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A Model on Heat Loss by Perspiration and Temperature Sensation Index——Equi-Skin Temperature Line with Inconstant Wettedness

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Abstract

The characteristics of three typical equations used in calculating of evaporative heat loss from the human skin surface to the environmental air were discussed considering the total heat balance equation including the heat losses by convection, radiation and respiration. The forms of the three equations are as follows——The first is the product of quantity of perspiration and the latent heat, the second is the product of the difference between the mean humidity at the skin surface and the humidity in the ambient air and the evaporative heat transfer coefficient, and the last is the product of the difference between the saturated humidity at the skin surface and the humidity in the environmental air and both the evaporative heat transfer coefficient and wettedness. As a result, it became clear that all the lines of equal skin temperature change linearly on a psychrometric chart and the slope of the skin temperature line with equi-mean' skin humidity is most gentle and that with equi-wettedness comes second and that with equi-evaporation is most steep.

From the analysis of the experimental data of subjects, a relation between wettedness and perspiration was found and a new model on the evaporative regulation was proposed. The feature of the present model is that the locus of the equi-skin temperature is a curved line on a psychrometric chart and that the wettedness on the equi-skin temperature line is not constant but takes various values.

1. Introduction

Sensible and insensible perspirations play an important role in the thermo-regulation of the human body. In particular, evaporation is the only channel of heat loss from the human surface to the outer space in an environment where the ambient air temperature is higher than the skin temperature or the rectal temperature and the thermal equilibrium is maintained as a result of this physiological action. The insensible perspiration is seen under any circumstance except when the skin surface is compl-

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etely wet and the sensible perspiration is the leading part under the high environmental temperature condition. In general, the value of heat loss by perspiration can be determined by two methods, i.e., one is the physiological method mainly based on weight -loss experiments using subjects and the other is the biophysical engineering method principally based on the heat balance equation between man and his thermal environment. The studies of evaporative heat exchange based on the thermal equilibrium equation have been made by various authors, namely, Gagge[1], Belding and Hatch[2], Givoni[3], Fanger[4], Nishi and Gagge[5], and Gagge, Stolwijk and Nishi[6].

In the present paper, a model of heat loss by perspiration in which wettedness is not constant on the line of an equal skin temperature is proposed taking into account the analysis of the experimental data using subjects in the high environmental temperature range.

2. Nomenclature

M	: metabolic heat production of the body, $Kcal/m^2h$
H_e	: evaporation heat loss from skin surface, $Kcal/m^2h$
H_c	: convection heat loss, $Kcal/m^2h$
H_r	: radiation heat loss, $Kcal/m^2h$
H_n	: respiration heat loss, $Kcal/m^2h$
G	: quantity of insensible perspiration and sweat secretion (at comfortable conditions, insensible perspiration alone), g/m^2h
L	: latent heat, $Kcal/g$
β	: evaporative heat transfer coefficient ($=\varkappa h_c$), $Kcal/m^2h$ (g/kg)
$\varkappa$	: modified Lewis relation, $°C/(g/kg)$
h_c	: convective heat transfer coefficient on man, $Kcal/m^2h$ $°C$
h_r	: linear radiation exchange coefficient on man, $Kcal/m^2h$ $°C$
T_s	: average skin temperature, $°C$
T_a	: ambient air temperature, $°C$
X_s	: mean skin humidity, g/kg
X_{ss}	: saturated humidity ratio for boundary layer at skin surface, g/kg
X_a	: humidity ratio in ambient air, g/kg
ψ_s	: skin percentage humidity, ND
W_{diff}	: wettedness due to diffusion, ND
W_{rsw}	: wettedness due to regulatory sweat, ND
W	: total wettedness, ND
V	: air movement, m/s

3. Equations of evaporative heat loss from skin surface and these characteristics

Evaporation is governed by air movement associated with the evaporative heat transfer coefficient and humidity gradient between the skin surface and ambient air.

