北海道大学工学部研究報告
第155号（昭和58年）

Bulletin of the Faculty of Engineeing,
Hokkaido University. No. 155 (1983)

Characteristics of Wettedness and Equi-Skin Temperature Line in the Evaporative Regulation Region

Tohru Mochida

(Received March 31, 1983)

Abstract

As a result of the analysis of physiological experimental data, the characteristics of the wettedness were clarified, i. e., the value of the wettedness is not constant but differs in accordance with the environmental humidity even when the skin temperature is the same, and it was shown that the evaporative heat loss from the skin surface is inversely proportional to the wettedness.

Based on the properties of the wettedness observed, a new thermal sensation chart in the evaporative regulation region was proposed as an index for evaluating the warmth or the coldness in the environment.

The feature of the present chart is that the locus of the equal skin temperature appears as a curved line on the psychrometric chart and that the wettedness on the equi-skin temperature line is not constant but takes varying values. The curved equal skin temperature line means that the influence of the environmental humidity on thermal sensation becomes smaller as the humidity of the environment is lowered.

1. Introduction

Many attempts have been made to establish thermal criteria, i. e., evaluation of levels of thermal sensation have been made, mainly based on two methods. One is the method which uses a thermal model —— a kind of instrument, and the other is the manner in which the thermal sensation is evaluated by using the diagram or nomogram. The instruments that belong to the former are: Kata Thermometer by Hill, Frigorimeter by Tilenius et al, Eupatheostat by Dufton, Globe Thermometer by Vernon, Coolometer by Weeks, Eupateoscope (Mark I and II) by Dufton et al, Frigograph by Pfleider et al, Rafraichmeter by Eda et al, Resultant Thermometer (Mark I and II) by Missenard, Thermo-Integrater by Winslow et al, Heated Globe Thermometer by Yaglou, and Aitken Thermometer by Dufton. These apparatuses were made before 1940 and now the thermal manikin has been made.

On the other hand, the diagrams or the nomograms obtained from the results of experiments using subjects or theoretical investigations are: Effective Temperature by Yaglou et al, Corrected Effective Temperature by Vernon et al, Resultant Temperature by Missenard, Equivalent Temperature by Dufton et al, Equivalent Warmth by Bedford, Operative Temperature by Gagge et al, Discomfort Index by Bosen et al, Heat Stress Index by Belding et al, Index of Thermal Stress by Givoni, Predicted Four-Hour Sweat Rate by McArdle, Wet Bulb Globe Thermometer Index by Minard, Temperature Humidity Index

Department of Sanitary Engineering, Faculty of Engineering,
Hokkaido University, Sapporo, 060, Japan

by Nevins et al, Comfort Chart by Fanger, Thermal Sensation Diagram by Nishi and New Effective Temperature by Gagge et al.

In the present paper, the experimental data obtained using subjects were analyzed and the tendency in which the value of wettedness varies mainly by the environmental humidity outwardly even when the skin temperature is the same was clarified. Here, on the basis of the characteristics of wettedness observed, an index for evaluating thermal sensation is proposed. The feature of this index is that the line of equal skin temperature or the equal thermal sensation describes a curve on the psychrometric chart and that the wettedness varies on the equi-skin temperature line.

2. Nomenclature

M : metabolic rate, kcal/m²h
H_c : convection heat loss, kcal/m²h
H_r : radiation heat loss, kcal/m²h
H_e : evaporation heat loss from skin surface, kcal/m²h
H_n : respiration heat loss, kcal/m²h
h_c : convective heat transfer coefficient for man, kcal/m²h°C
h_r : linear radiation exchange coefficient for man, kcal/m²h°C
ξ : effective radiation area factor, N. D.
κ : modified Lewis relation, °C/mmHg
T_s : mean skin temperature, °C

Table 1. Givoni's experimental data (1 met, unclothed) [2] and calculated values

experimental data (by Givoni)							calculated values (by author)	
experiment number	air temp. T_a [°C]	relative humidity R. H. [%]	air movement v [m/s]	average skin temp. T_s [°C]	thermal sensation vote T. S. V.*1 [−]	perspiration E [g/cap.h]	perspiration heat loss H_e [kcal/m²h]	total wettedness W [−]
1	35.0	54	0.15	35.0	5.8	170	49.1	0.63
2	35.4	25	0.15	35.2	5.9	174	50.2	0.40
3	32.2	87	0.15	34.5	6.1	144	41.6	1.10
4	35.9	70	0.15	35.4	6.9	179	51.7	1.04
5	35.0	80	0.15	35.9	6.9	170	49.0	1.12
6	40.0	21	0.15	36.5*2	7.0	217	62.5	0.46
7	36.2	76	0.15	36.4*3	6.7	181	52.6	1.10

