THERMAL EFFECTS OF ENVIRONMENTAL VARIABLES ON PEOPLE IN OPEN AIR

PART I, REVIEW AND EXPERIMENTAL STUDIES

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ABSTRACT

There are many instances in which a human body is exposed to a windy climate: on a veranda, at an outdoor-restaurant, in a courtyard, etc. The comfort sensations of a human being are very susceptible to environmental variables. However, few comfort criteria for outdoor thermal environments have been established, even though many research projects for indoor climate have been completed.

In this part of the paper, subjective experiments in open air and in a wind tunnel are mentioned. Based on experimental results, the effects of solar radiation, activity level, and the turbulence of air velocity on subjective sensations were analyzed. Comfort criteria for outdoor thermal environments will be proposed in the next part.

1. Introduction

Many studies on the heat balance of a human body and the related thermal sensations have been done for many years since Houghten and Yaglogl‌ou[1] presented Effective Temperature. Most of these previous studies have been interested in the indoor climate, and several formulas for acceptability based on the heat balance of a human body have been proposed by Fanger[2], Gagge, Stolwijk and Nishi[3], et al. As the sensation of thermal comfort is affected by various thermal factors, related acceptability are consequently expressed in complicated forms. On the contrary concerning thermal effects in outdoor flow, few works were made. To adapt the proposed criteria for indoor conditions to outdoor conditions, the differences of thermal effects on people between indoors and outdoors should be investigated: increase of metabolic rates; the added effect of solar radiation; the difference characteristics of flow, etc. It is considered that the range of acceptability in outdoor conditions is wider than that in indoor conditions. Formula for acceptability in outdoor conditions may be expressed in simple form.

This part of the paper describes the results of subjective experiments to acquire the effects of wind turbulence and solar radiation on people, etc. And comfort criterion will be proposed by modifying of indoor climatic criteria in the next part.

2. Previous Studies on Comfort Criteria in Outdoor Climate

2-1. The Heat Balance around the Body

As for the heat exchange surrounding the body, it is convenient to divide the heat transfer between the body core and the external environment into following three stages.

(a) Heat Exchange from the Body Core to the Skin Surface

The body may be regarded as a central core at uniform temperature T_b, surrounded by peripheral tissue having thermal resistance R_b. The equation of heat flow from the body core to the skin surface may be written:

$$M=H_b(T_b-T_s)=\frac{1}{R_b}(T_b-T_s), \quad (1)$$

or
$$T_b-T_s=\frac{1}{H_b}M=R_bM, \quad (2)$$

where M= metabolic rate of heat production, W/m^2,
H_b= thermal conductance of the peripheral tissue, W/m^2 °C,
R_b= thermal resistance of the peripheral tissue, m^2 °C/W,
T_b= body core temperature, °C,
and T_s= skin surface temperature, °C.

The metabolic heat reaches the skin surface by conduction and by blood flow, most of which is conveyed by blood flow. As one feels warm, the blood vessels in limbs and the body surface enlarge, and more warm blood flows near the skin. Thus the thermal resistance of the body tissue decreases, and heat dissipates rapidly to the surroundings. When one feels farther hot, sweat glands supply enough water due to vasodilation, and the quantity of the evaporative heat loss from the skin surface increases. At the same time, the skin temperature rises, and which improve the coefficient of the evaporative heat loss. When one feels cold, the blood vessels in limbs and the body surface constrict, and less blood flows to the limbs and the body surface. Thus the thermal resistance of the body tissue increases, and less heat loses to the surroundings. Moreover, an increase in quantity of metabolic heat production is caused by shivering.

(b) From the Skin Surface to the Clothing Surface

As k is the proportion of metabolic heat dissipated by means other than evaporation, kM is dissipated by conduction, convection and radiation to the clothing surface.

$$kM=H_{cl}(T_s-T_{cl})=\frac{1}{R_{cl}}(T_s-T_{cl}), \quad (3)$$

or
$$T_s-T_{cl}=\frac{1}{H_{cl}}kM=R_{cl}kM, \quad (4)$$

where k= the proportion of the metabolic heat dissipated by means other than evaporation,
H_{cl}= thermal conductance of clothing, W/m^2 °C, $(H=\frac{1}{R_{cl}})$
R_{cl}= thermal resistance of clothing, m^2 °C/W,
and T_{cl}= the area weighted mean outer surface temperature of the clothes and exposed skin, °C.

(c) From the Clothing Surface to the Surroundings

At the worn body surface, the heat is released to the surroundings by convection and radiation. It can be considered that this quantity is little affected by relative humidity unless this is extreme high. The equation of heat flow from the clothing surface to the surroundings is expressed as follows:

$$kM=H_c(T_{cl}-T_a)+H_r(T_s-T_r), \quad (5)$$

$$kM=(H_c+H_r)\cdot(T_{cl}-\frac{H_cT_a+H_rT_r}{H_c+H_r}), \quad (6)$$

$$kM\fallingdotseq(H_c+H_r)\cdot(T_{cl}-T_g), \quad (7)$$

$$T_{cl}-T_g=\frac{1}{H_c+H_r}kM=(R_c+R_r)kM, \quad (8)$$

where T_a= air temperature, °C,
T_r= mean radiant temperature, °C,
H_c= convective heat transfer coefficient, W/m^2 °C,
R_c= convective thermal resistance, m^2 °C/W,

H_r= radiative heat transfer coefficient, W/m^2 °C,

R_r= radiative thermal resistance, m^2 °C/W,

and T_g= globe temperature, °C.

The term $\frac{H_c T_a + H_r T_r}{H_c + H_r}$ is a weighted mean between T_a and T_r. It is the equilibrium temperature of an unheated object having convection and radiation coefficients in the same ratio as H_c and H_r. At low air velocities T_a and T_r have almost equal weight. Unless the difference between T_a and T_r is large, the precise values assigned to H_c and H_r do not critically affect the value of $\frac{H_c T_a + H_r T_r}{H_c + H_r}$, so the temperature of a globe thermometer, T_g, should adequately represent it for most indoor environments.

(d) **From the Body Core to the Surroudings**

When the rate of metabolic heat production is equal to that of heat loss through the clothing to the surroundings, the heat balance equation applies (9) or (10) adding equations (2), (4), and (8).

$$T_b - T_g = \frac{1}{H_b} M + \frac{1}{H_{cl}} kM + \frac{1}{H_c + H_r} kM, \tag{9}$$

or

$$T_b - T_g = R_b M + R_{cl} kM + (R_c + R_r) kM. \tag{10}$$

These equations are the heat balance formulas expressed by body temperature, radiant temperature, and metabolic rate as parameters.