There are different expressions about the heat loss by evaporation from the human skin surface to the surrounding environment. For instance, the equations are of the form:

$$H_e = G \cdot L \tag{1}$$

$$H_e = \beta(X_s - X_a) = \beta(\psi_s X_{ss} - X_a) \tag{2}$$

$$H_e = \beta(X_{ss} - X_a)W \tag{3}$$

Eq(1) represents the evaporation heat loss H_e which can be calculated by the product of quantity of perspiration G and the latent heat L corresponding to the skin temperature T_s, however, the problem is how to obtain the accurate weight loss by perspiration. Eq(2) shows that the evaporative heat exchange can be determined by the product of the evaporative heat transfer coefficient β[7] and the difference between the mean skin humidity X_s and the ambient air humidity X_a in which case the problem of how to obtain the mean skin humidity is left unsolved. Eq(3) is different from Eq (2) in the point of using wettedness W and saturated skin humidity X_{ss} equivalent to the skin temperature at all times, on the other hand, the skin humidity in Eq(2) is not always saturated, i.e., the skin percentage humidity ψ_s varies from unity to a certain minimum value. The value and tendency of wettedness in Eq(3) is an important problem. Although the above equations which are to be used in the calculation have features quite of their own, we can see the special characteristics by paying attention to the total heat balance equation[8] including the heat losses by convection, radiation and respiration[4] besides the perspiration.

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

In the uniform temperature field where the air temperature is equal to the radiant, the heat balance between an unclothed subject and the thermal environment is written as follows.

$$\begin{aligned} M &= H_e + H_c + H_r + H_n \\ &= H_e + (h_c + h_r)(T_s - T_a) + M(0.148 - 0.0014T_a - 0.0028X_a) \end{aligned} \tag{4}$$

We can obtain Fig. 1 by substituting Eqs(1)$\sim$(3) respectively into the term of the evaporation heat loss H_e in Eq(4) and by drawing the lines of equal skin temperature 36.0 °C on a psychrometric chart. Each line of equi-skin temperature with constant skin humidity X_s, constant wettedness W and constant evaporation G shows a straight line as shown in Fig. 1 and the slope of each line, which indicates the degree of influence of environmental humidity on thermal and comfort sensation, is different and steep in the order of constant evaporation, wettedness and skin humidity. The perpendicular line in Fig. 1 is drawn by neglecting the term of the heat loss by respiration H_n from Eq(4). The broken line in Fig. 1 is the case that wettedness on an equal skin temperature line varies as the environmental humidity changes and the details

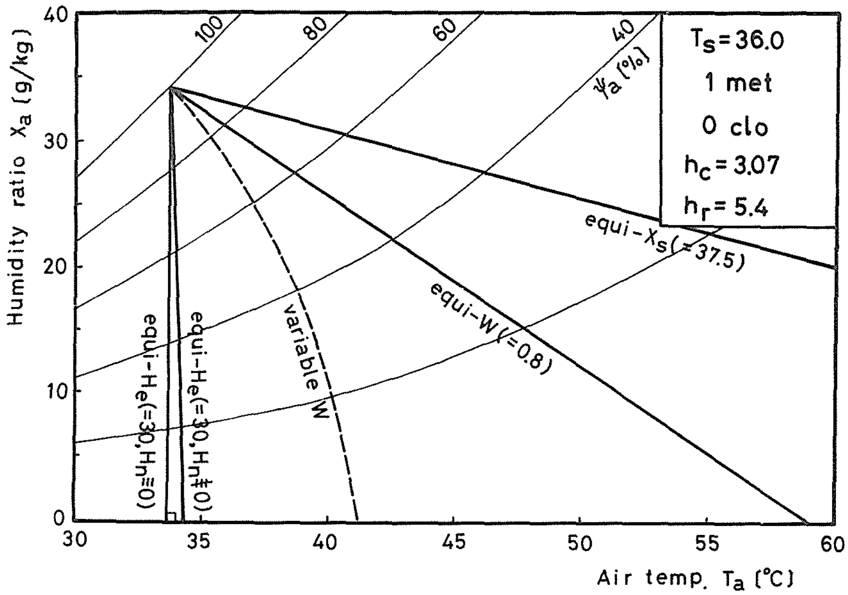

Fig. 1 Loci of equi-skin temperature lines with constant X_s, W and He

thereof will be stated in Chapter 4.