Notes : ○ The relation between thermal sensation vote *1 and figures are as follows.
1 : very cold 2 : cold 3 : cool 4 : comfortable 5 : warm 6 : hot
7 : very hot 8 : unbearably hot
○ The average skin temperatures (*2and*3) are assumed because of no description in the original data.
○ The total skin surface area is assumed to be 2m².
○ An experimental datum calculated to be wettedness 2.16 backwards is excluded in the above table although eight experiments were performed by Givoni.

T_a : ambient air temperature, °C
T_o : operative temperature, °C
P_{ss} : saturated vapor pressure for boundary layer at skin surface, mmHg
P_a : vapor pressure in ambient air, mmHg
W : total wettedness, N. D.
I : clo unit (1 clo = 0.18 m^2h°C/kcal), N. D.
η : moisture permeability coefficient, N. D.

3. Characteristics of wettedness

The characteristics of the wettedness which Gagge et al[1]have proposed are examined in this chapter.

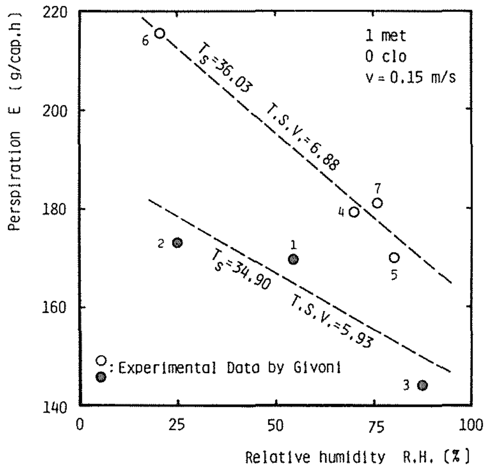

Fig. 1 Relation between perspiration and relative humidity

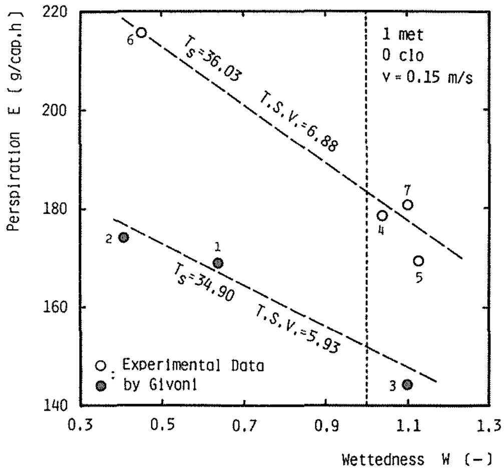

Fig. 2 Relation between perspiration and wettedness calculated

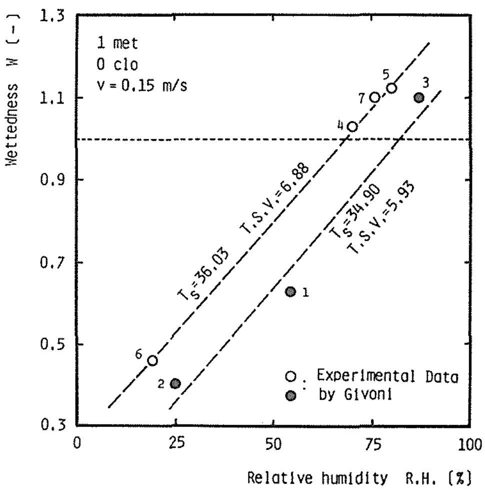

Fig. 3 Relation between wettedness calculated and relative humidity

We begin by investigating the experimental data reported by Givoni[2]in order to know the characteristics of the total wettedness.

Figs. 1, 2 and 3 show the relationships among the quantity of evaporation, the relative humidity and the wettedness calculated from Givoni's experimental data shown in Table 1. As seen in Table 1 or Figs. 1, 2 and 3, although some wettedness values calculated are more than unity, both the group marked ○ with the mean skin temperature 36.03°C and the mean thermal sensation vote 6.99 and the group marked ● with the mean skin temperature 34.90°C and the mean thermal sensation vote 5.93 show a similar trend respectively. In other words, the evaporation is large but the wettedness is small in the high environmental temperature and low humidity region, on the other hand, the wettedness is large but the evaporation is small in the environment where the air temperature is relatively low and the humidity is high. These facts indicate that in the high humidity range, the large wettedness compensates for the small difference between the skin humidity and the ambient air and that in the low humidity area, thermal equilibrium is maintained by the large difference between the skin humidity and the surrounding air, even when the wettedness in not very large.