2-2. Humphreys' Equation[12)]

Assuming uniform temperature, T_b, of 37°C in the heat balance equation (9) or (10), Humphreys defined comfort criterion that thermal resistance of the body, R_b, for acceptability lay between 0.04 m^2 °C/W (onset of sweating) and 0.09 m^2 °C/W (onset of shivering). He supposed that values of k in Eq. (10) were ranging from 0.70 to 0.75 at rest or approximately 0.6 at exercise, and expressed following equation for acceptability in normal indoor conditions:

$$37 - T_g = M(0.065 \pm 0.025) + 0.7MR_{cl} + 0.7MR_a, \tag{11}$$

where M= metabolic rate of heat production, W/m^2,

R_b= thermal resistance between body core and body shell, m^2 °C/W, $(0 \leqq R_b \leqq 0.1)$

and R_a= combined thermal resistance, m^2 °C/W. $(R_a = R_c + R_r)$

2-3. Penwarden's Equation[13)]

Penwarden adapted Humphreys' equation for outdoor conditions by adding a term for solar radiation, and expressed the equation as follows:

$$37 - T_a = (0.065 \pm 0.025) + 0.7M0.155R_{clo} + \frac{0.8M + S}{4.2 + 13\sqrt{U}}, \tag{12}$$

where S= solar heat input per square meter of body surface, W/m^2,
$(0 \leqq S \leqq 120)$

and R_{clo}= thermal resistance of clothing, clo.
(1clo=0.155m^2/W=0.186m^{2}h°C/kcal)

Based on Humphreys' suggestion Penwarden assumed that $(H_c + H_r)$ equals $(4.2 + 13\sqrt{U})$ W/m^2 °C for combined heat transfer coefficient, k equals 0.8 and maximum value equals 120 W/m^2 for solar heat input, and he regarded T_g in Eq. (11) as T_a. When appropriate values of M, R_{clo}, and S are substituted into Eq. (12) according to referential conditions, this equation allows the relation between air temperature, T_a, and air velocity, U, for comfort conditions. For typical outdoor conditions, Penwarden assumed that M equals 100 W/m^2 of metabolic rate for walking slowly around shopping area, and showed the thermal comfort zone for full sun (S=120 W/m^2) and for shade (S=0 W/m^2) in Figs. 1 and 2. Thus Eq. (12) becomes as follows:

$$T_a=37-(6.5\pm2.5)-12.4R_{clo}-\begin{cases}\dfrac{80}{4.2+13\sqrt{U}}, \cdots\cdots \text{ no sun}\\[2ex] \dfrac{200}{4.2+13\sqrt{U}}. \cdots\cdots \text{ full sun}\end{cases} \tag{13}$$

The values of thermal resistance of clothing chosen for calculation are 0 clo (nude), 0.5 clo (light summer clothes), 1.0 clo (typical British business suit), and 1.5 clo (typical winter clothing with overcoat). The central bold lines in Figs. 1 and 2 show the state of thermal neutrality for each thermal resistance of clothing. Both sides of shadowed areas show the upper bound (just sweating) and the lower bound (just shivering) of the thermal comfort regions for each thermal resistance of clohing. From Figs. 1 and 2, the needed value of thermal resistance of clothing can be seen to maintain thermal comfort under arbitrary air temperature and air velocity.

2-4. Green's Equation[15)]

Green proposed the heat balance equation (14) for thermal comfort conditions in outdoor climates, provided that a man feels comfortable at skin temperature T_s of 33°C:

$$T_s=T_a+\frac{1}{7}hm+\frac{m-15+120S(1-A)}{2+9\sqrt{0.1+U}}, \tag{14}$$

where m=metabolic rate, mcal/s,

m= 40 : light exercise

m=100 : walking in moderate pace

m=200 : very strenuous exercise

(m [mcal/s]=$2m$ [kcal/m^{2}h] assuming a people for body surface 1.8m^2)

S=coefficient of sunshine,

S=1 : at noon in midsummer

S=0.2 : at noon in midwinter

A=albedo of clothing,

A=0.7 : white cloth

A=0 : black cloth

and h=thickness of clothing, cm.

h=0.5 : thin cloth

h=1 : thick sweater

Green suggested that metabolic rate is 100 mcal/s for walking in moderate pace. Supposing A equals 0.3 for albedo of clothing, the heat balance equations, for full sun (S=1) and for shade (S=0), are expressed as follows:

$$T_a=33-\frac{100}{7}h-\begin{cases}\dfrac{85}{2+9\sqrt{0.1+U}}, \cdots\cdots \text{ no sun}\\[2ex] \dfrac{169}{2+9\sqrt{0.1+U}}. \cdots\cdots \text{ full sun}\end{cases} \tag{15}$$

Figures 3 and 4 illustrate the comfort lines, for h=0.5(thin cloth) and for h=1 (thick sweater), shown by Eq. (15), and also show Penwarden's comfort lines for similar results. Even if it is regarded h=0.5cm for thickness of clothing as 1clo and h=1cm as 1.5 clo, comfort lines described by Green's equation differ from Penwarden's at the lower wind speeds.

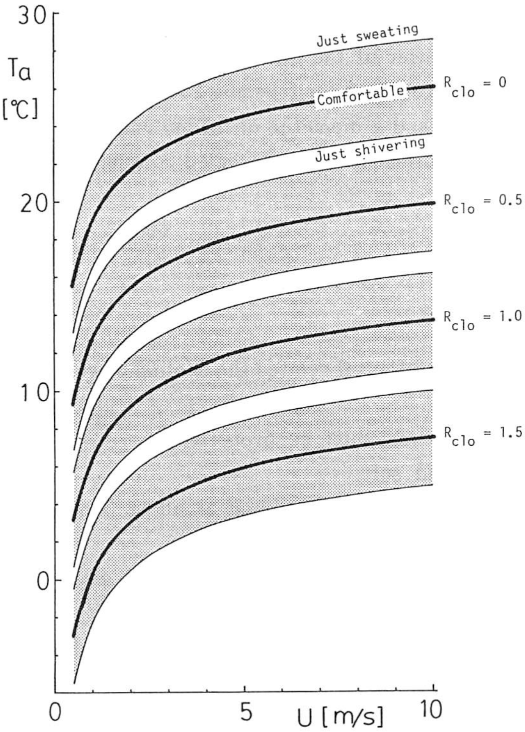


Fig. 1 Penwarden's comfort criterion (walking in full sun)

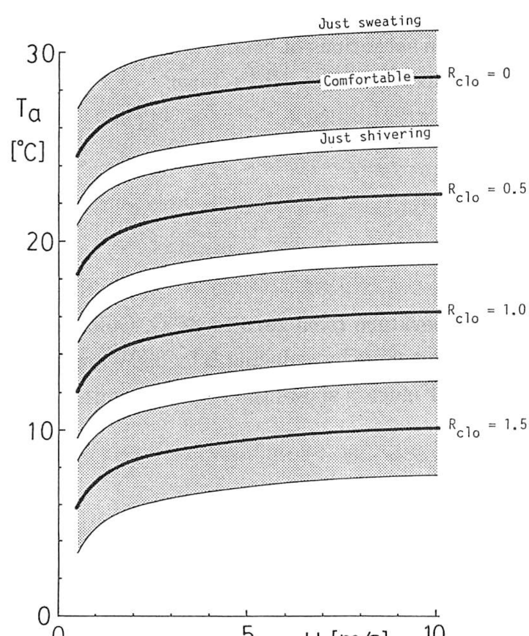


Fig. 2 Penwarden's comfort criterion (walking in no sun)

