CHARACTERISTICS OF WETTEDNESS OF NAKED AND CLOTHED SUBJECTS AT CONSTANT AVERAGE SKIN TEMPERATURE

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Key Words: Wettedness, Average skin temperature, Clothing ensemble, ET*, Thermal comfort.

ABSTRACT

Physiological and sensory responses, particularly paid attention to the skin wettedness under clothing at constant average skin temperature, were observed in two male subjects while they were seated on a balance. The clothing ensemble had an effective insulation of approximately 1 clo. From the analysis of the present experimental data, the following conclusions were found regarding characteristics of wettedness observed by clothed subjects at a constant average skin temperature,

1. Wettedness correlates negatively with the air temperature and correlates positively with the vapor pressure.
2. Evaporative heat loss from the skin surface correlates positively with the air temperature and correlates negatively with the vapor pressure.
3. Wettedness correlates negatively with evaporative heat loss.
4. At a constant average skin temperature, the value of wettedness is variable and both maximum and minimum values exist.

The results stated above indicate the same tendency as the results obtained from the experiments using naked subjects. Based on the above conclusions, it is clear that the theoretical locus of equal average skin temperature is not a straight line but is a curved line plotted on the psychrometric chart, totally different and independent of the equal ET*line.

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INTRODUCTION

For evaluating thermal sensation of thermal comfort and for designing and controlling thermal environments, two logical indices have been widely used throughout the world as the indices, i.e., PMV proposed by Fanger (Fanger, 1970) and SET*(ET*) by Gagge et al (Gagge et al, 1971). These two indices were made in early 1970's and have influenced the basic research concerning HVAC. However, several questions concerning PMV and SET* have been repeatedly raised as pointed out by Horikoshi in 1986 and 1996, by Nishi in 1992 and by Mochida in 1992.

The main point to be questioned of PMV is that as shown in the figure by Gagge et al (Gagge 1985), equal PMV lines drawn on the psychrometric chart are all parallel straight ones: Figure 1. In the ASRAE ET* scale, on the other hand, equal ET* lines in the zone of evaporative regulation against heat are not parallel and the slope of ET* lines shows a smaller gradient at a higher temperature region and it represents comparatively well of the thermal physiological characteristics of the human body. However, as seen in Figure 2, if it is accepted that the equal ET* line maintains the straight line down to the lower humidity environment, the sweating rate must be beyond the physiological response. Equal ET* lines drawn on a psychrometric chart are defined as the straight lines of both constant skin temperature and constant wettedness, and this is a model obtained by an assumption that the subject’s rate of sweating is unlimited.

The subject’s rate of sweating, however, is limited and Heat Stress Index proposed by Belding et al takes in this measurement. As the result, the equal HSI lines break on the way as shown in Figure 3 (Belding et al, 1955). From our experiments using naked subjects, contrary to the definition of ET*, it was found that even if the average skin temperature is constant, the values of wettedness are variable, and that a maximum value of wettedness and a minimum value exist at a constant average skin temperature (Mochida 1996).

In order to obtain the combinations of air temperatures and humidities for thermally comfortable condition, either PMV or SET* makes little difference in any of these cases. Nevertheless, in case of evaluating thermal sensation and control of thermal environment, there is a large gap between the values of PMV and SET*.

The purpose of the present investigation is to clarify the variation of wettedness of clothed subjects at the constant average skin temperature and to compare the characteristics of wettedness of a naked subject with that of a clothed subject, and also to examine its effect on the line of equal average skin temperature drawn by the heat balance equation for humans in their environment on the psychrometric chart.

In conclusion, this is a fundamental study in HVAC field and it will become a basis for revising the currently used indices of thermal sensation, thus presenting the thermal characteristics of human physiology more faithfully.

