Determination of Equal Thermal Sensation Lines in the Evaporative Regulation Region

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Abstract

An analysis of Givoni's physiological experimental data was conducted and the characteristics of wettedness were clarified, namely, even when the skin temperature is the same, the value of the wettedness is larger in the high humidity range of the environment and is smaller in the low environmental humidity zone.

Further it was shown that the heat loss by evaporation from the skin surface is inversely proportional to the wettedness.

An equal skin temperature line having the properties of the wettedness obtained was theoretically derived, based on the heat balance equation between a man and his surrounding environment and the metabolic heat production curve.

This line draws a curve on the psychrometric chart and the curve, not a straight line, means that the effect of the environmental humidity on thermal sensation is not constant but differs even on the same skin temperature line.

New thermal sensation charts for a resting-sitting subject when unclothed and for a sedentary normally clothed man were proposed drawing the equi-skin temperature lines at every skin temperature.

1. Introduction

The diagrams or the nomograms for evaluating the warmth and the coldness of the thermal environment have been proposed : 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, Predicted Four-Hour Sweat Rate by McArdle, Windchill Index by Siple, Wet Bulb Globe Thermometer Index by Minard, Index of Thermal Stress by Givoni, Temperature Humidity Chart by Nevins et al, Comfort Chart by Fanger, Thermal Sensation Diagram by Nishi and New Effective Temperature by Gagge et al.

It is the purpose of the present paper to provide a new thermal sensation chart.

We begin by analyzing physiological experimental data observed using subjects and we aim to report the relations among skin temperature or thermal sensation, relative humidity in the environment, evaporative heat loss and wettedness. A curved equi-skin temperature line considering the properties of wettedness is theoretically derived based on man's heat balance equation. By drawing the curved lines at every skin temperature on the psychrometric chart, we obtain a new thermal sensation chart possible for evaluating the

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levels of thermal sensation.

2. Nomenclature

M : total metabolic rate, $kcal/m^2h$
M_f : fundamental metabolic rate (minimum heat production, for instance, $50kcal/m^2h$ for sedentary while comfortable), $kcal/m^2h$
M_{nst} : metabolic rate by non-shivering thermogenesis, $kcal/m^2h$
M_{st} : metabolic rate by shivering thermogenesis, $kcal/m^2h$
M_{ht} : increased metabolic rate in warm or hot regions, $kcal/m^2h$
H_c : convection heat loss, $kcal/m^2h$
H_r : radiation heat loss, $kcal/m^2h$
H_e : evaporation heat loss from skin surface, $kcal/m^2h$
H_n : respiration heat loss, $kcal/m^2h$
H_w : work accomplished, $kcal/m^2h$
h_c : convective heat transfer coefficient in man, $kcal/m^2h°C$
v : air movement, m/s
h_r : linear radiation exchange coefficient in man, $kcal/m^2h°C$
ξ : effective radiation area factor, N. D.
κ : modified Lewis relation, °C/mmHg
T_s : mean skin temperature, °C
T_a : air temperature, °C
T_r : mean radiant 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 ($1clo=0.18m^2h°C/kcal$), N. D.
η : moisture permeability coefficient, N. D.
$T.S.V.$: thermal sensation vote (T.S.V. value will range from 1 to 8, where 1 is very cold ; 2-cold ; 3-cool ; 4-comfortable ; 5-warm, ; 6-hot ; 7-very hot ; 8-unbearably hot), N. D.

3. Metabolic heat production curve

The relation of heat production against environmental temperature is shown schematically in Fig.1 [1]. In the thermal neutral zone between the lower and the upper critical temperatures, the metabolic rate remains constant and shows a minimum value. As the environmental temperature falls, the heat production begins to rise and the human body can maintain its body temperature constant. When the temperature of incipient hypothermia fall is exceeded, shivering commences to occur and the body temperature can no longer be maintained and the human body goes into hypothermia. On the other hand, at the upper critical temperature in the warm side of the thermal neutral zone, the metabolic rate begins to rise again. When the environmental temperature continues to rise and the temperature of incipient hyperthermia rise is exceeded, the body temperature rises.