4. A perspiration model with inconstant wettedness on the line of equi-skin temperature

Gagge et al have presented a wettedness model on the heat loss by perspiration and the total wettedness W is given by the following relation using both the skin wettedness due to diffusion W_{diff} and the skin wettedness due to sweating W_{rsw}[6].

$$W = W_{diff} + (1 - W_{diff})\ W_{rsw}$$
$$= 0.06 + 0.94\ W_{rsw} \quad (5)$$

In the present study, we will attempt to make a model of evaporation heat loss under the major concept of " the total wettedness W " while considering the values and characteristics of the skin wettedness due to diffusion and sweating.

Let us now imagine a resting-sitting unclothed subject in a normally ventilated and high environmental temperature room. Drawn by using Eqs(3) and (4) substituted the values concerned with the thermal characteristics as stated below, an equal skin temperature line with constant wettedness shows a straight line as shown in Fig. 2. In this case, the evaporation heat loss in the hot environment where the humidity is absolutely zero amounts to 238 Kcal/m^{2}h and this value is approximately the quintuple of the metabolic rate, as is evident from Fig. 2. Even in the environmental humidity 40%, the evaporative heat loss is more than twice the quantity of the metabolic heat production of the body. The calculations above are based on the values of $M = 50$ Kcal/m^{2}h, $T_s = 36.0$ °C, $W = 0.8$, $h_c = 3.07$ Kcal/m^{2}h °C ($V = 0.15$ m/s)[9], $h_r = 5.4$ Kcal/m^2 h °C[9], $\beta = 7.68$ Kcal/m^{2}h (g/kg). However, the two following facts, namely the

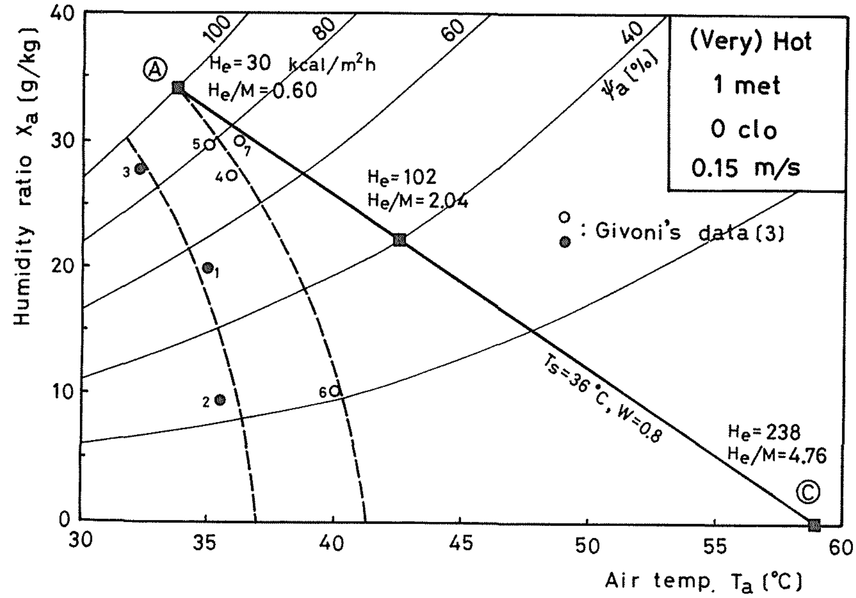

Fig. 2 Equi-skin temperature 36.0 °C line with constant wettedness 0.8 and the evaporative heat loss in the hot environment

experimental report that the evaporative heat loss while sedentary in the shade in a desert[10] is almost twice the quantity of the metabolic rate and Givoni's experimental data[3] in the hot circumstances shown in Fig. 2, suggest that an equi-skin temperature line or an equal thermal sensation line might not change linearly and would describe a curve. From the above-mentioned limit of sweating and the analyses of experimental data, a thermal sensation line with the equal skin temperature and variable wettedness is expected and the line would draw a curve, as would be extrapolated from the broken lines in Fig. 2.