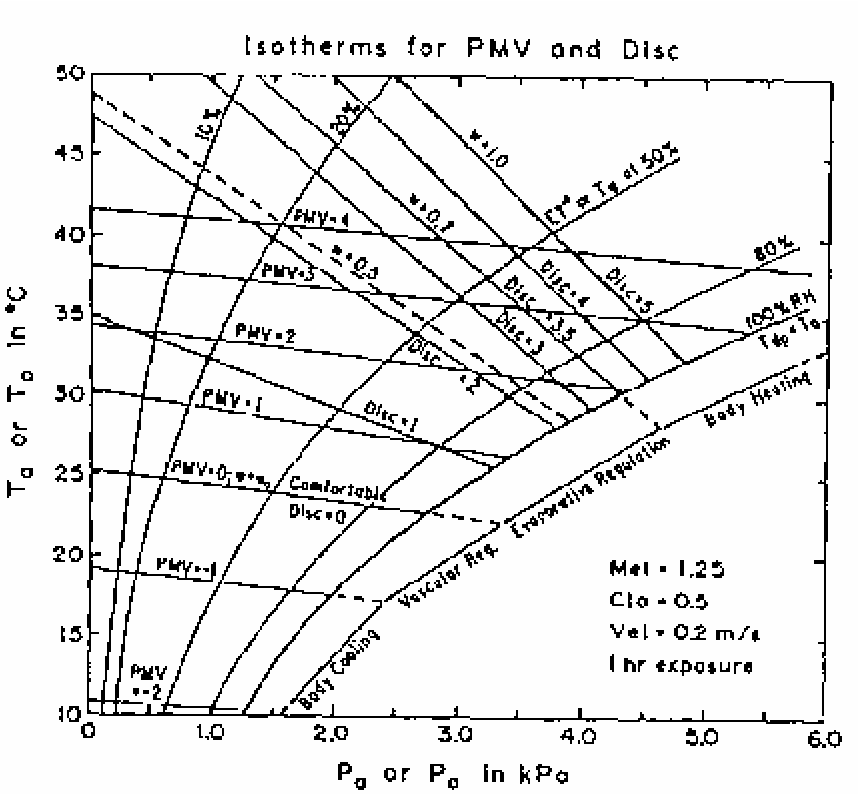

Figure 1 Equal PMV lines (Gagge, 1985)

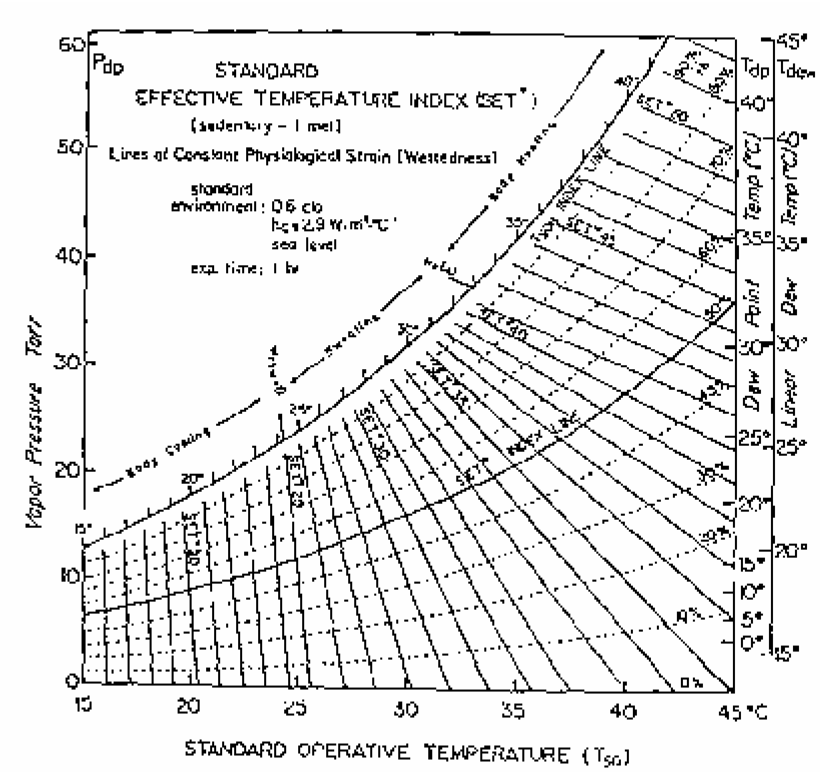

Figure 2 Equal SET* lines (Gagge et al, 1971)

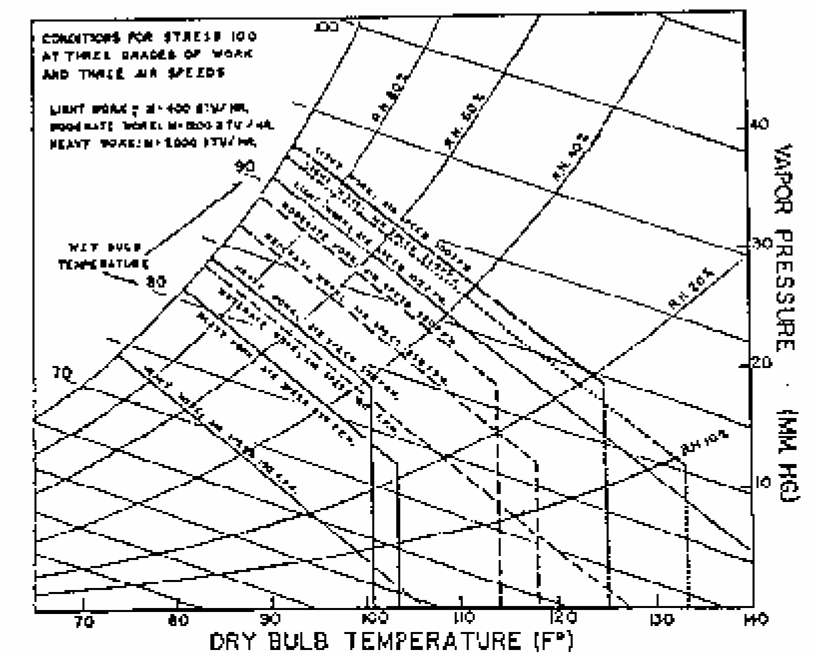

Figure 3 Equal HIS lines (Belding et al, 1955)