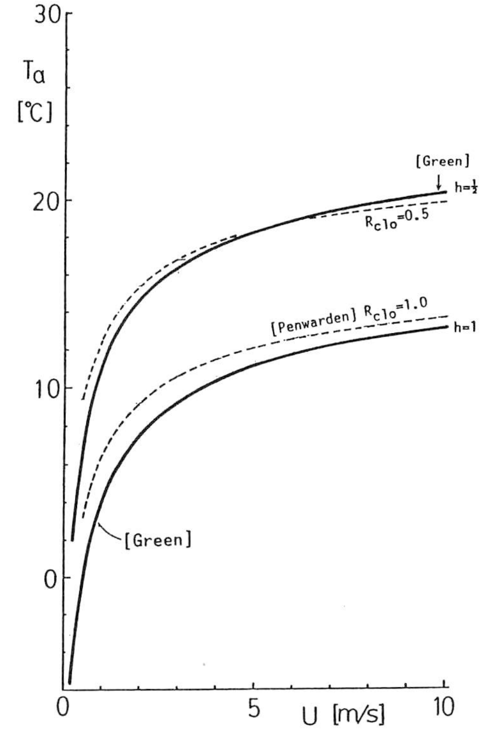


Fig. 3 Green's comfort criterion (walking in full sun)

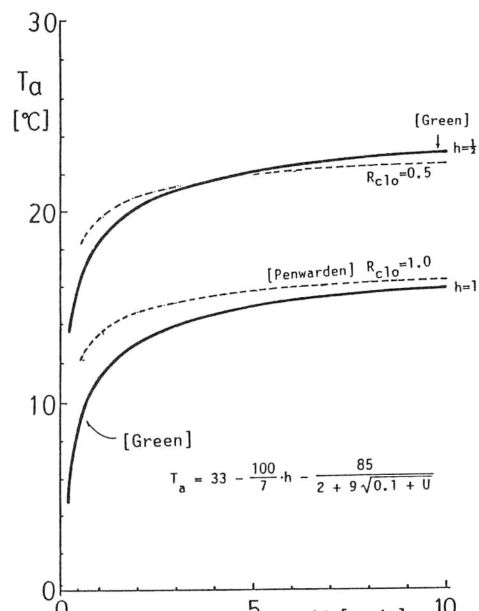


Fig. 4 Green's comfort criterion (walking in no sun)

2-5. Wind Chill Index by Siple and Passel[16]

Siple and Passel studied the relation between cooling power of the atmosphere and the thermal sensations in sub-freezing conditions. They measured the time required for freezing 250 grams of water in cylinder made of synthetic resins having a length of 15cm and a diameter of 5.7cm, and calculated cooling power of the atmosphere from the result of the measurement. They revealed cooling power H could be shown following equation:

$$H=(10\sqrt{U}+10.45-U)\cdot(33-T_a), \quad (16)$$

where H=cooling power of the atmosphere, kcal/m²h,

U=air velocity, m/s,

and T_a=air temperature, °C.

$(10\sqrt{U}+10.45-U)$ term is called "Wind Chill Index". Siple and Passel related the cooling power, H, to the thermal sensations as follows:

H= 100kcal/m²h …… Nude sun-bathing possible but eyes must be protected,

H= 400 …… Snow surface becomes tacky and soft,

H= 600 …… Conditions considered as comfortable while skiing at about 3 miles/h, (metabolic output about 200 kcal/m²h)

and H=1000 …… Pleasant conditions for travel cease on foggy and overcast day

Figure 5 shows comfort lines in relation between air temperature, T_a, and air velocity, U, for the value of cooling power, H=100, 400, 600, and 1000 kcal/m²h. Siple and Passel's work was based on the experimental results in sub-freezing conditions in the Antarctic. However, the characteristics of cooling effects differ from those of a human being. Thus it is uncertain that their works can be suitable for usual atmosphere.

2-6. Gold's Equation[19]

Gold related cooling power of the atmosphere, H, to his own sensations of comfort. However the rate of cooling, measured by means of a katathermometer, was expressed in Hill's form:

$$H=(36.5-T_a)\cdot(9.72+17.7\sqrt{U}), \quad (17)$$

or

$$T_a=36.5-\frac{H}{9.72+17.7\sqrt{U}}, \quad (18)$$

where H=cooling rate, kcal/m²h,

T_a=air temperature, °C,

and U=air velocity, m/sec.

The formula applied at windspeeds up to 18m/sec in air temperature from zero to 26°C. Gold related values of H to his comfort sensations, making an allowance for sunshine by reducing H by 630W/m² in full sun, 290W/m² with light cloud, and 125W/m² with thick cloud. Figure 5 shows the thermal comfort lines described by Eq. (18).

2-7. Studies of Hunt, et al. and Jackson[20),21)]

Hunt, et al. and Jackson reported studies on the thermal sensations in a outdoor flow in similar methods. However, the work by Hunt, et al. was based on the experimental results in wind tunnel, and Jackson's was based on the results of questionnaire in the city. Figure 6 shows the results of both the studies. The numerial values in Fig. 6 express *hot*(100) − *cold*(0) vote.

Penwarden's equation is famous among comfort criteria in outdoor windy environments above mentioned. However, it has not been clarified experimentally whether his equation may be suitable to