The following four items can be estimated from the examinations of Figs. 1, 2 and 3 based on the analysis of Givoni's data.

On the line of the equal skin temperature or the equal thermal sensation vote,

1. the wettedness is not constant but takes varying values.
2. the evaporation heat loss is inversely proportional to the wettedness.
3. the value of the wettedness in a high range of environmental humidity is larger than that in a low range.
4. the line of the equal skin temperature is expected not to be straight but is expected to be curved on the psychrometric chart.

4. Heat balance equation for the human body

4-1. The line of the constant skin temperature and wettedness

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

In the uniform temperature field where the ambient air temperature is equal to the radiant, the heat balance between an unclothed subject and the thermal environment is written as follows, if we use the wettedness defined by Gagge et al and the expression of the respiratory heat loss proposed by Fanger [3] .

$$\begin{aligned} M &= H_c + H_r + H_e + H_n \\ &= (h_c + \xi h_r)(T_s - T_a) + \kappa h_c (P_{ss} - P_a)\ W \qquad (1) \\ &\quad + M(0.1488 - 0.0014T_a - 0.0023P_a) \end{aligned}$$

We can obtain the straight line Ⓐ-Ⓖ in Fig. 4 by using Eq (1) substituting the values concerned with the thermal characteristics as stated below, if it is assumed that on the line of the constant skin temperature, the wettedness is also constant. On the equi-skin temperature 36 °C and wettedness 0.8 line, the evaporation heat loss in the hot environment where the humidity is absolutely zero amounts to 241 kcal/m²h and this value is approximately the quintuple of the metabolic rate, as is evident from Fig. 4. Even in the environmental humidity of 40 %, the evaporative heat loss is more than twice the quantity of the metabolic heat production of the body. The figures used in the calculation of the straight lineⒶ-Ⓖin Fig. 4 are : $M=50$ kcal/m²h, $T_s=36$ °C, $P_{ss}=44.57$ mmHg, $W=0.8$, $h_c=3.07$ kcal/m²h°C ($v=0.15$m/s) 〔4〕,〔5〕,$h_r=5.15$kcal/m²h°C〔4〕,〔5〕 $\xi=0.75$ (for the unclothed and $\xi=0.8$ for the clothed subject) 〔6〕 .

