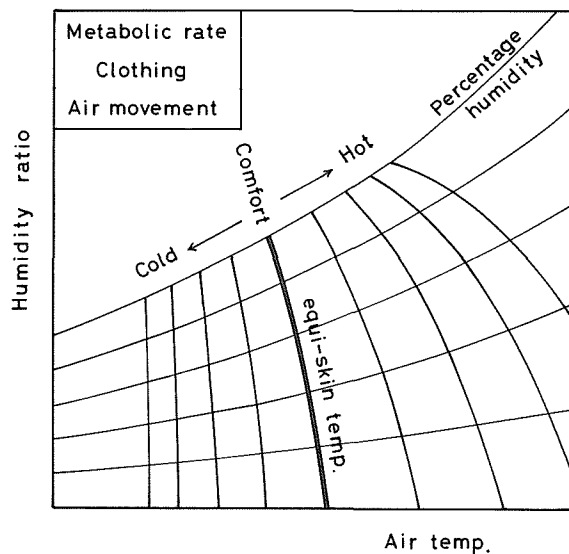


Fig. 6 Schematic lines of equal skin temperature on the psychrometric chart by the present model

Givoni. In comfortable conditions, the same idea that evaporative heat loss would be inversely proportional to wettedness might be applied as the same as in the case in the hot conditions. Under the above assumptions, the schematic comfort line of equal skin temperature drawn by the heat balance equation containing the present evaporation model is shown in Fig. 6 and the locus is not a straight line but a curve on a psychrometric chart similar to the results of investigations under hot conditions. This conclusion agrees with an empirical fact that the influence of humidity on thermal sensations becomes smaller as the humidity of environment is lowered. A numerical relation between the quantity of evaporation and wettedness in comfort condition and a comfort line in this case will be described in chapter 7. Further, the loci of other equal thermal sensation lines based on the present model will be also shown in Fig. 6.

## 6. Respiration heat loss

The following expression proposed by Fanger[9] is applied to calculate heat loss by respiration in the present paper.

$$H_n = M (0.148 - 0.0014T_a - 0.0028X_a) \quad (6)$$

## 7. Comfort diagram

### 7-1. Equilibrium on the human body

#### 1) Heat balance equation of the nude man

In a steady state a human body exchanges heat with the surroundings through four main channels, namely, radiation, convection, evaporation and respiration, when a small quantity of heat by the rate of external mechanical work and so forth is neglected.

The heat balance between an unclothed man and the thermal environment is expressed by substituting all the heat loss terms derived above in the form of

$$\begin{aligned} M &= H_r + H_c + H_e + H_n \\ &= h_r (T_s - T_r) + h_c (T_s - T_a) + \kappa h_c (X_{ss} - X_a) W \\ &\quad + M (0.148 - 0.0014T_a - 0.0028X_a) \end{aligned} \quad (7)$$

In the uniform temperature field where the air temperature is equal to the radiant, Eq (7) is converted to Eq (7)′.

$$\begin{aligned} M &= h (T_s - T_a) + \kappa h_c (X_{ss} - X_a) W \\ &\quad + M (0.148 - 0.0014T_a - 0.0028X_a) \end{aligned} \quad (7)'$$

#### 2) Heat balance equation of the clothed man

When clothed, the following heat balance equation is obtained by taking into consideration heat and vapor resistance of clothing worn.

$$\begin{aligned} M &= H_r + H_c + H_e + H_n \\ &= h_r P (T_s - T_r) + h_c P (T_s - T_a) + \kappa h_c R (X_{ss} - X_a) W \\ &\quad + M (0.148 - 0.0014T_a - 0.0028X_a) \end{aligned} \quad (8)$$