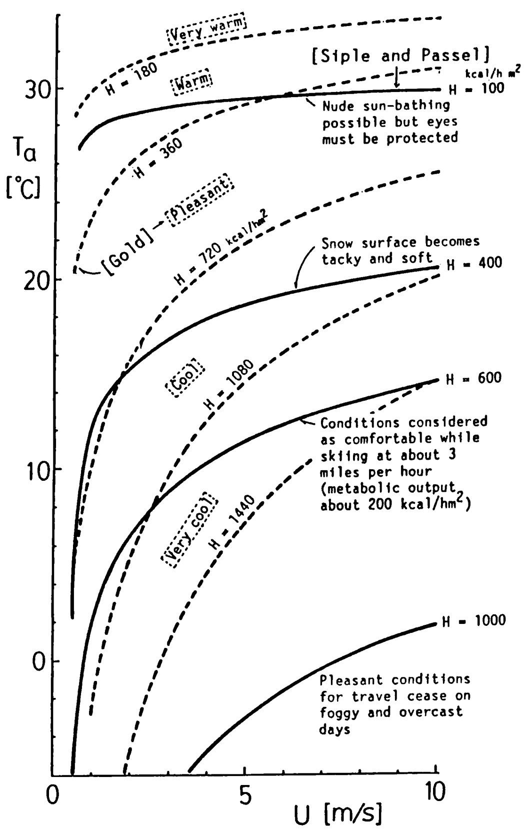


Fig. 5 Comfort criteria by Siple and Passel, and Gold

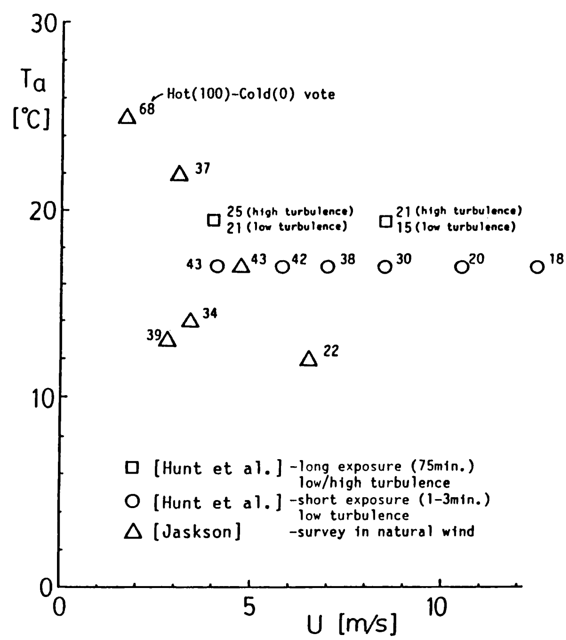


Fig. 6 Studies on thermal sensation by Hunt, et al. and Jackson

practical conditions. From these points of views, it is required that comfort criteria should be improved for the outdoor climate based on experimental results.

3. Experiments in Open Air and in wind Tunnel

The authors have made experiments in open air and in wind tunnel with the purpose of acquiring the effects of solar radiation, activity level, and the characteristic of air flow on sensations of a human body.

3-1. Outline of Experiment

The experiments have been performed under seven different conditions as shown in Table 1, for

Table 1 Types of experiment

	Open Air				Wind Tunnel		
Solar Radiation	Sunshine		Shade		(Shade)		
Activity Level	Sedentary	Walking	Sedentary	Walking	Sedentary		
Characteristic of Air Flow	Natural Flow				2.0m/s Uniform	1-3m/s Changeable (period:10min)	1-3m/s Changeable (period:30sec)
'85Autumn	—	—	—	—	○	○	—
'86Summer	○	○	○	○	○	○	○
'86Autumn	○	○	○	○	○	—	○

Table 2　Data of subject

Subject (sex)	Age	Height (cm)	Weight (kg)	Thermal Resistance of Clothing(clo) '85autumn	'86summer	'86autumn
A(m)	22	173.0	63.0	1.77	0.65	1.28
B(m)	21	163.0	53.0	1.59	0.73	1.44
C(m)	21	160.0	57.0	1.60	0.66	1.35
D(f)	20	161.0	53.0	—	0.51	1.85
E(f)	22	157.0	50.0	1.41	0.62	1.45
F(f)	18	156.0	50.0	—	0.57	1.55
G(f)	18	157.0	50.0	1.49	—	—
H(f)	18	169.0	58.0	1.68	—	—

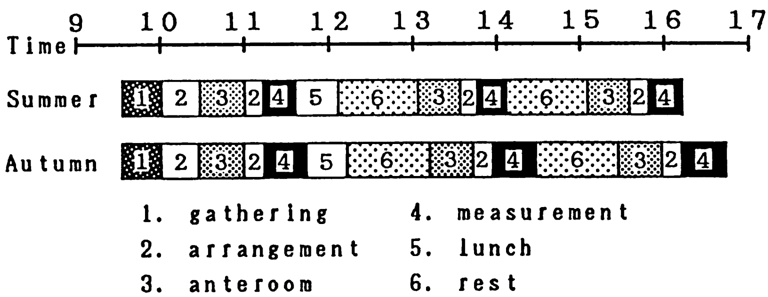


Fig. 7　Experimental schedule

summer and for autumn, during the period from November 22 in 1985 to November 23 in 1986. Six students (3 males and 3 females) are chosen as subjects for each experiment, and were healthy and young. Their heights and weights are listed in Table 2. Thermal resistances of their clothes are also shown in this table. The subjects wore the typical clothing for each season during the experiments: a thermal resistance of summer clothes was approximately 0.6 clo (1 clo=0.186m^2 °Ch/kal), and that of autumn clothes was approximately 1.5 clo. Figure 7 shows the experimental schedule.

(a)　**Open Air Test**

The experiments were carried out at the courtyard in Kagoshima University. A plan of the mesuring site is illustrated in Fig. 8. The west end opens onto small street and three other ends are enclosed with buildings.

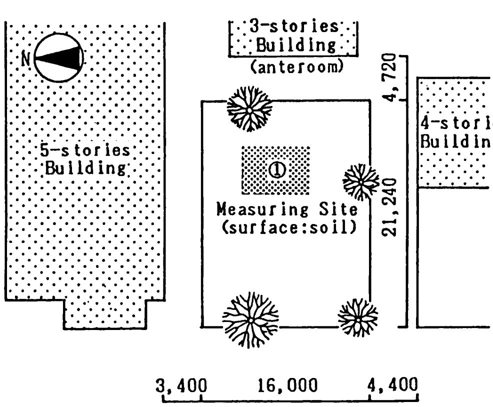


Fig. 8　Plan of the measuring site in open air

Range of Thermal Variables

Air temperature and humidity during the experiments varied roughly as follows:

	(summer)	(autumn)
air temperature	: 24.0～30.0°C,	16.3～29.4°C,
relative humidity	: 35.0～76.0%,	24.0～65.6%.

Condition of Solar Radiation

In case of "sunshine", the subjects kept a sedentary posture in south direction. Under the condition of "shade", solar radiation was covered by the roof of a white tent at the measuring site ① [Fig. 8]. Moreover, the experiments in shade were performed in cloudy days in order to reduce the influence of radiant heat from the surface of the tent.

Condition of Air Flow

Mean air velocity and turbulent intensity in open air tests are covered roughly as follows:

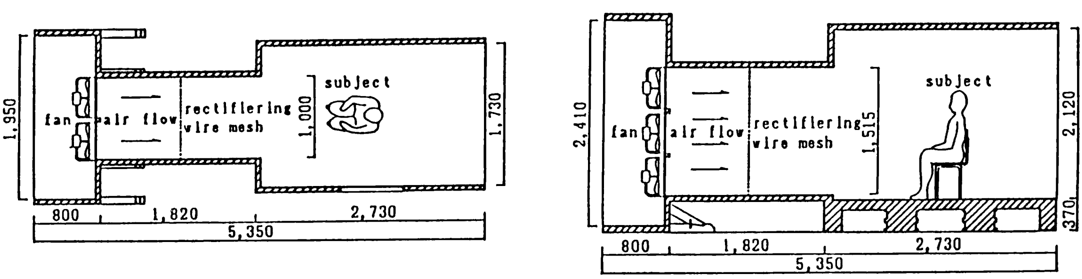
	(summer)	(autumn)
mean air velocity	: 1.40m/s,	1.44m/s,
turbulent intensity	: 31.0%,	26.0%.

Activity Levels

The subjects were examined at sedentary (approx. 50 kcal/m^2h [27]) and at walking at approximately 3.2km/h (approx. 100 kcal/m^2h [27]). During the experiment at walking, the subjects walked around rectangular site ① (approx. 5.5m×4.0m) as shown in Fig. 8.

