THERMAL COMFORT REQUIREMENTS UNDER HOT AND HUMID CONDITIONS

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ABSTRACT

The purpose of this study was to investigate thermal comfort for subjects under hot and humid conditions with a view to energy conservation.

In the first part of this paper, thermal comfort under hot and humid conditions is discussed based on previous experimental data. The neutral temperature for Japanese was 79.4 F (26.3°C), which was not significantly different from previous studies with Danes and Americans. High relative humidity was associated with a high percentage of uncomfortable subjects.

In the second part of this paper, effects of air movement on thermal comfort were investigated. During the summer season, 64 college-age Japanese subjects were exposed under various air velocities. It was found that above 100 fpm (0.5 m/s) present results of thermal sensation were much smaller than those predicted by PMV (Predicted Mean Vote). The PMV (Predicted Mean Vote) - PPD (Predicted Percentage of Dissatisfied) model for evaluation of a hot and humid environment was regarded somewhat differently from the current study.

INTRODUCTION

The purpose of the present study was to investigate thermal comfort requirements for subjects with a view to energy conservation in buildings under hot and humid conditions.

For energy efficient air conditioning, it is desirable to make the set point temperature and humidity close to the outdoor conditions within the acceptable range. From this point of view, it is important to know thermal comfort characteristics of the building occupants.

In the first part of this paper, thermal comfort for subjects under hot and humid conditions is discussed. It is widely believed that the people living in a hot region prefer warmer conditions than do people living in a cold region. Is this true or not? It is well known that the people in a hot region have more sweat glands than people in a cold region. Since skin wettedness has a strong influence on subjective thermal comfort, it is important to know the evaporative heat loss from the people living in hot and humid regions.

There are several laboratory studies on subjective thermal comfort for the people living in hot and humid regions (Miura et al. 1962, 1963; Ogawa et al. 1974, 1975; Naruse et al. 1978, 1979; Tanabe and Kimura 1986). However, as the total number of subjects in these studies was small, it is difficult to make statistically valid comparisons with American and European data (Nevins et al. 1966; Rohles and Nevins 1971; Fanger 1970), and it is impossible to calculate the acceptable range of temperature and humidity. During one summer, 172 Japanese college-age

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subjects wearing 0.6 clo standard clothing were exposed under sedentary activity for three hours to 11 different thermal conditions in a climate chamber (Tanabe et al. 1987). The present study of thermal comfort for subjects under hot and humid conditions is based on the data of that experiment.

Many field studies have been conducted on the subjective thermal comfort in hot and humid regions (Ellis 1952, 1953; Wyndham 1963; Ballantyne et al. 1967; Ballantyne and Spencer 1972; Ballantyne et al. 1979; Dedear and Auliciems 1985; Foo and Phoon 1986). It was generally recognized that the results of these studies agreed well with those made in the test chambers, although several researchers pointed out there were some differences in comfort conditions between laboratory and field studies.

In the second part of this paper, effects of air movement on thermal comfort were investigated. Since under hot and humid conditions higher air movement in a ventilated space would make occupants feel cooler because of greater heat loss from their bodies, it is important to determine the effects of air movement on thermal comfort. Use of fans or natural ventilation for cooling in a non-air-conditioned space is quite energy efficient in achieving thermal comfort under hot and humid conditions.

Based on these two experimental studies recently conducted in Japan, it was considered necessary to discuss the reliability of PMV (Predicted Mean Vote) - PPD (Predicted Percentage of Dissatisfied) model for evaluation on hot and humid environment.

THERMAL COMFORT IN HOT AND HUMID REGIONS

Do the People Living in Hot and Humid Regions Prefer Warmer Conditions than Europeans and North Americans Do?