With reference to Fig. 1, the experimental results [2] and Fig. 2 [3], we assume the heat production versus the mean skin temperature curve for a sedentary condition as shown in Fig. 3. The region between the mean skin temperatures 33℃ and 34℃ in Fig. 3 is equivalent to the zone of thermal neutrality and the zone is also a region of minimum heat production. The metabolic rate rises on the warm and the cool sides of the neutral zone. In the present study, we deal with a steady state condition, i. e., the region where the body temperature maintains constant. In this region, we make the assumptions of the lower 31°C and the upper 36℃ limits as the mean skin temperatures and a metabolic rate curve as shown in Fig. 3.

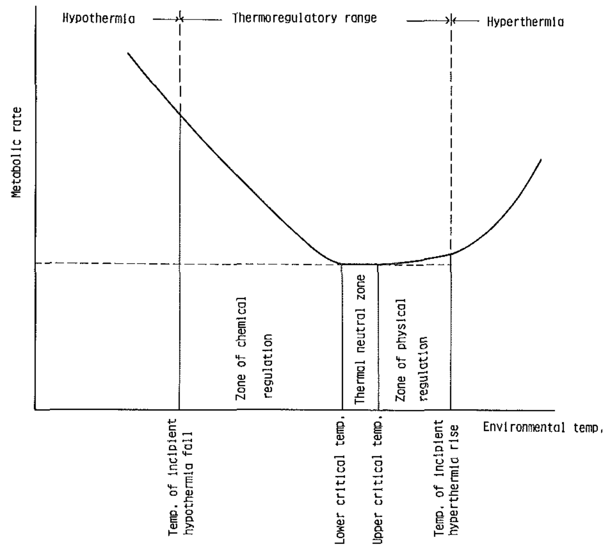

Fig. 1 Heat-production versus environmental temperature curve schematically shown [1]

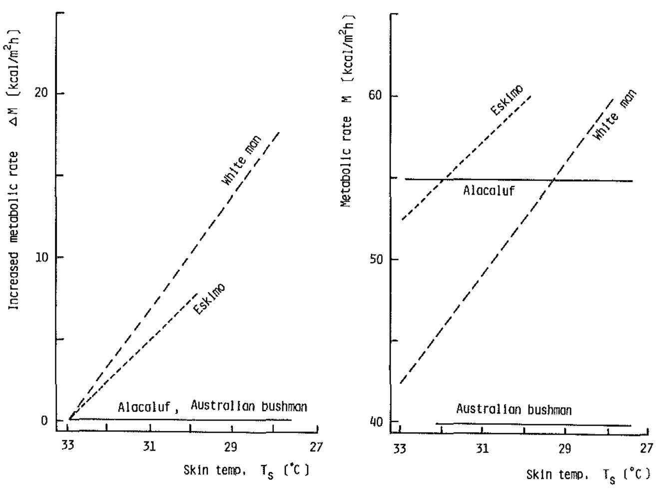

Fig. 2 Relation between metabolic rate and skin temperature [3]

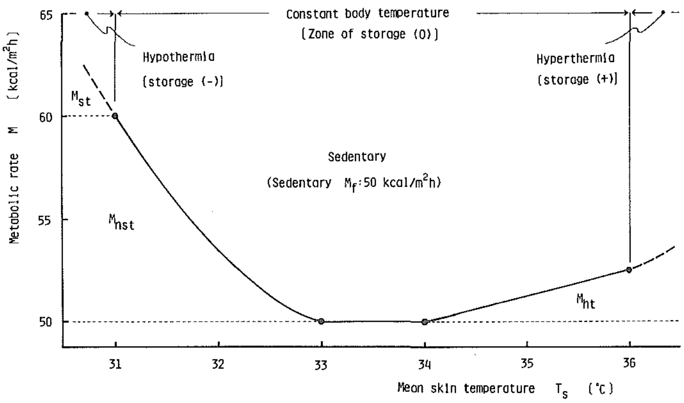

Fig. 3 Heat-production versus skin temperature curve assumed

4. Heat equilibrium of man

In a steady state, the human body exchanges heat with the surroundings through the avenues by convection, radiation, perspiration, respiration and external mechanical work.