(b) Wind Tunnel Test

The experiments were carried out in wind tunnel with six fans (capacity of ventilation=2,640m^3/h, output power=50w). A plan and a section of the wind tunnel are illustrated in Fig. 9. Turbulent intensity in working section is about 4% in average.



(a) plan (b) section

Fig. 9 Wind tunnel

Range of Thermal Variables

In wind tunnel, air temperature, relative humidity and mean radiant temperature could not be controlled, so that the thermal conditions are dependent on natural climate. Air temperature and humidity during the experiments varied roughly as follows:

	(summer)	(autumn)
air temperature	: 28.5～31.0°C,	14.0～21.0°C,
relative humidity	: 35.0～76.0%,	24.0～70.0%.

Characteristic of Air Flow

The subjects were examined under three flows with different characteristics: flow A, flow B and flow

C. Flow A is an uniform one with mean velocity of 2m/s. Under flow B, velocity changes alternately between 1m/s and 3m/s with 5-minute intervals. Velocity under flow C changes sinusoidally within the range of 1m/s～3m/s with a period of thirty seconds. However, all the wind tunnel flows have the same mean velocity of 2m/s (see Fig. 15).

3-2. Measuring Methods

0.3mmϕ C–C thermo-couples were employed to measure air temperature and globe temperature. In open air, both of them were measured at 1.2m above the ground surface. To reduce the influence of solar radiation on air temperature measurement the sensor was arranged under the shade by a tree. In wind tunnel, the air temperature was measured at height of 0.8m and the globe temperature at height of 1.1m.

Air velocity in open air was measured at 1.2m above the ground surface. An anemometer of transistor typed was employed, and wind data were recorded continuously by analog pen-recorder.

Using Assmann's aspiratory psychrometer, the relative humidity was measured, at height of 1.2m every 5 minutes in open air and at height of 1.5m before and after experiment in wind tunnel tests.

The global horizontal solar radiation at 2.0m above the ground surface is measured by Eppley Black and White typed pyranometer.

Skin temperatures of the subject were measured by 0.1mmϕ C–C thermo-couples taped to skin surface with 3M surgical tapes. Measuring points are illustrated in Fig. 10. Mean skin temperature is obtained by averaging each temperature weighted by DuBois fractional area as shown in Fig.10.

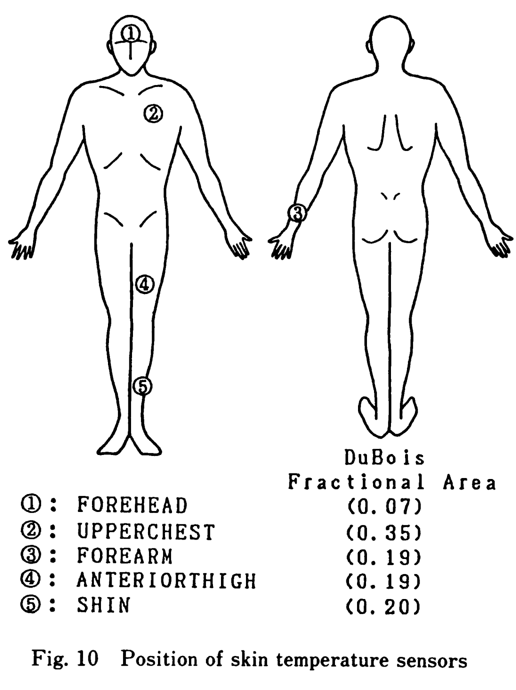


Fig. 10 Position of skin temperature sensors

The measured signals of the solar radiation and the skin temperatures were recorded by a potentiometer at 1 minute interval.

Oral temperature was measured before and after experiment by means of a digital clinical thermometer.

As for the psychological sensations, the subject voted for thermal sensation, comfort sensation and draft sensation on the category scale, as given in Table 3, with multi-point switch at all times, and the numerical number of each sensation was recorded every minute.

The arrangement of instruments are listed in Table 4.

Table 3 Category scales

Thermal Sensation	Comfort Sensation	Draft Sensation
-3 : cold -2 : cool	1 : uncomfortable	1 : none
-1 : slightly cool 0 : neutral	2 : slightly uncomfortable	2 : slightly definite
+1 : slightly warm +2 : warm	3 : slightly comfortable	3 : definite
+3 : hot	4 : comfortable	4 : strong

Table 4 Arrangement of instrument

Item	Height and Location		Method
	WindTunnel	Open Air	
Air temperature	0.8m	1.2m	C-C Thermo-couple (0.3mm φ)
Globe temperature	1.1m	1.2m	C-C Thermo-couple (0.3mm φ) in black globe with a diameter of 15cm
Air velocity	—	1.2m	Transistor-typed Anemometer
Relative humidity	1.5m	1.2m	Assmann's Aspiratory Psychrometer
Global harizontal solar radiation	—	2.0m	Epprey B & W Pyranometer
Skin temperature	Forehead, Upperchest, Forearm, Shin and Anteriorthigh		C-C Thermo-couple (0.1mm φ)
Oral temperature	—		Digital Clinical Thermometer
Psychological sensation	—		Multi-point Switch