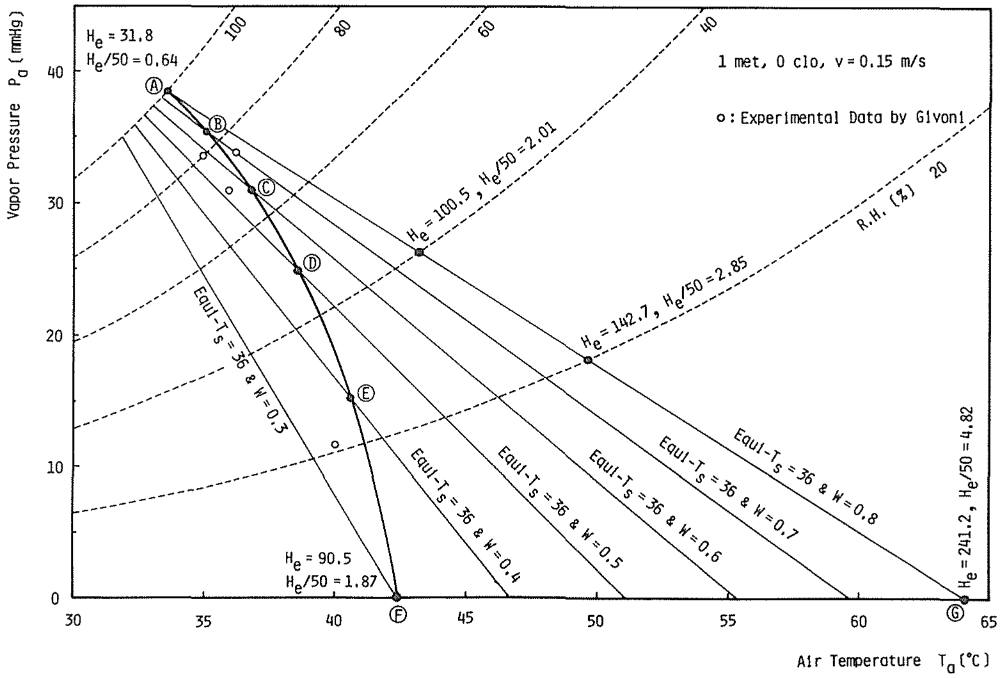

Fig. 4 Calculated lines of equi-skin temperature 36℃——Comparison of the lines by constant wettedness and variable wettedness

4-2. The line of the constant skin temperature and variable wettedness

The two following facts, i. e., the experimental report that the 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〔2〕in the hot circumstances shown in Table 1 and in Fig. 4, suggest that an equal skin temperature line or an equal thermal sensation line might not change linearly and would describe a curve. From the abovementioned limit of sweating and the analyses of the experimental data, a thermal sensation line with the equal skin temperature and variable wettedness is expected and the curved lineⒶ-Ⓕis calculated as Fig. 4. On the curved lineⒶ-Ⓕ, the value of the wettedness varies between 0.8 and 0.3, although the skin temperature 36 °C is constant, and the maximum quantity of evaporation heat loss is 90.5 kcal/m²h at the absolutely dry environment and the ratio to the metabolic rate under the sedentary condition is 1. 87.

The curved lineⒶ-Ⓕin Fig. 4 can be drawn in the following process. The first assumption is to fix the maximum wettedness 0.8 and the minimal 0.3 on the maximum skin

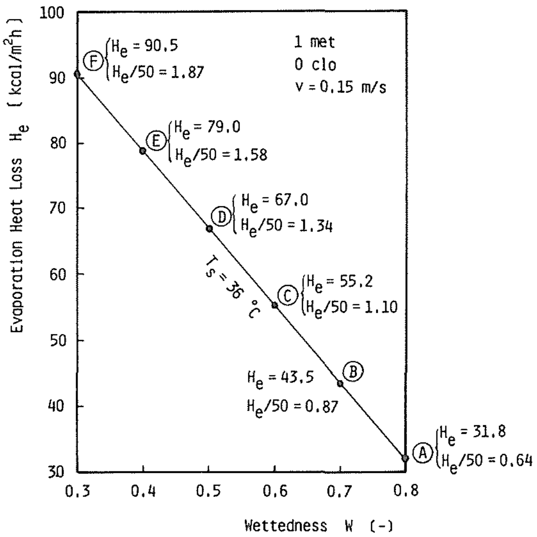

Fig. 5 "Control rule of perspiration" under the hot condition——Relation between evaporation heat loss and wettednees

temperature line in the zone of evaporative regulation considering the relation of Figs. 1, 2 and 3 but on the other hand there is no clear evidence in the literature that in the air the body can become 100 % wet. By substituting these two wettedness values 0.8 and 0.3, the mean skin temperature 36 °C which expresses a very hot sensation and the other values of thermal characteristics concerned into Eq (1), the two points Ⓐ and Ⓕ are found on the psychrometric chart as shown in Fig. 4. The point Ⓐ is the point where the skin temperature 36 °C line with the wettedness 0.8 and the environmental saturated humidity line meet, and the point Ⓕ is the point where the skin temperature 36 °C line with the wettedness 0.3 and the axis of the abscissa or the absolute dry humidity cross each other. In other words, the point Ⓐ shows a point with the mean skin temperature 36 °C and the wettedness 0.8, and the point Ⓕ represents a point with the mean skin temperature 36 °C and the wettedness 0.3. The two environments obtained also indicate that the starting point and the terminus of the very hot sensation line——the equi-skin temperature line in this case, and these are the points that show the minimal amount of evaporation from the skin surface and the maximum respectively. Our next step is to calculate the value of the evaporation heat loss at the two environments Ⓐ and Ⓕ using the equation of H_e in Eq (1), and to prepare for completion of Fig.5 or a "control rule of perspiration". The solid line shown in Fig. 5 is assumed to be the first approximation, although there will be innumerable lines which connect the two points Ⓐ and Ⓕ in Fig. 5 [8]. Finally we can obtain the equal skin temperature 36 °C line with variable wettedness, by connecting the points in the order which satisfy both the perspiration rule of Fig. 5 and Eq (1) at the same time. The slight difference between the present line Ⓐ-Ⓕ and the previous line [8] is due to the difference of the values substituted, for instance, h_r, ξ and so forth.