EXPERIMENTS CONCERNING SKIN WETTEDNESS UNDER CLOTHING

Tests were conducted in a test chamber in which the air temperature was controlled equal to the radiant temperature. The desired combinations of the average skin temperature, Ts, the air temperature, Ta, and the relative humidity (RH) were as indicated in Table 1. Changes in wettedness were observed when the average skin temperature showed constant value in high-, middle-, or low-humidity environments. Air movement was nearly 0.15 m/s. The air temperature and humidity were maintained constant throughout each experiment. In these environments, only two healthy young Japanese males were used as subjects, because the characteristics of skin wettedness had been clarified in the experiments made with naked subjects (Mochida 1996). Table 2 indicates the physical data of these males. The subjects sat on meshed chairs that were set on a digital balance and the clothing ensemble consisted of sweat pants and shirt, sweat shirt, under shirt, T-shirt, briefs and socks (Table 3). This ensemble had an effective insulation of 1.06 clo. Each subject was measured continuously for one hour under these conditions in order to obtain the human physiological responses, including skin temperatures, weight loss, and subject temperature and comfort sensation. The skin temperatures were recorded from the seven sites specified by Hardy-DuBois's seven-average method. Both the skin temperature and the oral temperature were measured with thermocouples. Temperature and comfort sensations were recorded every 10 minutes. These experiments were made with one subject at a time in the test chamber. A standard metabolic rate of 58.2 W/m^2 for sitting/resting was used for calculations.

Table 1 Desired combinations of Ta and RH, and other experimental conditions

Air temp. Ta [°C]	31～33	33～35	35～37
Relative humidity RH [%]	80～70	60～50	30～20
Air movement v [m/s]	0.15		
Metabolism	1 met (Sitting / Resting)		
Clothing worn	1 clo		

Table 2 Physical data of subjects

Subject	Age	Height [cm]	Weight [kg]	Body surface area [m^2]
A	21	172.5	61	1.67
B	21	173.5	62	1.69

Table 3 Wears used in the experiments

Wears	Materials	Weight [kg]
Sweat pants and shirt	polyester 100%	0.83
Sweat shirt	cotton 100%	0.66
Under shirt	cotton 100%	0.59
T-shirt	polyester 65% + cotton 35%	0.13
Briefs	cotton 100%	0.06
Socks	cotton 50% + nylon 50%	0.03

RESULTS OF EXPERIMENTS

Figures 4 through 8 show the results of these experiments. In these Figures the results of experiments using naked subjects are indicated for comparison.