$$M = H_c + H_r + H_e + H_n + H_w \tag{1}$$

In Eq (1), the total metabolism, the heat losses by convection, radiation, perspiration and respiration [4] may be written by,

$$M = M_f + M_{nst} + M_{st} + M_{ht} \tag{2}$$

$$H_c = h_c Z\ (T_s - T_a) \tag{3}$$

$$H_r = \xi h_r Z\ (T_s - T_r) \tag{4}$$

$$H_e = \kappa h_c R\ (P_{ss} - P_a)\ W \tag{5}$$

$$H_n = M\ (0.1488 - 0.0014 T_a - 0.0023 P_a) \tag{6}$$

where,

$$Z = \frac{1}{0.18I\ (h_c + \xi h_r)\ + 1},\quad R = \frac{1}{0.18I \eta h_c + 1}.$$

In the above equations, M is the total metabolic rate, M_f is the fundamental metabolic rate or the minimum heat production, for instance, 50kcal/m²h for sedentary condition while comfortable, M_{nst} is the non-shivering thermogenesis, M_{st} is the shivering thermogenesis, M_{ht} is the increased metabolic rate in the high temperature environment, η is moisture permeability coefficient [5] as a measure of vapor diffusion through clothing ensembles and W is the total wettedness defined by Gagge et al [6]. The theoretically derived relation between moisture permeability coefficient and clo unit is as follows.

$$\eta = 1.644\ (0.18I)^{1/8} \tag{7}$$

Further, the convective heat transfer coefficient and the linear radiation exchange coefficient used in the present calculations are as follows [7], [8].

$$h_c=(270v^2+23)^{1/3} \tag{8}$$

$$h_r=-\frac{3}{10}I+5.15 \tag{9}$$

Rearranging Eqs (1), (2), (3), (4), (5) and (6), the heat equilibrium between a man and his thermal environment in a uniform temperature field where the ambient air temperature is equal to the radiant becomes the following equation, since it is regarded that there is no shiverimg thermogenesis in a steady state.

$$\begin{aligned} M &= M_f+M_{nst}+M_{ht} \\ &=(h_c+\xi h_r)\ Z\ (T_s-T_a)\ +\kappa h_c R\ (P_{ss}-P_a)\ W \\ &\quad +M\ (0.1488-0.0014T_a-0.0023P_a)+H_w \end{aligned} \tag{10}$$

5. Characteristics of wettedness

Figs. 4, 5 and 6 show the relationships among the quantity of evaporation, the environmental relative humidity and the wettedness calculated from the raw data of physiological experiments performed by Givoni under hot circumstances [9], [10]. What is evident from Figs. 4, 5 and 6 is that both the group marked ○(T_s=36.03°C, *T.S.V.* =6.88) and the group marked ● (T_s=34.90°C, T.S.V. =5.93) show a similar trend respectively, although some wettedness values calculated are more than unity. 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 may be explained as follows in the high humidity range, the large wettedness compensates for the small difference between the skin humidity and the ambient air and in the low humidity area, the evaporative heat loss depends on the large difference between the skin humidity and the surrounding air rather than the wettedness.

The following four items can be estimated from 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 wettedness value in a high range of environmental humidity is larger than that in a low range.
4. the locus of the equal skin temperature is expected not to be straight line but is expected to be a curve on the psychrometric chart.

As an equal skin temperature line with the above features on wettedness, the writer previously derived a curved one [10] which coincides with experimental data. As seen in Fig. 7, on the curved line Ⓐ-Ⓕ of the equal skin temperature 36°C, the wettedness value is not constant but changes from the maximum 0.8 to the minimum 0.3, and the curve obtained theoretically almost coincides with the experimental data observed using human subjects. If the wettedness maintains the value 0.8 to the low environmental humidity range, the evaporative heat loss in this case will be very large and the amount of the heat