In a uniform temperature field,

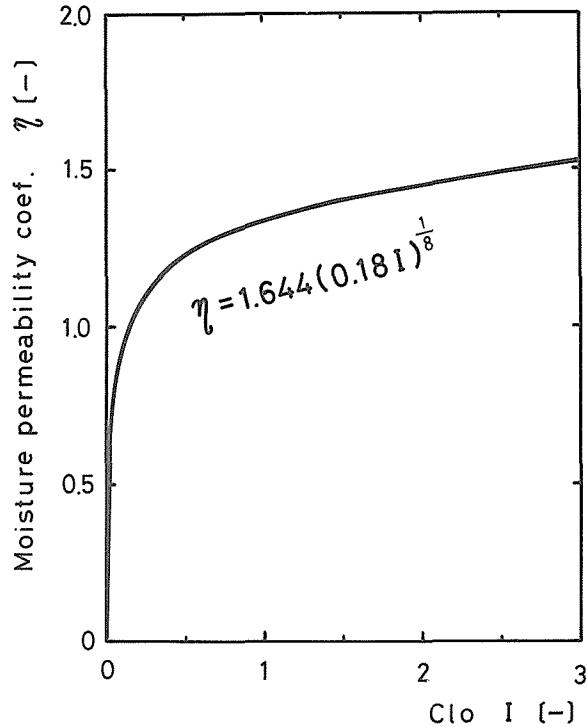


Fig. 7 Relation between moisture permeability coefficient and clo value [10]

$$M = hP(T_s - T_a) + \kappa h_c R(X_{ss} - X_a)W + M(0.148 - 0.0014T_a - 0.0028X_a) \quad (8)'$$

where,

$$P = \frac{1}{0.18Ih + 1} \quad R = \frac{1}{0.18I\eta h_c + 1}$$

In the above equation,  $I$  is a clo unit to evaluate thermal resistance of clothing and  $\eta$  is moisture permeability coefficient [10] as a measure of vapor diffusion through a clothing ensemble. The theoretically derived relation between moisture permeability coefficient and clo value is shown in Fig. 7.

## 7-2. Comfort lines by the present model

The characteristics of the present comfort index is as follows.

In this paper, mean skin temperature  $33.5^\circ\text{C}$  with wettedness which turns from 0.09 (at saturated humidity environment) to 0.06 (in an absolute dry environment) represents thermal comfort or a neutral condition after being investigated from various viewpoints.

We describe the procedure for the determination of the present comfort line.

Let us imagine an unclothed resting man in a comfortable room with still air movement. We begin with finding out two intersections on the psychrometric chart of Fig. 8—the point  $\textcircled{A}$  where the skin temperature  $33.5^\circ\text{C}$  line with wettedness 0.09 and the saturated humidity line meet, and the intersection  $\textcircled{B}$  where the skin temperature