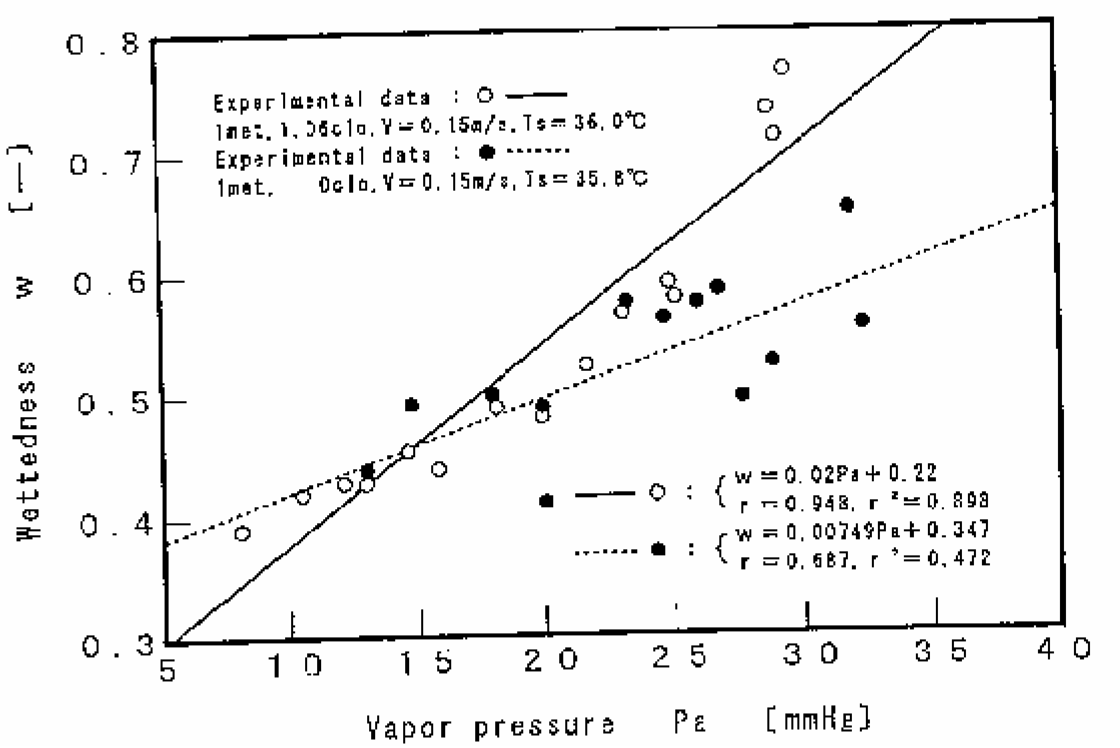

Figure 4Observed relation between wettedness, w, and vapor pressure, Pa

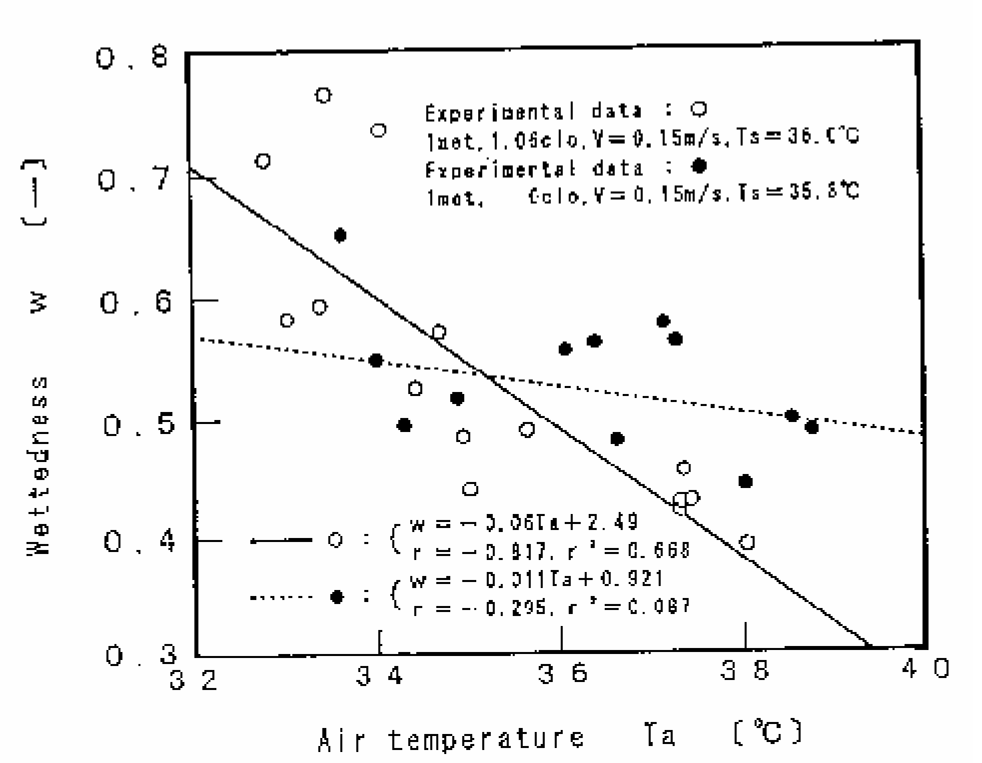

Figure 5Observed relation between wettedness, w, and air temperature, Ta