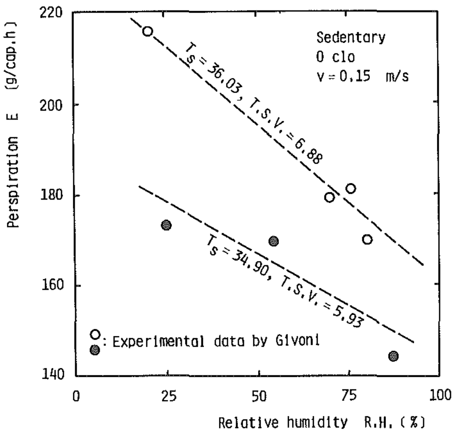

Fig. 4 Relation between perspiration and relative humidity

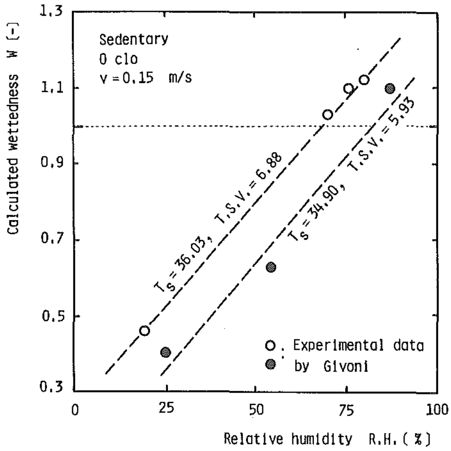

Fig. 5 Relation between relative humidity and calculated wettedness

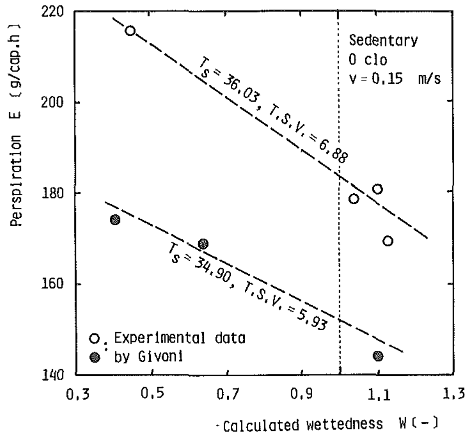

Fig. 6 Relation between perspiration and calculated wettedness

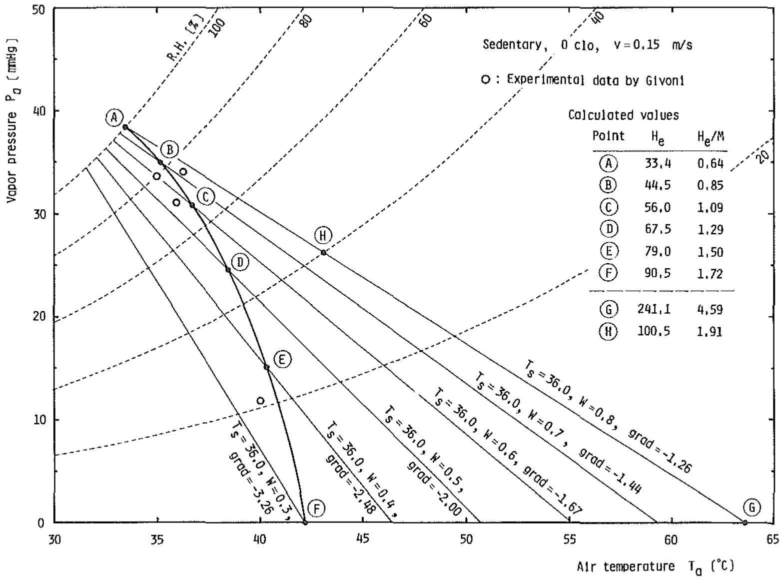

Fig. 7 Calculated lines of equi-skin temperature ——Comporision of the lines by constant wettedness and variable wettedness

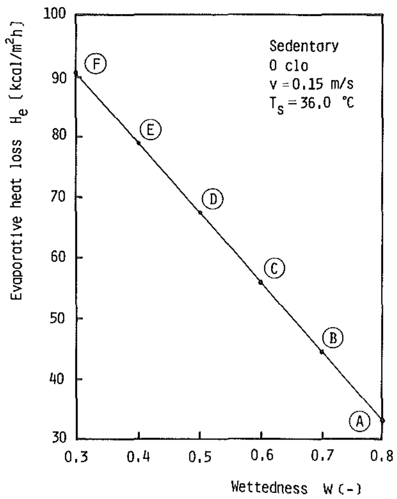

Fig. 8 A control rule of perspiration —— a graph in order to fix the environments Ⓑ, Ⓒ, Ⓓ and Ⓔ in Fig. 7 [10]