5. Thermal sensation chart

5-1. Relationship between mean skin temperature and wettedness

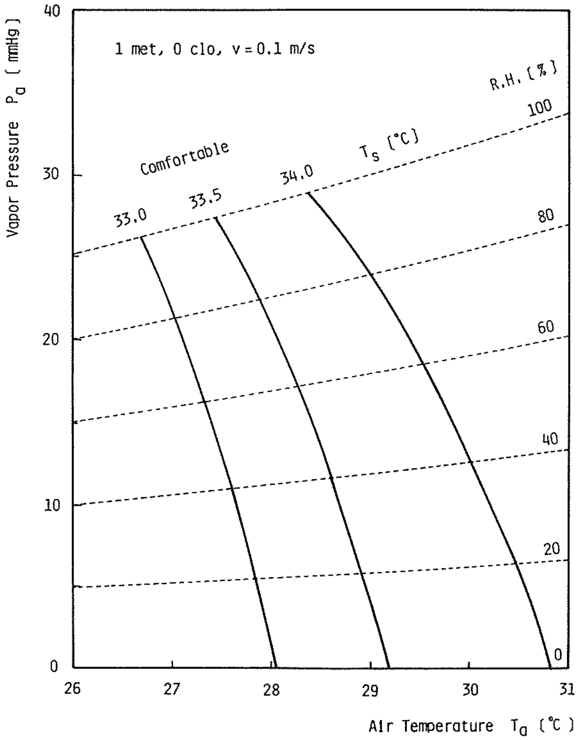

Fig. 6 Comfort range of 1 met-0 clo-0.1m/s

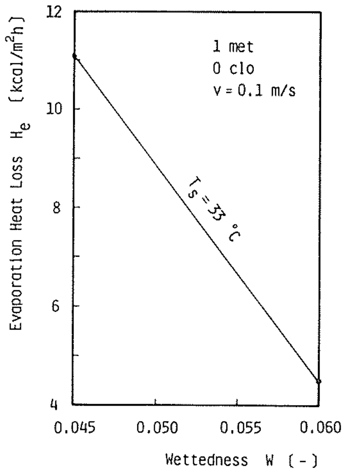

Fig. 7 Control rule of perspiration

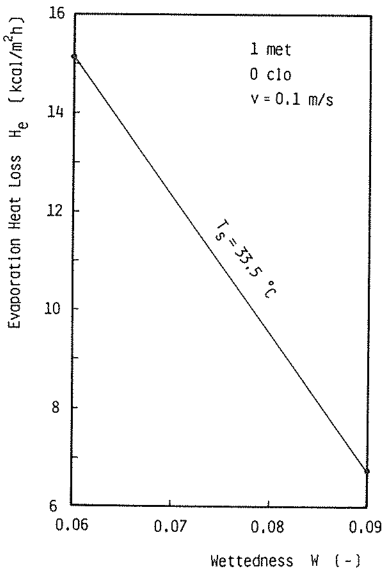

Fig. 8 Control rule of perspiration

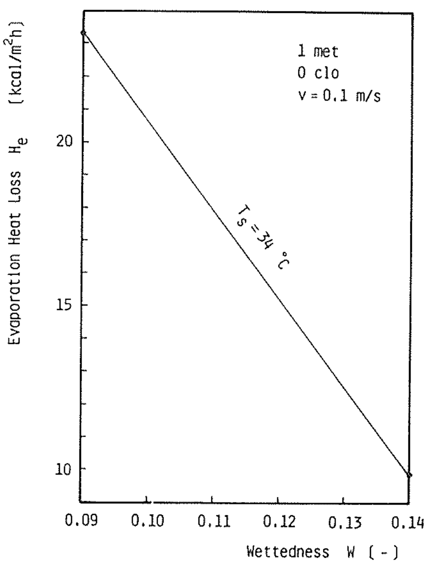

Fig. 9 Control rule of perspiration

With reference to the results of investigations of experimental data under the heat stress condition, at a comfortable condition and at other thermal sensation states, it is also assumed that the similar perspirative regulation is done and the same treatment in drawing the equi-skin temperature line is also carried out.