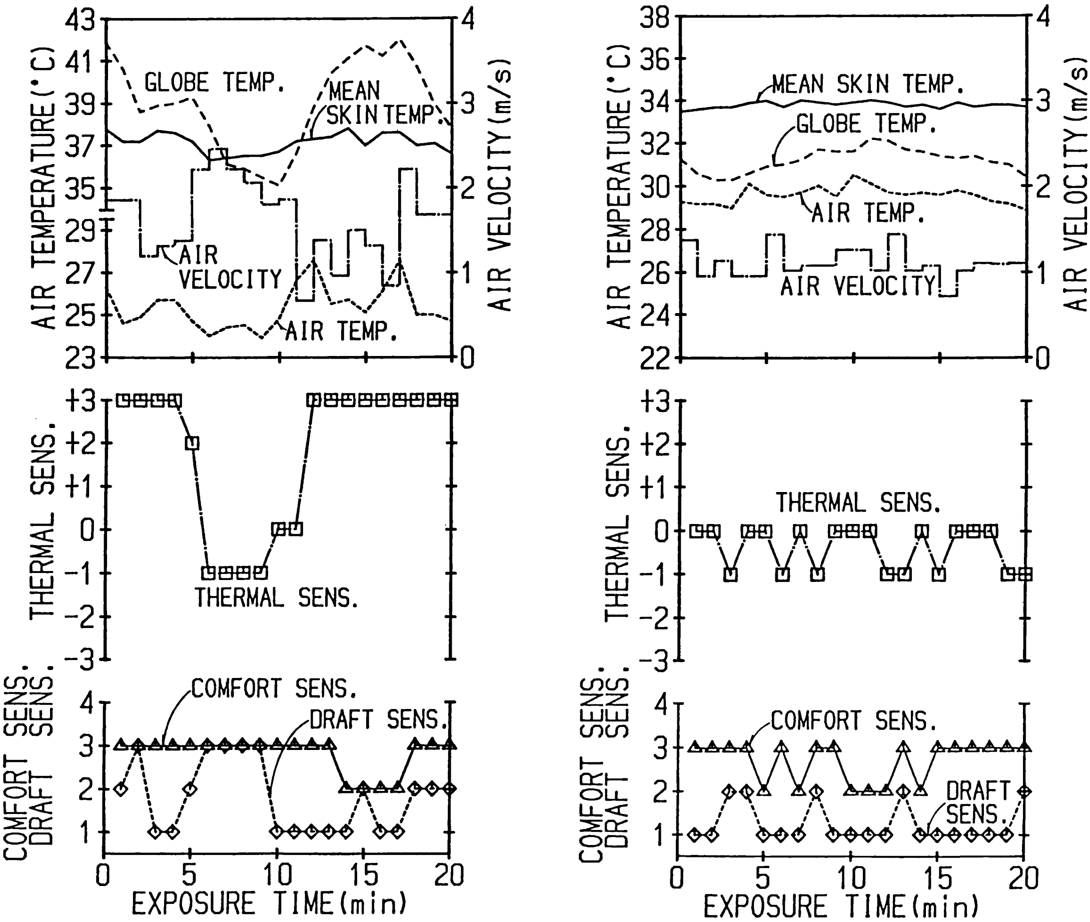
3-3. Result of Outdoor Experiment

Experiments in Summer

Figures 11(a) and 11(b) show the changes with time of mean skin temperatures, subjective sensations and the environmental variables of subject(A) at sedentary.

In sunshine [Fig. 11(a)], the changes of mean skin temperature and thermal sensation correspond well to those of globe temperature. Comfort sensation votes follow relatively the change of air velocity. In shade [Fig. 11(b)],the change of comfort sensation corresponds relatively to that of air velocity.

Though mean air temperature in shade is about 4°C higher than that in sunshine, comparing experimental results in sunshine with those in shade, many votes at the upper grade, hot〔+3〕, of thermal sensation are made in sunshine, and is three grades higher than that in shade. It is considered that thermal sensation is affected significantly by solar radiation. However, comfort sensations under two differnt conditions of solar radiation agree almost within the range of slightly comfortable〔3〕 to slightly uncomfortable〔2〕. It is supposed that increases of air velocity and its changes make subjects comfortable in case of sunshine [Fig. 11(a)].

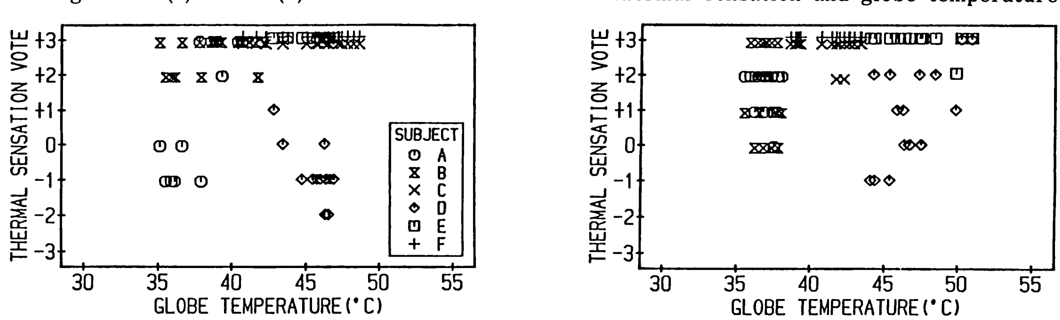


(a) sedentary in sunshine (b) sedentary in shade

Fig. 11 Changes with time of mean skin temperature, subjective sensations and environmental variables in summer [subject(A)]

As for skin temperature, similar results are obtained about the other subjects. Concerning each psychological sensation, a precise tendency could not be obtained because of an individual scatter.

Figures 12(a) and 12(b) show the relation between thermal sensation and globe temperature in

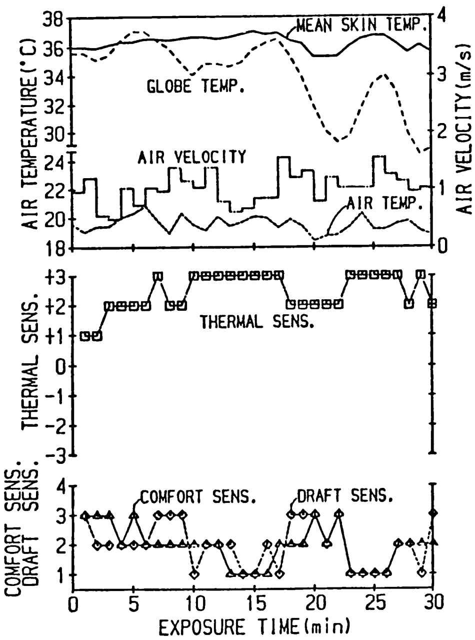


(a) at sedentary (b) at walking

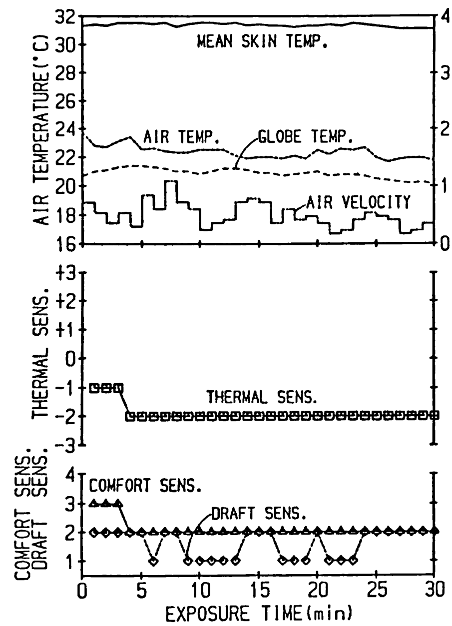
Fig. 12 Relation between globe temperature and thermal sensation in sunshine (summer) sunshine in summer. As numerous thermal sensation votes of hot〔+3〕 are made in sunshine due to the effect of solar radiation, precise correlations between thermal sensations and globe temperature could not be recognized. Comparing the effects of activity levels between sedentary and walking [comparing Fig. 12(a) with 12(b)], almost no difference on thermal sensation is recognized. In summer, it can be considered that there is no effect of difference of activity level on thermal sensation between sedentary and walking because solar radiation has great effect upon thermal sensation.

Experiments in Autumn

The changes with time of mean skin temperatures, subjective sensations and environmental variables of subject(D) at sedentary are shown in Figures 13(a) and 13(b).