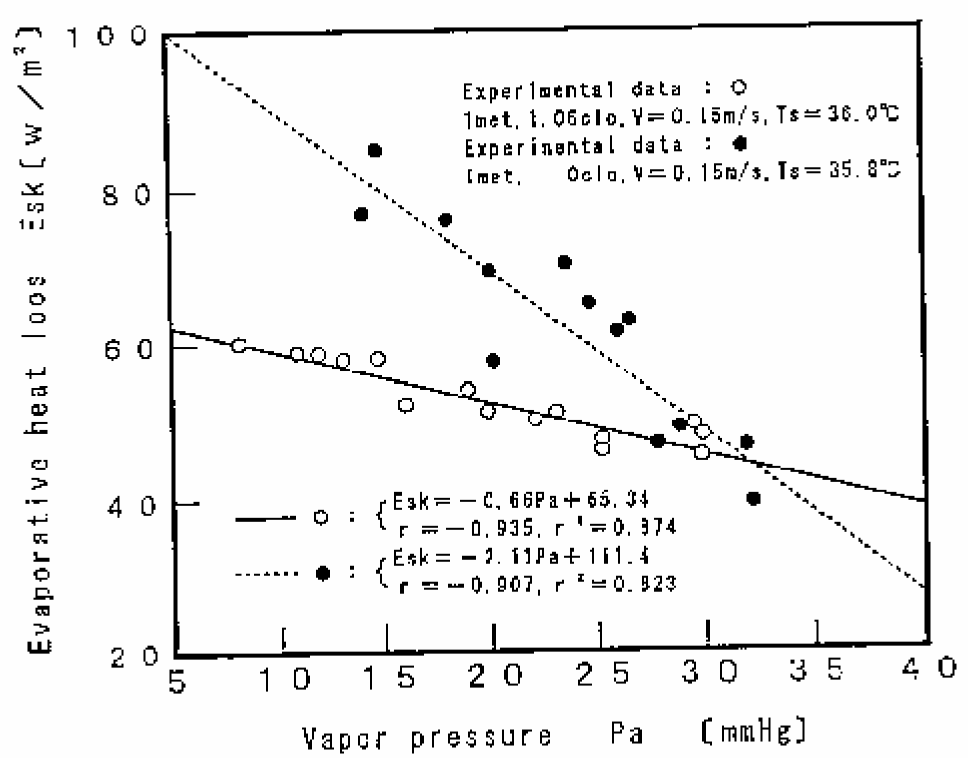

Figure 6Observed relation between evaporative heat loss, Esk, and vapor pressure, Pa

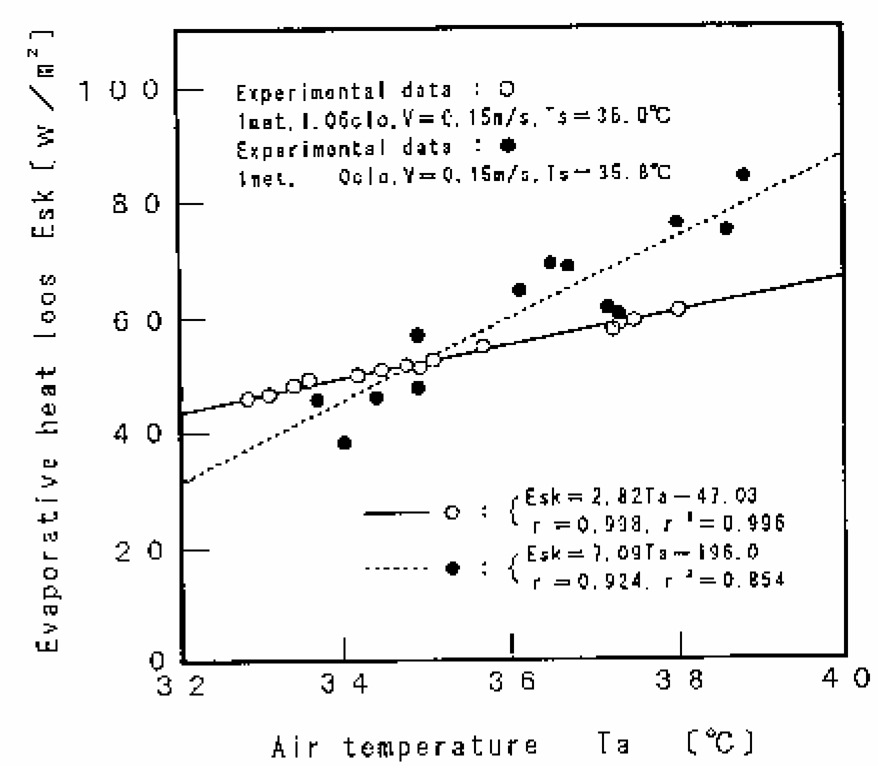

Figure 7Observed relation between evaporative heat loss, Esk, and air temperature, Ta