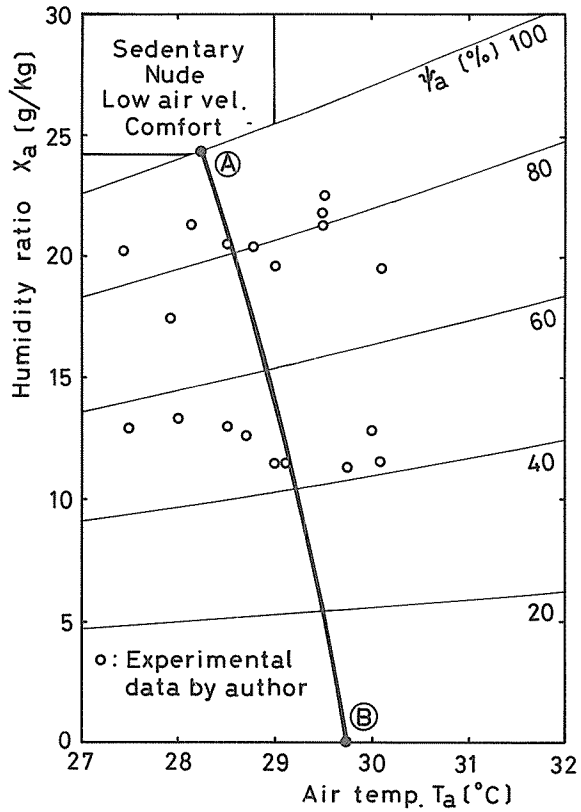


Fig. 8 Verification of the present comfort line

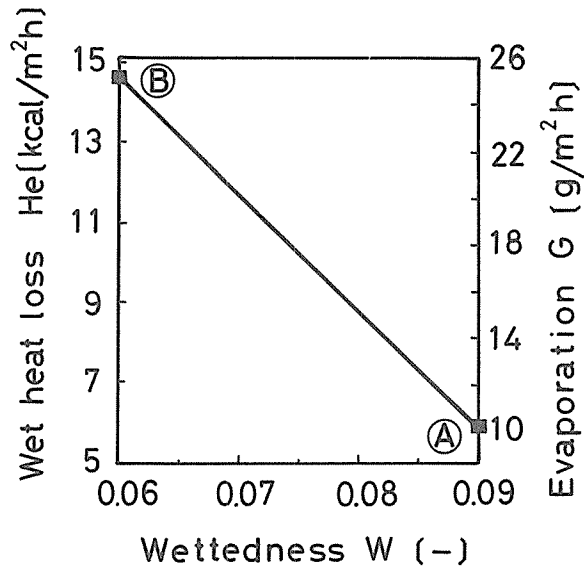


Fig. 9 Control rule of perspiration in comfort condition — relation between wettedness and evaporation [5]

33.5°C line with wettedness 0.06 and the axis of abscissa or the absolute dry humidity line cross each other—by using Eq (7)' substituted values concerned. Two environments obtained indicate that the starting point and the terminus of the comfort line in this case and these are also the points that show the minimal amount of evaporation from skin surface and the maximum respectively. After these procedures, by using Eq (5) we calculate the quantities of evaporation at the two points obtained and prepare for making Fig. 9 or a control rule of perspiration. Next, although the lines which connect the two quantities of evaporation determined as mentioned above will be various, a solid line shown in Fig. 9 is assumed to the first approximation [5]. By connecting the points in the order that satisfy both the perspiration rule of Fig. 9 and Eq (7)' at the same time, we obtain an equal skin temperature line with variable wettedness on a psychrometric chart.