In the present study, the mean skin temperature 33.5 °C with the wettedness which turns 0.09 (at the saturated humidity environment) to 0.06 (in the absolute dry environment) represents the most comfortable condition and the range between the skin temperatures 33°C (the wettedness: 0.06-0.045) and 34 °C (the wettedness: 0.14-0.09) is defined as comfortable or thermally neutral. Drawn by using these thermal characteristic values concerned with a neutral condition and by the same procedure as stated above in a very hot condition, the comfort range containing the most comfortable line for an unclothed resting-sitting person is obtained as Fig. 6. Figs. 7, 8 and 9 are the control rule charts of perspiration corresponding to the conditions in Fig. 6.

5-2. Thermal sensation chart

When clothed, the following heat balance equation is given by considering heat and vapor resistance of clothing worn.

$$\begin{aligned} M &= H_c + H_r + H_e + H_n \\ &= h_c P(T_s - T_a) + \xi h_r P(T_s - T_r) + \kappa h_c R(P_{ss} - P_a)W \\ &\quad + M(0.1488 - 0.0014T_a - 0.0023P_a) \end{aligned} \tag{2}$$

In the uniform temperature field where the air temperature is equal to the radiant, Eq (2) is converted to Eq (2).′

$$\begin{aligned} M &= (h_c + \xi h_r)P(T_s - T_a) + \kappa h_c R(P_{ss} - P_a)W \\ &\quad + M(0.1488 - 0.0014T_a - 0.0023P_a) \end{aligned} \tag{2$'$}$$

where,

$$P = \frac{1}{0.18I(h_c + \xi h_r) + 1}, \qquad R = \frac{1}{0.18I\eta h_c + 1}$$

In the above equation, I is clo unit to evaluate thermal resistance of clothing and η is moisture permeability coefficient [9] as a measure of vapor diffusion through clothing ensembles. The theoretically derived relation between moisture permeability coefficient and clo unit is as follows.

$$\eta = 1.644(0.18I)^{1/8} \tag{3}$$

Further, the convection heat transfer coefficient h_c and the radiation h_r used in the calculation are as follows.

$$h_c = \sqrt[3]{270v^2 + 23} \tag{4}$$

$$h_r = -\frac{3}{10} I + 5.15 \tag{5}$$

Table 2 Maximum and minimal wettedness to mean skin temperature

T_s [°C]	29.0	30.0	31.0	32.0	33.0	33.5	34.0	34.5	35.0	35.5	36.0
Max. W [−]	0.001	0.005	0.010	0.030	0.060	0.090	0.140	0.210	0.330	0.500	0.800
Min. W [−]	0.001	0.004	0.008	0.022	0.045	0.060	0.090	0.135	0.190	0.245	0.300