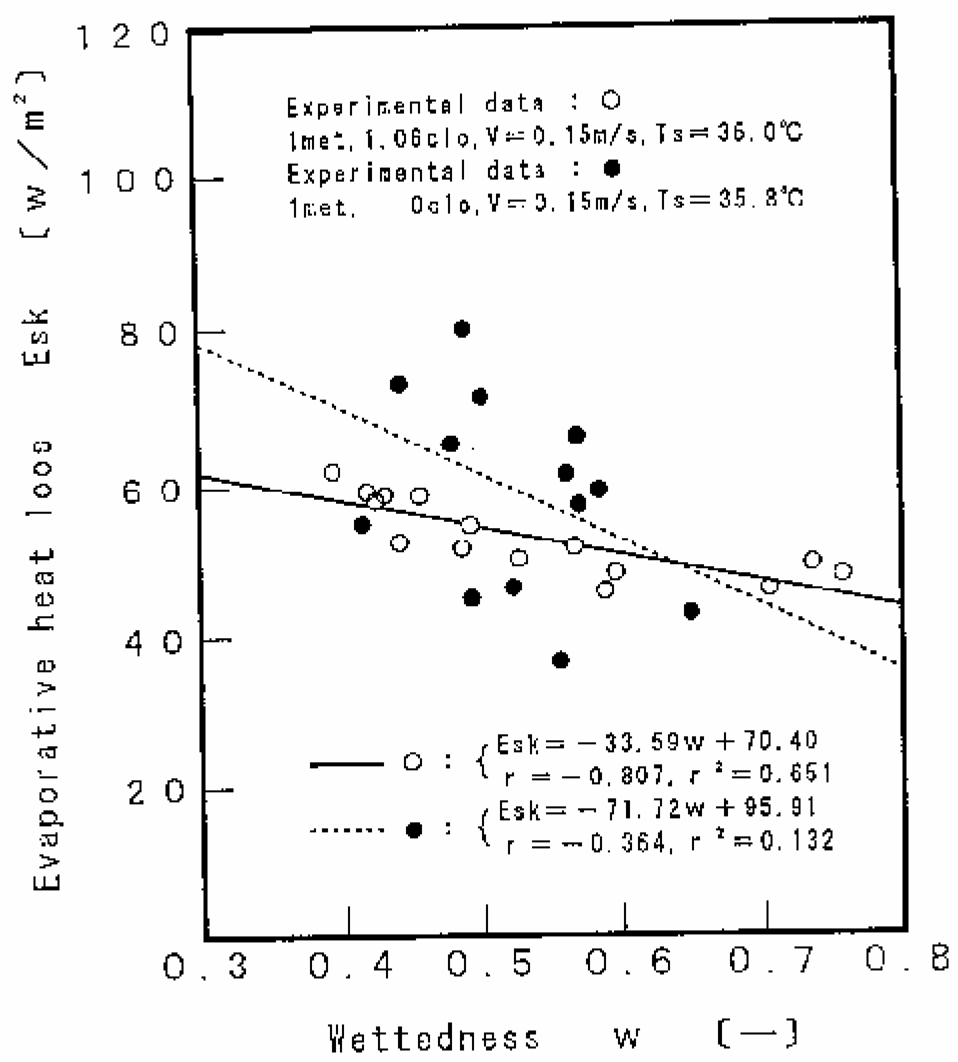

Figure 8Observed relation between evaporative heat loss, Esk, and wettedness, w

With regard to the relation between the wettedness and the vapor pressure, Figure 4 indicates that the higher the vapor pressure, the greater the wettedness value. Concerning the relation between the wettedness and the air temperature, Figure 5 shows that the higher the air temperature, the smaller the wettedness value. The data reveal that even if the average skin temperature is constant, the value of wettedness is variable and that a maximum value of wettedness and a minimum value exist at a constant average skin temperature. Figure 8 shows the relationship between the wettedness and the observed evaporative heat loss. The data show a negative correlation between the wettedness and the obtained evaporative heat loss.

Under the conditions of resting/sitting, a 1 clo-wear, still air movement and constant average skin temperature 36°C;

- Wettedness correlates positively with the vapor pressure but correlates negatively with the air temperature
- Evaporative heat los correlates positively with the air temperature but correlates negatively with the vapor pressure

■ At a constant average skin temperature, the value of wettedness is variable and both maximum and minimum values exist.

From the analysis of the present experimental data obtained by using the clothed subjects, it was concluded that the value of wettedness at the constant average skin temperature does not remain constant. These results indicate the same tendency observed in the experiments using the naked subjects, that is, the value of wettedness tends to become larger al the environmental humidity becomes higher, while it tends to become smaller as the humidity becomes lower (Mochida 1996).

HEAT BALANCE EQUATION AND COMPARISON OF EQUAL AVERAGE SKIN TEMPERATURE LINE

The human body, at steady state, exchanges heat with the surroundings mainly through the four avenues of convection, radiation, perspiration, and respiration, provided the heat losses by conduction, clothing ventilation, and mechanical work are considered small in comparison. This heat balance can be written as

$$M = C + R + Esk + Cres + Eres \tag{1}$$

where

M = net rate of metabolic heat production (W/m^2),
C = heat gained or lost by convection (W/m^2),
R = heat gained or lost by radiation (W/m^2),
Esk = evaporative heat loss (W/m^2),
and
Cres+Eres = heat gained or lost by respiration (W/m^2).