We begin by investigating the experimental data reported by Givoni[3]. Fig. 3 is a relation between the quantity of evaporation and wettedness calculated from Givoni's experimental data shown in Table 1. As seen in Table 1, although some wettedness values calculated are more than unity, in Fig. 3, both the group marked ○ with the mean thermal sensation vote 6.88 and the average skin temperature of 36.03 °C and the group marked ● with mean thermal sensation vote 5.93 and average skin temperature 34.90 °C show a similar trend respectively. In other words, the evaporation is large but the wettedness is small in the high environmental temperature and low environmental humidity, on the other hand, the wettedness is large but the evaporation is little in the environment where the air temperature is low and the humidity is high. These facts mean that, in the high humidity range, the increasing wettedness compensates for the small difference between the skin humidity and the ambient air and that, in the low humidity zone, thermal eqilibrium is maintained because of the large difference between the skin humidity and the air, even when wettedness is not very large.

Table 1 Givoni's experimental data (1 met, unclothed) [3] and calculated values.

experimental data (by Givoni)							calculated values (by author)	
experiment number	air temp. T_a [℃]	relative humid. R. H. [%]	air movement V [m/s]	average skin temp. T_s [℃]	thermal sensation vote T.S.V.*1 [-]	perspiration G [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 (*2 and *3) are assumed because of no description in the original data.

○ The total skin surface area is assumed to be 2 m².

○ An experimental datum calculated to be wettedness 2.16 backwards is excluded in the above table though eight experiments were performed by Givoni.

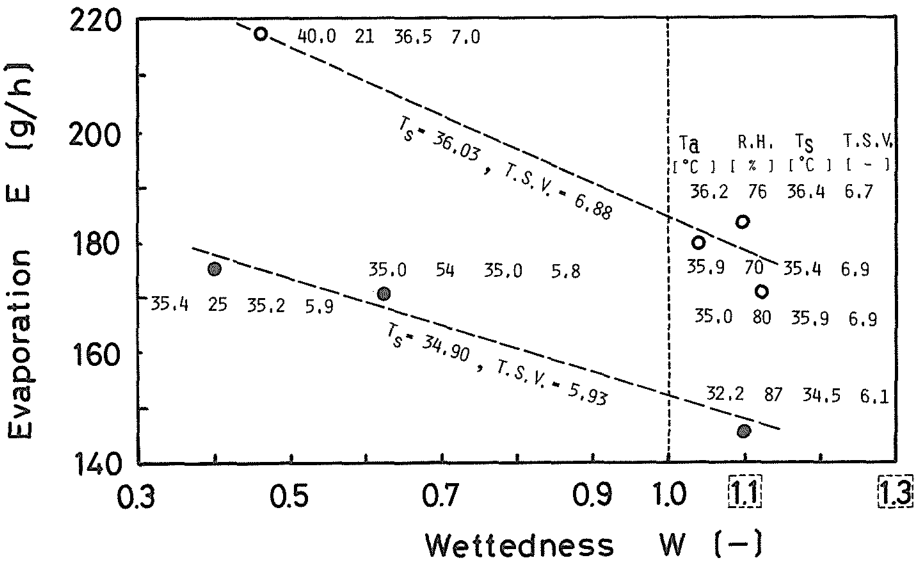

Fig. 3 Relation between wettedness and evaporation obtained from rearranging Givoni's experimental data

The following four items will be estimated from the examination of Fig. 2 and analyses of Givoni's data. On the line of equal temperature sensation,

1. wettedness is not constant but takes varying values.
2. evaporative heat loss is inversely proportional to the wettedness.

3. the value of wettedness in a low range of humidity is smaller than that in a high range.
4. the line of equal skin temperature is not a straight one but draws a curve on a psychrometric chart.