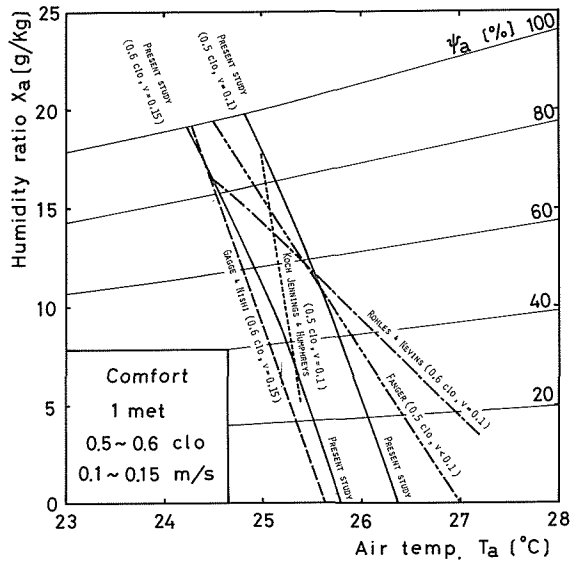


Fig. 10 Comparison of comfort lines

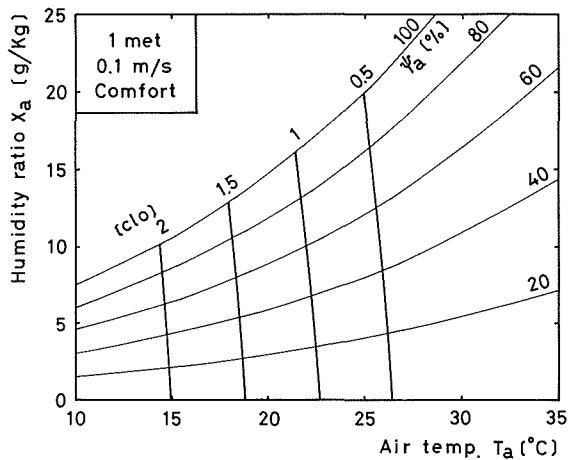


Fig. 11 Comfort lines

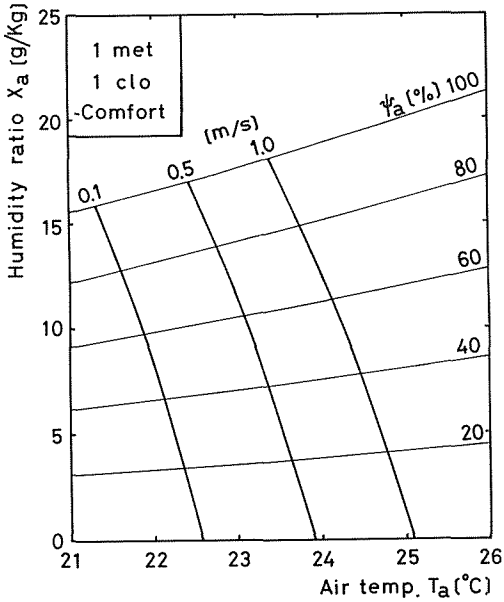


Fig. 12 Comfort lines

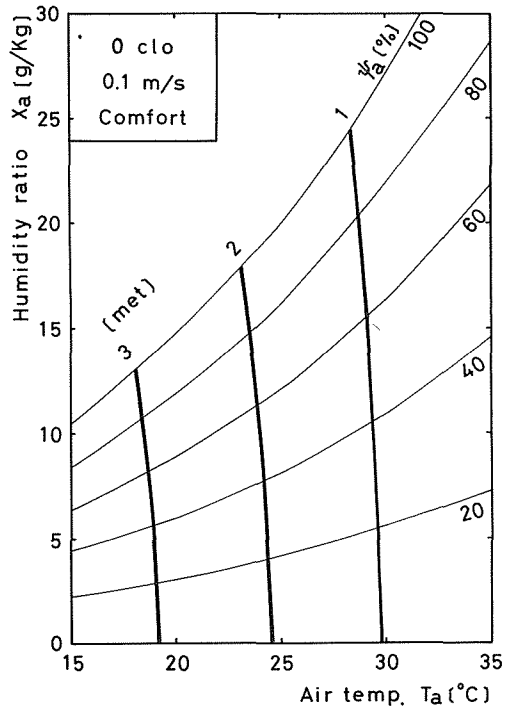


Fig. 13 Comfort lines

The curved line of equal skin temperature drawn by plotting as the above is shown in Fig. 8 in comparison with experimental data.

Although the experimental values are scattered, the present theoretical comfort line agrees with the measured results.

The comfort lines for a clothed man drawn in the same manner are shown in Fig. 10 and compared with comfort lines by earlier workers—Gagge et al [6], Fanger [9], Koch et al [11] and Rohles et al [12].

Good agreements between the 0.6 clo-0.15m/s comfort line by Gagge et al and the present one can be read off Fig. 10. On the other hand, we can see that under conditions of 0.5 clo-0.1m/s, the slope, which seems to indicate the rate of the effect of humidity on thermal sensation, of the present line lies between the line set forth by Fanger and that by Koch et al.

Comfort lines in Fig. 11 to 13 represent combinations of environment factors to give comfort sensation for the denoted conditions.

## 8. Conclusions

As an index of comfort sensations, a comfort diagram was proposed based on a rational heat balance equation between the thermal environment and the human body.

The four main channels of heat exchange, i. e., radiation, convection, evaporation

from the skin surface and respiration, are considered and especially, a new linear radiation exchange coefficient derived theoretically by applying and developing the absorption factor method, a convective heat transfer coefficient taking into consideration both natural and forced convection, and a control method of perspiration followed by a definite relation between evaporation and wettedness, were introduced.

A characteristics of equal thermal sensation line based on the present model is not a straight line but a curve line on a psychrometric chart. This shows that in conclusion the effect of humidity on thermal sensations becomes smaller as the humidity of environment is lowered. Comfort lines under various conditions were drawn and compared with experimental data using subjects or calculated comfort lines, which are all shown by a straight line with a negative gradient on a psychrometric chart, by earlier workers. According to the present results, comfort lines derived show a fairly good approximation in comparison with some earlier comfort indices.

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