(a) sedentary in sunshine

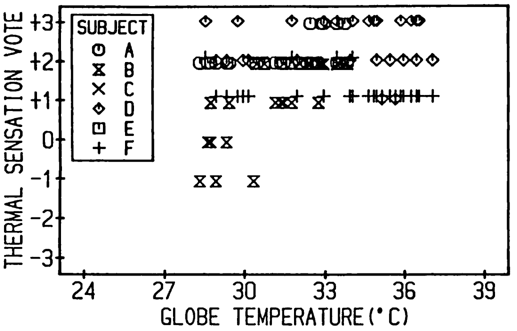


(b) sedentary in shade

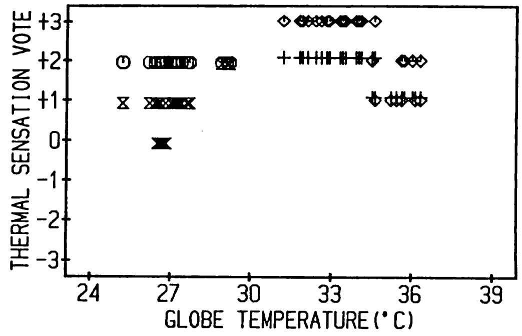
Fig. 13 Changes with time of mean skin temperature, subjective sensations and environmental variables in autumn [subject(D)]

In sunshine [Fig. 13(a)], the changes of mean skin temperature and thermal sensation correspond relatively to those of globe temperature same as the experimental results in summer [see Figs. 11(a) and 11(b)]. Comfort sensation votes follow comparatively the change of air velocity by contrast to the experimental results in summer: as air velocity increases, comfort sensation votes are made at the lower grade of uncomfortable〔1〕; as air velocity decreases, they are made at the upper grade of comfortable〔4〕. Since the change of globe temperature is small in shade [Fig. 13(b)], an uniform thermal sensation votes 〔−2〕 are made except that thermal sensation changes once one grade lower at four minutes after the start of measurement.

Figure 14(a) shows the relation between thermal sensation and globe temperature in sunshine at sedentary in autumn and Fig. 14(b) is the same as Fig. 14(a) but at walking. Thermal sensation votes change the upper grade of hot〔+3〕 as globe temperature increases, and the correlation could be recognized slightly. The remarkable difference of effects of activity levels between sedentary and walking could not be recognized.



(a) at sedentary



(b) at walking

Fig. 14 Relation between globe temperature and thermal sensation in sunshine (autumn)

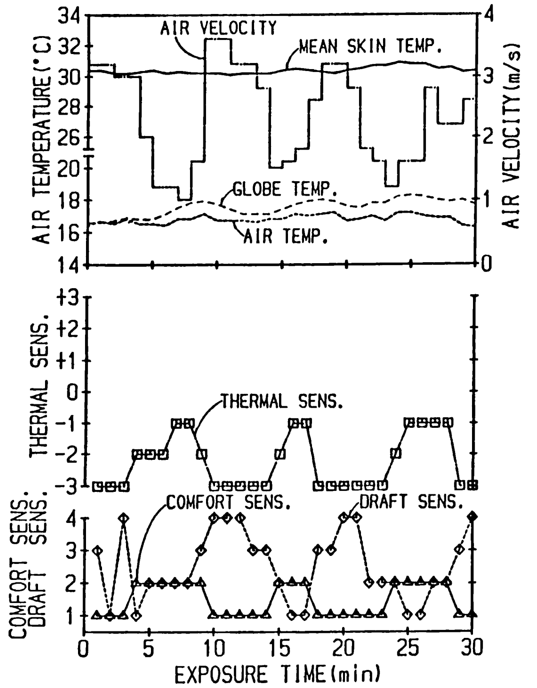
3-4. Relation between Turbulent Intensity of Air Flow and Subjective Sensation

The effects of the turbulence of air velocity on subjective sensations are discussed on basis of experimental results in wind tunnel, because air velocity and its turbulence in each open air test vary widely. Comparing results in wind tunnel with those in open air, examples under each flow in autumn of subject(B) at sedentary are shown in Fig. 15, which are relatively similar one another in mean air temperature and mean air velocity. Figure15(a) shows the change with time of mean skin temperature, subjective sensations, and environmental variables in open air test in shade, and Figures 15(b) and 15(c) show those in wind tunnel.

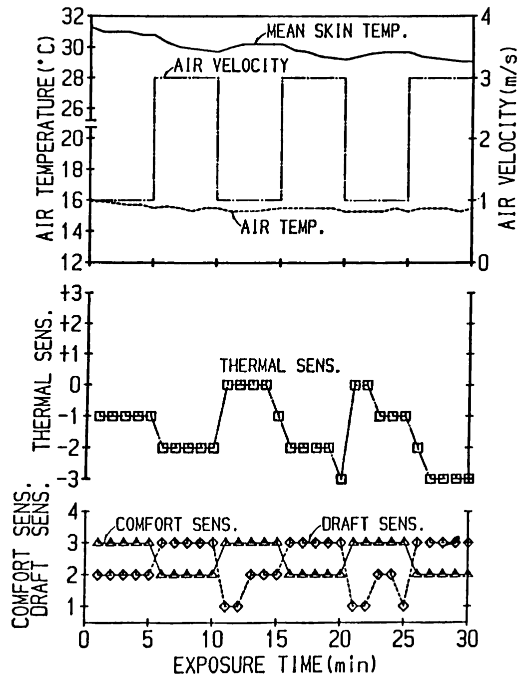
Comparing the experimental results in open air with those in wind tunnel, since the shape of the change of air velocity in open air [Fig. 15(a)] resembles comparatively that of flow B in wind tunnel [Fig. 15(b)], both ways of the change of thermal sensation and those of comfort sensation show similar tendencies. However, the range of the comfort sensation votes in open air is one grade lower as compared with that at flow B, and corresponds to that at flow C [Fig. 15(c)]. Moreover, similar results are obtained for subject(A) who is examined with subject(B) at same time. It can be therefore considered that the effects of flow C corresponds most closely to that of air flow in open air.

The relation between comfort sensation and thermal sensation in wind tunnel flowB in autumn is shown in Fig. 16(a) and that at flow C is shown in Fig. 16(b). As thermal sensation vote of cool〔−2〕 expected uncomfortable in autumn is made, comfort sensation votes of comfortable〔4〕 are made at flow B. However, in wind tunnel flow C [Fig. 16(b)] no comfort sensation vote of comfortable〔4〕 is made in the range of thermal sensation from neutral〔0〕 to cool〔−2〕. It is considered that increase of the change of air velocity affects the subjects uncomfortable in the cool season.