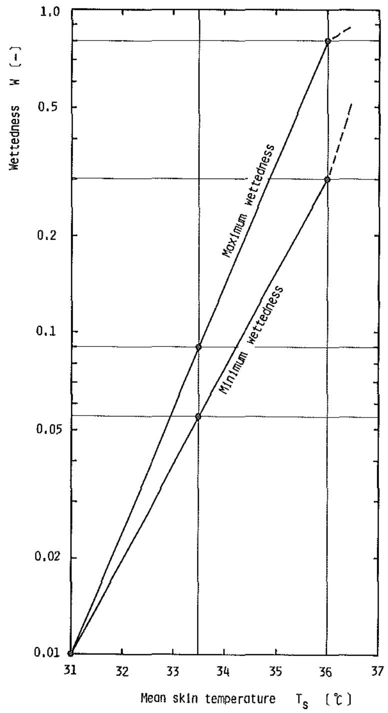

Fig. 9 Combinations of maximum and minimum wettedness against mean skin temperature

loss by evaporation does not agree with the values reported by Kuno [11] and the straight line Ⓐ-Ⓖ with the constant wettedness value 0.8 does not coincide with Givoni's data.

The idea of varying wettedness found from analyzing the experimental data in hot circumstances is applied and extended to the other condition of thermal sensation, and combinations of maximum and minimum wettedness against mean skin temperature are also assumed as shown in Fig. 9, based on the three points, the maximum wettedness 0.8 (T_s=36°C), the minimum 0.3 (T_s=36°C) and the constant wettedness 0.01 (T_s=31°C) of lower limit. The maximum value 0.09 and the minimum value 0.055 are obtained as the wettedness to the mean skin temperature 33.5°C and the locus drawn using these values, as seen in Fig. 10, agrees approximately with the report [11] that the ratio of the evaporative heat loss to the metabolic rate is about 1/5～1/4 under a comfortable condition. In the present paper, the skin temperature 33.5°C represents the most comfortable condition and the region between the mean skin temperatures 33℃ and 34℃ shows thermal neutrality or comfort zone. The wettedness and the mean skin temperatures corresponding to thermal neutral zone are shown in Figs. 9 and 11.

6. Thermal sensation chart

Fig. 12 shows the equi-skin temperature lines drawn by means of man's heat balance equation (10), Fig. 3 and Fig. 9, and is a chart for a resting-sitting, unclothed person and the

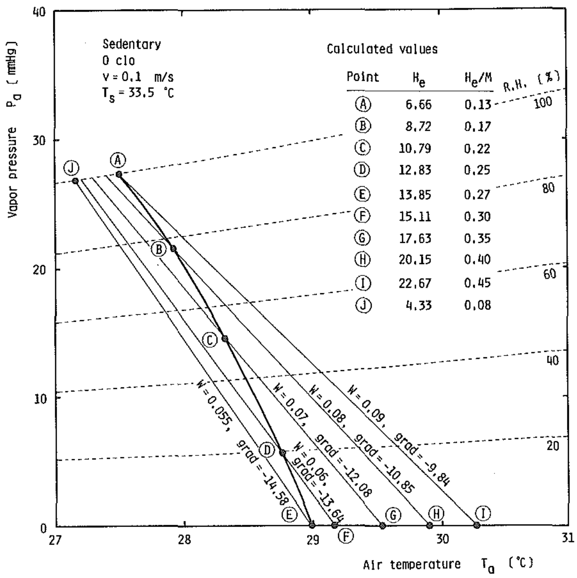

Fig. 10 Equi-skin temperature curve and calculated values of evaporative heat loss while comfortable under a sedentary unclothed condition

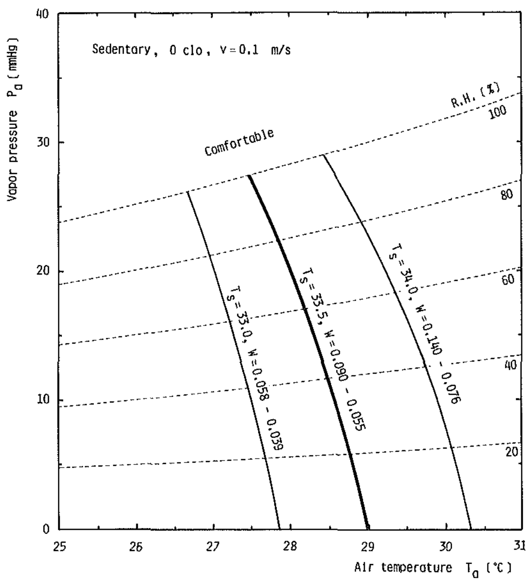

Fig. 11 Comfort range for a sedentary unclothed subject

environmental air movement 0.1m/s. In the calculation process, work accomplished H_w was neglected and 2.2℃/mmHg [12] as modified Lewis relation κ and 0.75 [13] for unclothed and 0.8 [13] for clothed man as effective radiation area factors ξ were used. We can see that in Fig. 12, all the equi-skin temperature lines describes curved ones except one line of