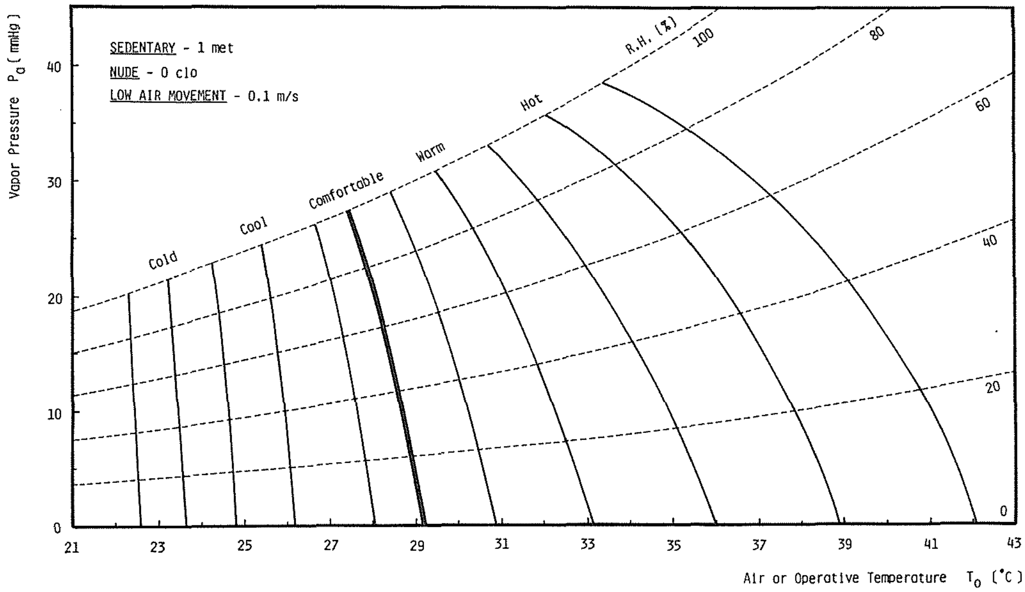

Fig.10 Thermal sensation chart— 1 met- 0 clo-0.1m/s

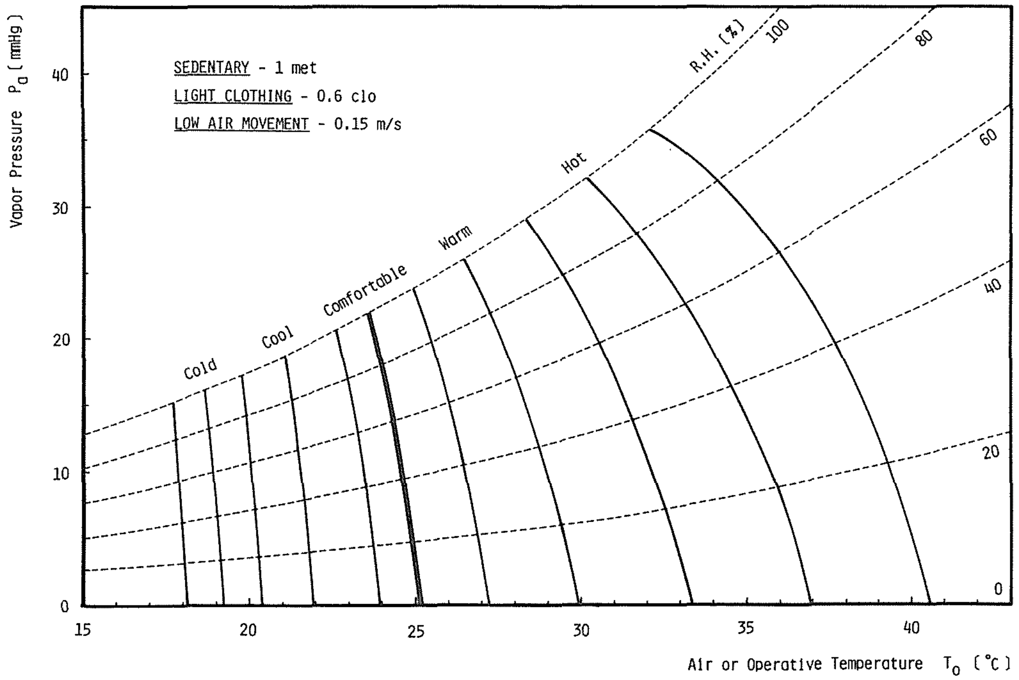

Fig.11 Thermal sensation chart— 1 met-0.6 clo-0.15m/s

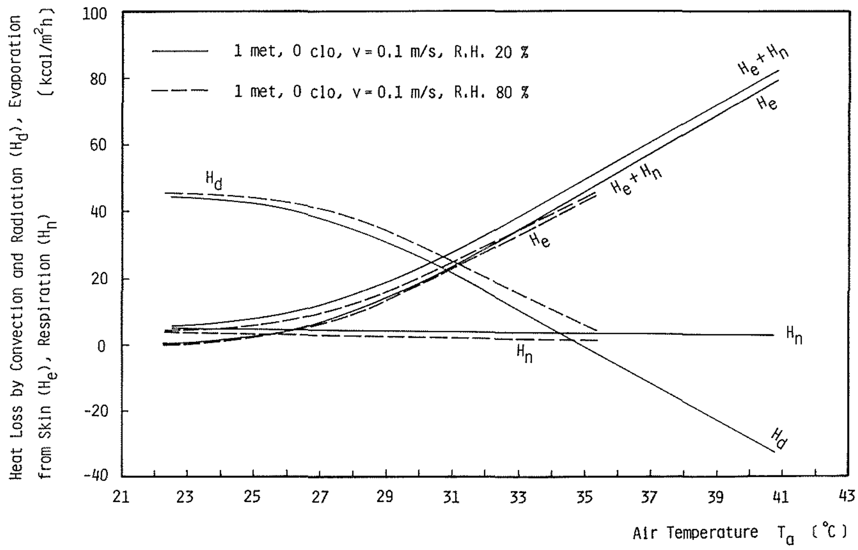

Fig.12 Relation between air temperature and heat losses calculated from Fig.10

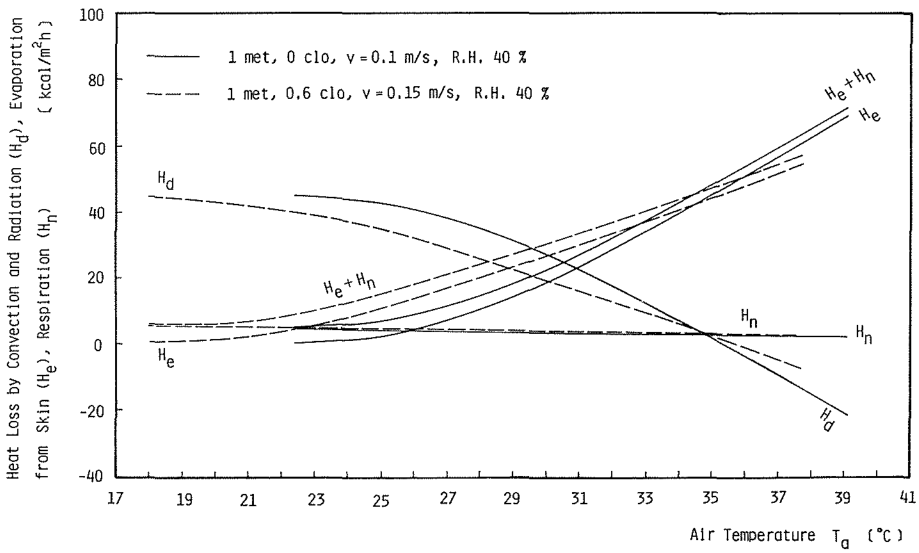

Fig.13 Relation between air temperature and heat losses calculated from Figs. 10 and 11

By using the values of the mean skin temperature and the wettedness as shown in Table 2, we can obtain thermal sensation charts (Figs. 10 and 11) [10] as an index for evaluating thermal environments. As shown in Figs. 12 and 13, the relations between the heat losses and air temperature are also calculated from Fig. 10 and 11.

6. Conclusions

The following four items became evident as a result of the analyses of the physiological experimental data observed by Givoni.

On the line of the equal skin temperature or the equal thermal sensation,

1. the wettedness is not constant but takes varying values.
2. the evaporative heat loss from the skin surface is inversely proportional to the wettedness.
3. the value of the wettedness in a high range of the environmental humidity is larger than that in a low range.
4. the line of the equal skin temperature is not a straight one but is plotted as a curve on the psychrometric chart.

With these considerations above in mind, a new index for evaluating thermal sensation of man was proposed on the basis of the heat balance equation for the human body.