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. We may regard Fig. 4 as an expression of the mechanism of perspiratory regulation inside the human body by wettedness on the skin surface.

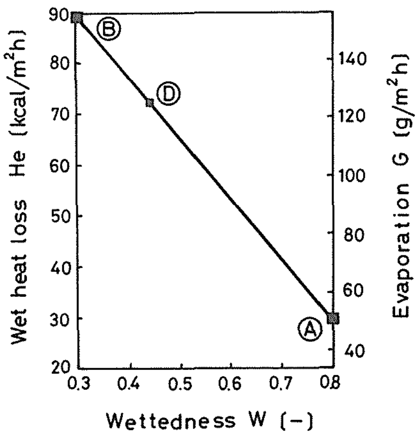

Fig. 4 "A control rule of perspiration" in hot condition ——relation between wettedness and evaporation

Fig. 5 can be made in the following process. The first assumption is to fix the maximum wettedness 0.8 and the minimal 0.3 on the maximum skin temperature line in the zone of evaporative regulation considering both the relation of Fig. 3 and no clear evidence in the literature that in the air the body can become 100% wet, although the maximum value for wettedness, i.e., unity, occurs when the skin is 100% wet. By substituting these two wettedness 0.8 and 0.3, the average skin temperature 36.0 °C which expresses hot sensation and the other

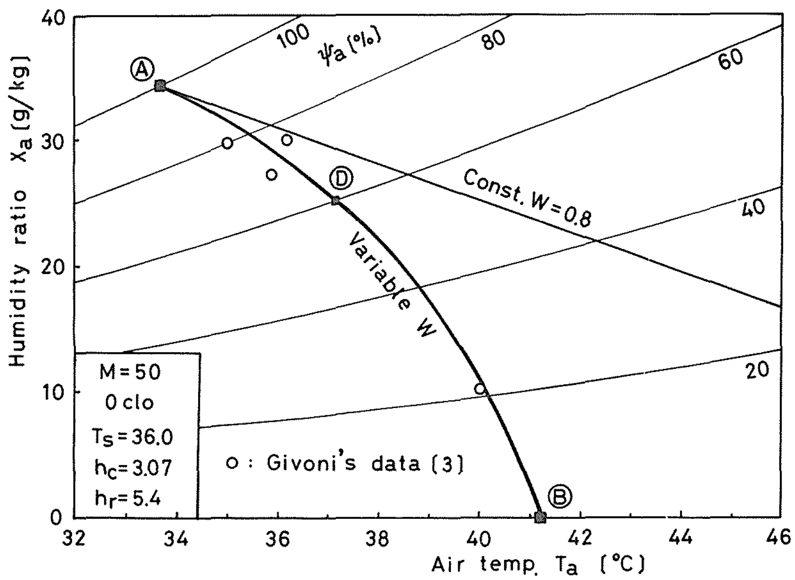

Fig. 5 Calculated lines of equi-skin temperature 36.0 °C——comparison of the lines by constant wettedness and by variable wettedness based on the present model

values of thermal characteristics concerned into Eq(4) combining Eq(3), the two points A and B are found on the psychrometric chart as shown in Fig. 5. Namely, the point A is the point where the skin temperature 36.0 °C line with wettedness 0.8 and the saturated humidity line meet, and the intersection B is the point where the skin temperature 36.0 °C line with wettedness 0.3 and the axis of the abscissa or the absolute dry humidity line cross each other. The point A shows a point with average skin temperature 36.0 °C and wettedness 0.8, and the point B represents a point with average skin temperature 36.0 °C and wettedness 0.3. The two environments obtained indicate that the starting point and the terminus of the hot sensation line——the equi-skin temperature line——in this case, and these are also the points that show the minimal amount of evaporation from skin surface and the maximum respectively. Our next step is to calculate the values of evaporation heat loss at the two environments A and B using Eq(3) and to prepare for completion of Fig. 4 or a " control rule of perspiration ". Although the lines which connect the two quantities of evaporation obtained as mentioned above will be innumerable, a solid line shown in Fig. 4 is assumed as the first approximation. By connecting the points in the order to satisfy both the perspiration rule of Fig. 4 and Eq(4) including Eq(3) at the same time, we can obtain the equal skin temperature 36.0 °C line with variable wettedness. In other words, the conclusion is that the value of wettedness on the equi-skin temperature line varies with the humidity in the environmental air outwardly. The curved line of equi-skin temperature A - D - B drawn by plotting as above is shown in Fig. 5 in comparison with Givoni's data.