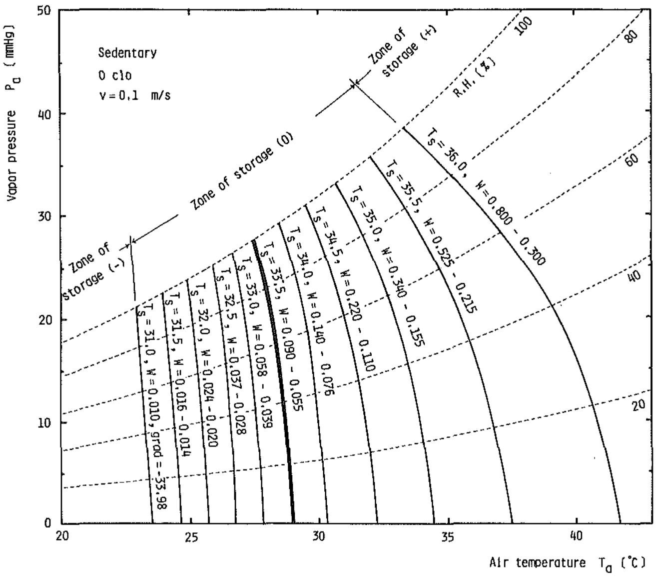

Fig. 12 Equi-skin temperature lines and the ranges of wettedness

the skin temperature 31°C, which shows the lower limit of the storage zero zone. The curved equal skin temperature line 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 at the hotter circumstances in the chart.

Fig. 13 is a thermal sensation chart for a resting subject when unclothed and Fig. 14 is a chart applicable to a normally clothed subject.

7. Conclusions

The physiological experimental data observed by Givoni were analyzed and the results made the following four items clear.

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

1. the wettedness does not maintain constant but takes varying values
2. the evaporative heat loss from the skin surface is in inverse proportion to the wettedness.
3. the wettedness value in a high humid environment is larger than that in a low.
4. the locus of the equal skin temperature is not a straight one but is plotted as a curve on the psychrometric chart,

A curved line of the equi-skin temperature was theoretically derived and the line contains the properties of the wettedness above-mentioned and coincides with the experimental data.

A new index for evaluating the warm and the cold in the environment was proposed introducing the idea of the varying wettendness, on the basis of the heat balance equation of a human body and the heat production curve assumed. The present thermal sensation index is characteristic of a curved equi-skin temperature line, not a straight one, on the