A characteristics of the present thermal sensation index is that the equi-skin temperature line is not a straight one but a curve on the psychrometric chart. This means that in conclusion the effect of the environmental humidity on thermal sensation becomes smaller as the humidity of the environment is lowered and that this tendency is seen more clearly in the hotter region of the chart.

References

〔1〕Gagge, A. P., J. A. J. Stolwijk and Y. Nishi: An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Trans., Vol. 77, p. 247, 1971

〔2〕Givoni, B.: Estimation of the effect of climate on man—— Development of a new thermal index, Doctoral thesis, 1963

〔3〕Fanger, P. O.: Calculation of thermal comfort: Introduction of a basic comfort equation, ASHRAE Trans., Vol. 73, Part II, 1967

〔4〕Mochida, T.: Convective and radiative heat transfer coefficient for the human body, Trans. of the Archtictural Institute of Japan, No. 258, p. 63, 1977

〔5〕Mochida, T.: Clothed man's convective and radiative heat transfer coefficients, Trans. of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, No. 15, p. 1, 1981

〔6〕Horikoshi, T. and Y. Kobayashi; Configuration factors between the human body and rectangular planes and the effective radiation area of the human body, Trans. of the Architectural Institute of Japan, No. 322, p. 92, 1982

〔7〕Kuno, Y.: Human perspiration, Koseikan, 1971

〔8〕Mochida, T.: A model on heat loss by perspiration and temperature sensation index——Equi-skin temperature line with inconstant wettedness, Bulletin of the Faculty of Enginering, Hokkaido University, No. 107, p. 1, 1982

〔9〕Mochida, T. and S. Yokoyama: Moisture permeation efficiency of clothing, Trans. of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, No. 3, p. 79, 1977

〔10〕Mochida, T.: A proposal of thermal sensation index, Annual meeting of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 1983