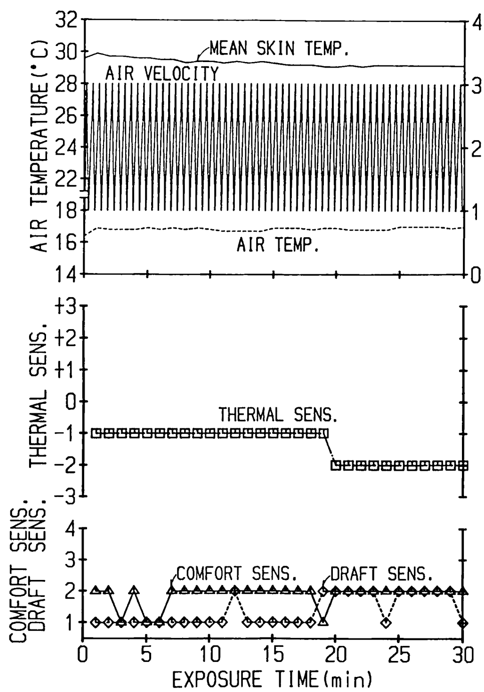
Figure 17 shows the relations between comfort sensation and thermal sensation in wind tunnel flow B and C in summer. In the range of thermal sensation of warm〔+2〕 of hot〔+3〕 which were expected sensation of uncomfortable in summer, comfort sensation votes of slightly comfortable〔3〕 and comfortable〔4〕 are also made at flow C. [Fig. 17(b)] Therefore, it is considered that turbulence mitigates uncomfortability by humidness in summer.



(a) at open air flow
(mean air velocity=2.3m/s: turbulent intensity=25%)

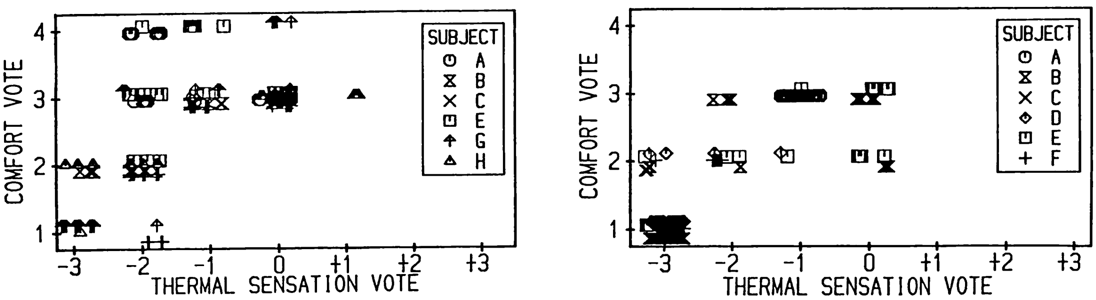


(b) at flow B



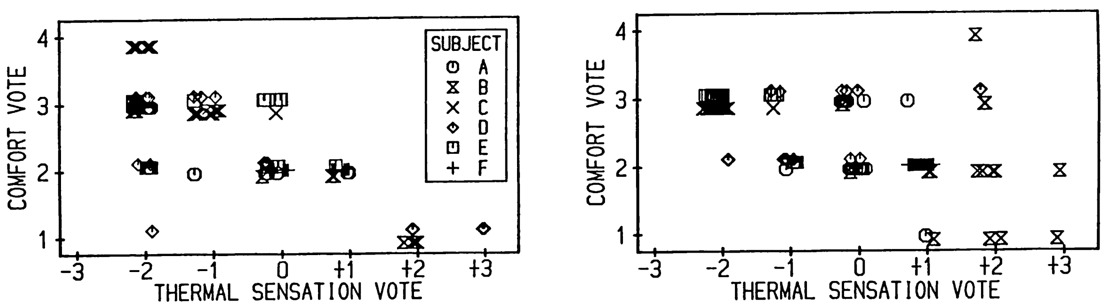
(c) at flow C

Fig. 15 Comparision of subjective sensations in autumn [subject(C)]



(a) at flow B (b) at flow C

Fig. 16 Relation between thermal sensation and comfort sensation in autumn

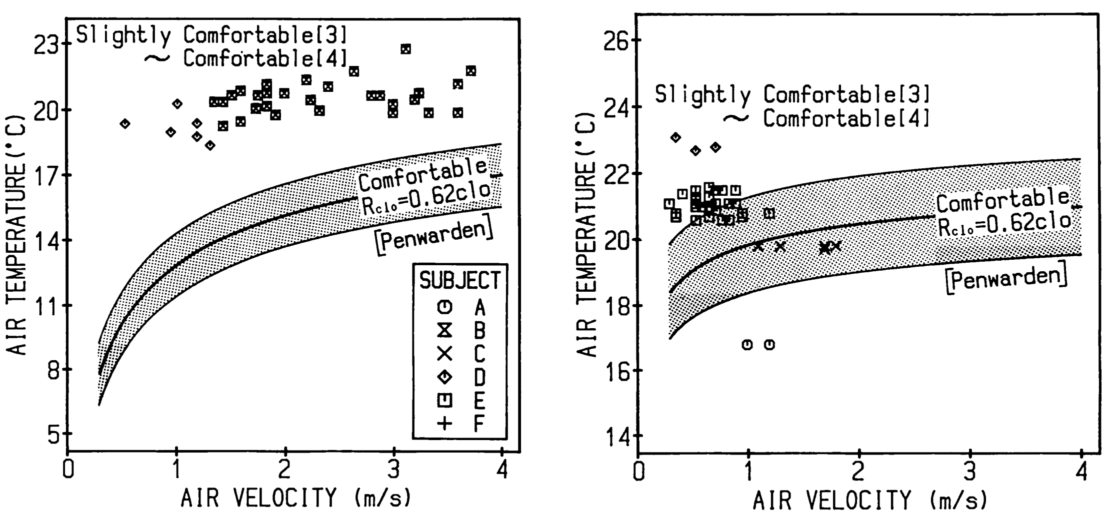


(a) at flow B (b) at flow C

Fig. 17 Relation between thermal sensation and comfort sensation in summer

3-5. Comparison with the Penwarden's Comfort Criterion

As thermal sensation vote of slightly comfortable〔3〕 or comfortable〔4〕 is made in outdoor experiment at sedentary in autumn, the experimental results are compared with calculated results by Penwarden's equation(12) as function with air temperature and air velocity in Fig. 18.



(a) sedentary in sunshine (b) sedentary in shade

Fig. 18 Comparision with Penwarden's comfort criterion in autumn

In sunshine [Fig. 18(a)], the observed values for air temperature are distributed in the part of approximately 6°C high as compared with Penwarden's comfort criterion. In shade [Fig. 18(b)], the distribution of observed values for air temperature varies widely, and that is distributed in the part of approximately 2°C high. It is supposed that the difference of the distribution of observed values of air temperature in sunshine is larger than that in shade by reason that maximum value for solar input is allowed 120W/m^2 by Penwarden and differs remarkably from measured value 203W/m^2 for radiant heat input in author's outdoor experiments in sunshine.

Concluding Remarks

Subjective experiments have been performed in wind tunnel and in open air; in summer and in autumn, to clarify the effects of environmental variables on the sensation for thermal acceptability. The results are summarized briefly as follows:

(1) The changes of skin temperature and thermal sensation correspond relatively to those of globe temperature.

(2) Solar radiation has a great effect on thermal sensation.

(3) In summer, increases of air velocity and its change make subjects comfortable. In autumn, those make subjects uncomfortable.

(4) In summer, the difference of activity levels between sedentary and walking has no effect on thermal sensation because solar radiation has a great effect on thermal sensation.

(5) The value for solar heat input in Penwarden's comfort criterion is estimated lower than its actual value.

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