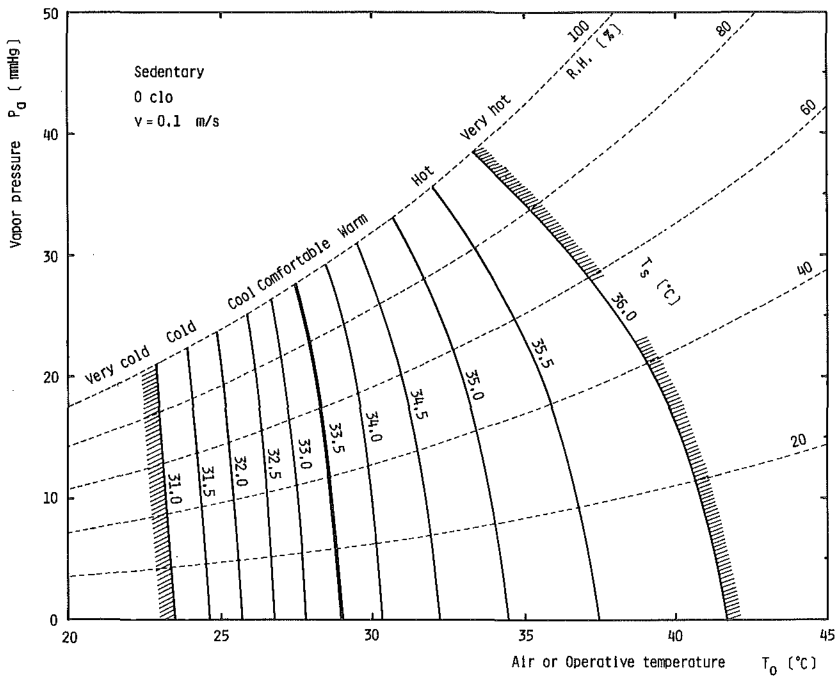

Fig. 13 Thermal sensation chart for a sedentary unclothed subject

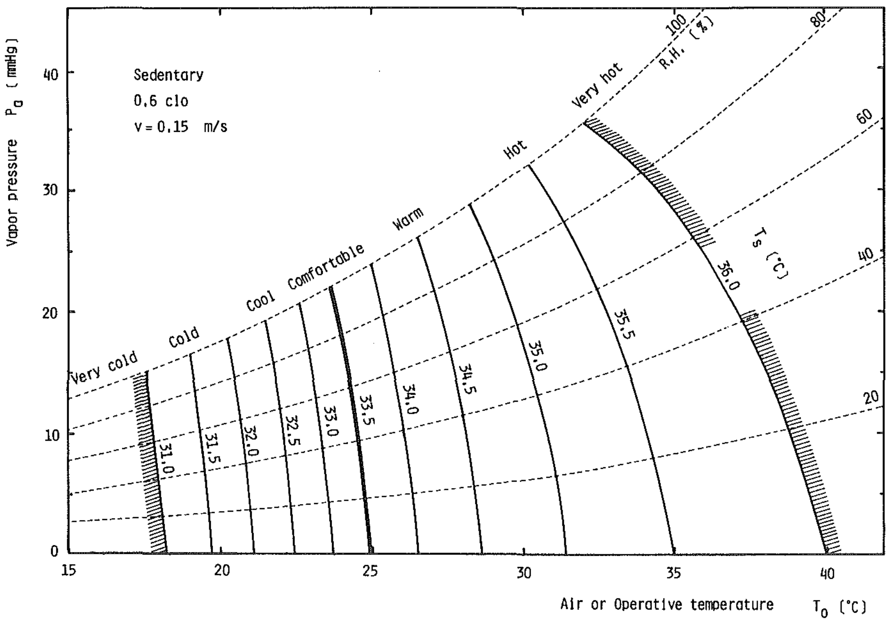

Fig. 14 Thermal sensation chart for a sedentary normally clothed subject

psychrometric chart. A curved equal skin temperature line may be concluded that the effect of the environmental humidity on thermal sensation becomes smaller as the humidity of the environment is lowered and that such a tendency is seen more clearly in the hotter regions in the chart.

References

[1] T. Nakayama et al : Thermophysiology, Rikogakusha, p. 362, 1981

[2] Yokoyama, S. and H. Ogino : Prediction of obligatory and regulatory non-shivering thermogenesis and shivering thermogenesis in man, The Annals of Physiological Anthropology, Research Society of Physiological Anthropology, Vol. 2, No. 1, 1983

[3] Carlson, L. D. and A. C. L. Hsieh : The Physiology of Human Survival, 45, Academic Press (Cited in Japanese Handbook of Physiology, Vol. IX, Physiology of Adaptation and Integration, p. 388, 1970)

[4] P. O. Fanger : Thermal Comfort —— Analysis and Application in Environmental Engineering, Danish Technical Press, 1970

[5] Mochida, T. and S. Yokoyama, Moisture permeation efficiency of clothing, Trans. of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, No. 2, p. 79, 1977

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

[7] T. Mochida : Convective and radiative heat transfer coefficients for the human body, Trans. of the Architectural Institute of Japan, No. 258, p. 63, 1977

[8] T. Mochida : 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

[9] B. Givoni : Estimation of the Effect of Climate on Man —— Development of a New Thermal Index, Doctoral thesis, 1963

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

[11] Y. Kuno : Human Perspiration, Koseikan, 1971

[12] Nishi, Y. and A. P. Gagge : Moisture permeation of clothimg —— A factor governing thermal equilibrium and comfort, ASHRAE Trans., Vol. 76. Part I, p. 137

[13] 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. 332, p. 92, 1982