In Fig. 4, although we assume a relation between the two points A and B and connect them with a straight line, the tendencies of equi-skin temperature line on the basis of the other curved lines of perspiration rule will be investigated, since the lines which connect the two points A and B in Fig. 4 exist innumerably. If we assume that the five typical lines $\boxed{B}\sim\boxed{F}$ except a straight line $\boxed{A}$ in Fig. 6 are the lines of control rule of perspiration, the equi-skin temperature lines draw a straight line or a curve corresponding to these control rules on the psychrometric chart of Fig. 7. Especially, it is an interesting fact that a straight line $\boxed{A}$ in Fig. 6 draws a curve in Fig. 7 and that a curved line $\boxed{E}$ in Fig. 6 shows a straight in Fig. 7. Further, the delicate difference of control rule lines in Fig. 6 represents the rate of influence of the environmental humidity on thermal sensation.

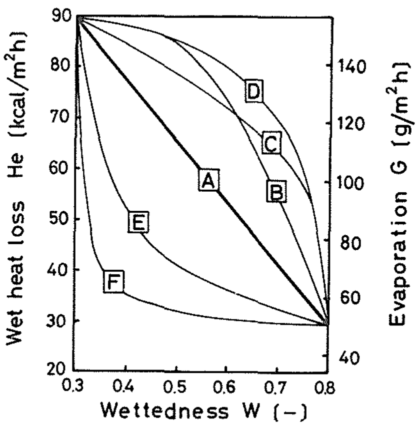

Fig. 6 Various lines of control rule of perspiration

From the results of investigations and experimental data in heat stress condition, we also assume that at comfortable temperature state, a similar manner on perspiratory regula-

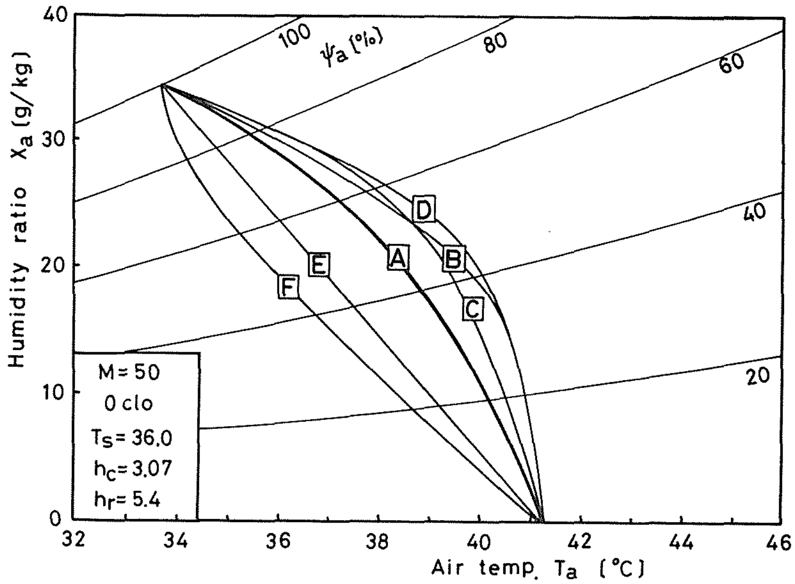

Fig. 7 lines of equi-skin temperature corresponding to each line of control rule of perspiration in Fig. 6