In equation(1), the heat losses by convection, radiation, perspiration, and respiration (Fanger 1970) are written by

$$C = Fcl.hc(Ts-Ta), \tag{2}$$

$$R = Fcl.hr(Ts-Tr), \tag{3}$$

$$Esk = Fpcl.LR.hc(P^*s-Pa)w, \tag{4}$$

$$Cres + Eres = M(0.1491-0.0014Ta-0.0173Pa) \tag{5}$$

$$Fcl = \frac{1}{1 + 0.155(hc + hr)Iclo} \tag{6}$$

$$\mathrm{Fpcl} = \frac{1}{1 + 0.143 \,.\, \mathrm{hc} \,.\, \mathrm{Iclo}} \tag{7}$$

where
hc = convective heat transfer coefficient (W/m^{2}°C),
hr = liner radiation exchange coefficient (W/m^{2}°C),
LR = modified Lewis relarion (°C/mmHg [=2.2]),
Ts = average skin temperature (°C),
Ta = ambient air temperature (°C),
Tr = mean radient temperature (°C),
P*s = saturated vapor pressure for boundary layer at skin surface (mmHg),
Pa = vapor pressure in ambient air (mmHg),
w = total wettedness (dimensionless) (Gagge 1937),
Fcl = Burton’s efficiency factor (dimensionless),
and
Fpcl = permeation efficiency factor (dimensionless) (Nishi et al 1970).

From Equations (1) ~ (7), the heat equilibrium transfer (or loss) between the man and the thermal environment in a uniform temperature field in which the ambient air temperature is equal to the mean radiant temperature is given by the following equation:

$$\begin{aligned} M = {} & \mathrm{Fcl}(hc + hr)(Ts - Ta) + \mathrm{Fpcl.LR.hc}(P^{*}s - Pa)w \\ & + M(0.1491 - 0.0014Ta - 0.0173Pa) \end{aligned} \tag{8}$$

Using both the heat balance equation (Equation (8)) and Figure 8, a line of equal average skin temperature, 36°C, is theoretically derived as shown in Figure 9. As seen in Figure 9, the equal skin temperature, 36°C, line (A) - (B) on the psychrometric chart, is a curved one. On this line, the wettedness value is not constant but changes from a maximum of 0.8 to a minimum of 0.35 and agree with our experimental data collected using the clothed subjects. If the wettedness maintains the value of 0.8 in the region of middle- and low-environmental humidity, the evaporative heat loss will be too large and does not agree with the value of the present experimental data. The straight line (A) - (C), the constant wettedness line, corresponds to the idea of ET* (Gagge et al 1971). The results of Figure 9 is the same tendency as the results of naked subjects: Figure 10 (Mochida 1996).

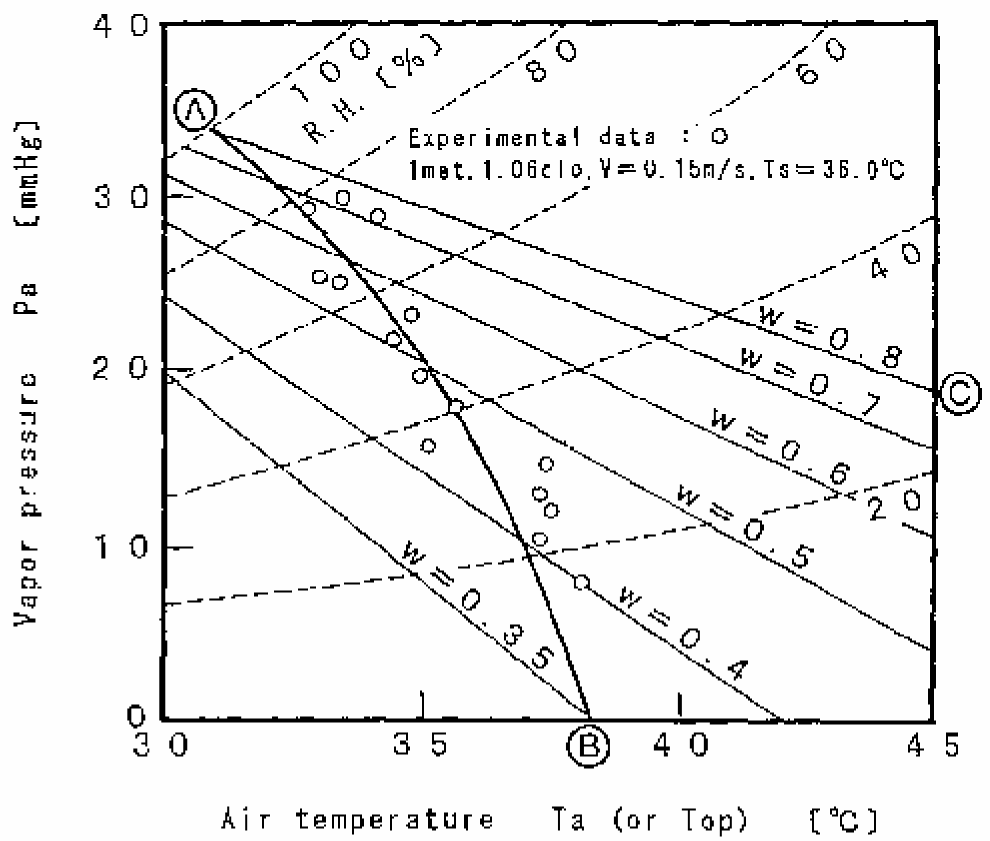

Figure 9 Comparison of equal skin temperature, Ts, lines (clothed subjects)

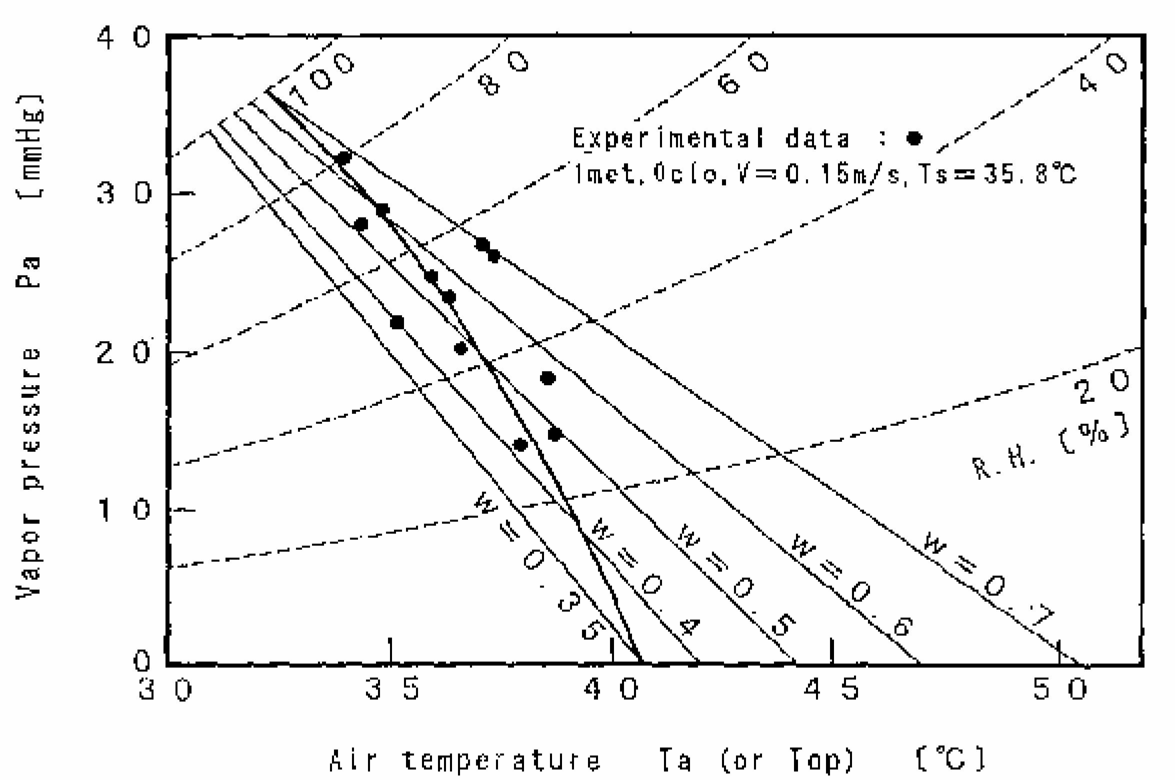

Figure 10 Comparison of equal skin temperature, Ts, lines (naked subjects)

CONCLUSIONS

This paper had dealt with the variability of wettedness observed in our experimental results and with its effect on the equal skin temperature line. The experiments were carried out using young, healthy male Japanese students to investigate the values of wettedness in high-, middle-, and low-humidity environments in hot conditions. The experiments were conducted on sitting-resting subjects in a test chamber. The subjects were dressed in the clothing ensemble of 1 clo and were exposed to several thermal conditions for one hour.

From the basic measurements of both environmental parameters and human physiological responses, the following results were obtained concerning the characteristics of wettedness under constant average skin temperature.

- There is a positive correlation between wettedness and environmental humidity.
- There is a negative correlation between wettedness and air temperature.
- There is a positive correlation between the evaporative heat loss from the skin surface and the air temperature.
- There is a negative correlation between evaporative heat loss and environmental humidity.
- There is a negative correlation between wettedness and evaporative heat loss.
- Wettedness does not remain constant but takes varying values (i.e., both maximum and minimum wettedness values exist) corresponding to each average skin temperature.

Considering these itemized results of experiments and the thermal equilibrium between humans and their environment, it is theoretically concluded that the locus of equal skin temperature is not a straight line but is a curved line plotted on the psychrometric chart.

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