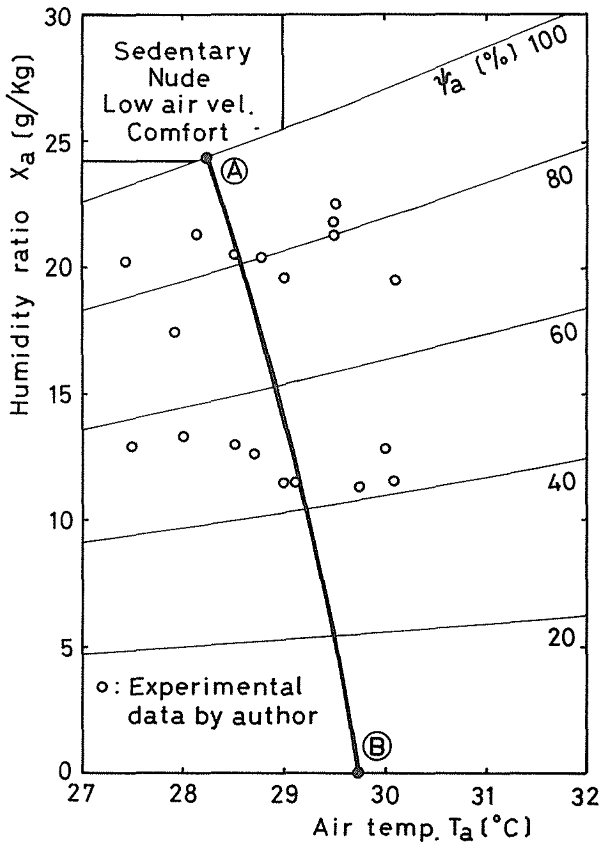

Fig. 8 Verification of the present comfort line

tion——a model of variable wettedness on the equi-skin temperature line——would be carried out inside the human body. In the present paper, the average skin temperature 33.5 °C with wettedness which turns from 0.09 (at the saturated humidity environment) to 0.06 (in the absolute dry environment) represents thermal comfort or a neutral condition after being investigated from various viewpoints. Drawn by using these thermal characteristic values concerned with a neutral condition and by the same procedure as stated above in the hot condition, a comfort line, i.e., an equi-skin temperature 33.5 °C line, for an unclothed resting -sitting person, is obtained as Fig. 8. Although the experimental values are scattered, the present theoretical comfort line exists nearly in the center of the measured results. Fig. 9 is a control rule chart of perspiration corresponding to the condition of Fig. 8.

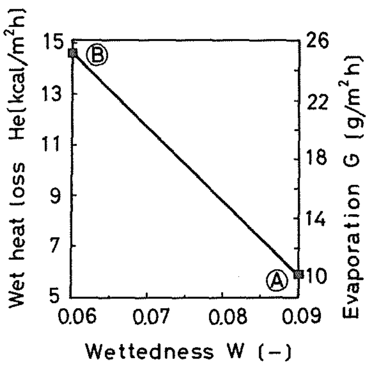

Fig. 9 "A control rule of perspiration" in comfort condition ——relation between wettedness and evaporation

5. Conclusions

Different expressions of humidity for the skin boundary layer give several forms on the evaporation heat loss by perspiration. In the present study, among these expressions, the chaacteristics of the following equations, i.e., the product of the quantity of perspiration and the latent heat, the product of the difference between the mean humidity at the skin surface and that in ambient air and the evaporative heat transfer coefficient, and the product of the difference between the saturated humidity at the skin surface and that in the environmental air and both the evaporative heat transfer coefficient and wettedness, were discussed and the lines of equal skin temperature based on man's heat balance equation were examined. As a result, it became clear that all the equal skin temperature lines change linearly on a psychrometric chart and the slope of the skin temperature line with equi-mean skin humidity is most gentle and that with equi-wettedness follows the second.

From the analysis of Givoni's experimental data using subjects, the following four items became evident:

On the line of the equal average skin temperature,

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

With these considerations above in mind, a new model on the evaporation heat loss was proposed. In conclusion, the locus of the equi-skin temperature based on the present model describes a curved line on the psychrometric chart and the line is in satisfactory agreement with the experimental results.

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