Figure 1 shows the mean thermal sensation vote versus modified temperature for Japanese, Danish, and American college-age subjects (Tanabe et al. 1987). Modified temperature (MT) (Tanabe and Kimura; Tanabe et al. 1987) is defined as the air temperature that would be felt equally warm at 50% rh, 0.1 m/s air velocity, 1.0 met, 0.6 clo, and mean radiant temperature equal to the air temperature as in the actual environment to be derived from a calculation by Fanger's (1970) PMV model. It was found that thermal sensation had a good relation to the modified temperature. In other words, thermal sensation for Japanese has a good relationship to PMV. In Table 1, for Japanese, Danish (Fanger 1970), and American (Nevins et al. 1966; Rohles and Nevins 1971) subjects, the calculated regression equations for the estimated mean thermal sensation vote are given as a function of the modified temperature. The modified temperature corresponding to the neutral mean vote (Y=4) is defined as the neutral temperature. The neutral temperature of Japanese subjects was 79.4 F (26.3°C). Japanese subjects preferred 1.1 F (0.6°C) higher temperature than Danish subjects and 1.4 F higher (0.7°C) than Americans, but these differences were not statistically significant.

Fanger (1973) described comfort conditions for different national geographic groups and for groups of people regularly exposed to extreme cold or hot. The results indicate that there are only slight differences between the various groups as regards both the preferred ambient temperature and the physiological parameters under the comfortable conditions. But sometimes it is misunderstood that agreement of the neutral temperatures among different groups of subjects can prove agreement of all thermal sensations. Linear regression analysis like the Thurstone model (Guilford 1971), which is used for these studies, normally gives good estimation around the median point, but equal sensation changes on the thermal sensation scale may not always correspond to equal temperature changes for the entire temperature range.

Criticizing Fanger's work, Clark and Edholm (1985) suggested it seems unlikely that the influences of exercise, body size, body composition, sex, age and effects of adaptation or acclimatization to particular conditions have little or no effect on thermal comfort. It was not clearly understood that Fanger did not statistically check thermal comfort for the entire temperature range but only around the neutral point among different groups of subjects. It is apparent that people living in hot and humid areas are acclimatized and have the increased ability to endure a hot environment (Frisancho 1981), which does not mean acclimatized persons would prefer warmer conditions. Since the interindividual differences are rather large (Fanger and Langkilde 1975), it is quite difficult to determine statistically the differences in the neutral temperature among different groups of subjects. Laboratory study by Tanabe et al. (1987) also indicated that around the thermally neutral point there were few differences in thermal

Sensations among Japanese, Danes and Americans.

Field Studies on Thermal Comfort in Hot and Humid Regions - A Review

In most laboratory and field studies of thermal comfort, there are no significant differences in the neutral temperature among different groups of subjects. Ellis (1953) found that in Singapore the comfortable levels of warmth for groups of acclimatized European men and women and Asian men and women residents were very similar and not markedly affected by differences in race, age, or sex. Ballantyne et al. (1967) reported that the preferred temperature established at the survey for Caucasians was 77 F (25.0°C), which was 0.36 F (0.2°C) lower than that predicted by the comfort equation (Fanger 1970). Wyndham (1963) also reported similar data.

On the other hand, some researchers found differences between the experimental data of the laboratory and those of the field. Ballantyne et al. (1979) published a thermal comfort study from Port Moresby, New Guinea, and found that the preferred temperature for Melanesians was 80.1 F (26.7°C), which was 2.5 F (1.4°C) higher than predicted by the comfort equation. But Ballantyne could not find convincing evidence to support the possibility of diurnal or seasonal acclimatization, and any differences due to the sexes or to eating were judged to be minor. Humphreys (1978) summarized field studies from around the world, reanalyzed these data, and found that the pattern from field studies differed in some respects from that provided by the heat-exchange model of thermal comfort, which seemed to make too little allowance for people's adaptability to variations in their thermal environment. Dedear and Auliciems (1985) investigated the thermal comfort of office workers in Darwin, Brisbane, and Melbourne, finding that simple linear regression equations based on the findings from 50 years of field surveys of thermal comfort were better predictors of the survey groups' neutral temperatures than the sophisticated PMV model.

In daily life people regulate their clothing to avoid discomfort in their thermal environment. Thermal environment and subjective conditions (metabolic rate and so on) might change from time to time. On the other hand, in test chambers, subjects were sometimes exposed to an unwanted thermal environment for data analysis. For example, if subjects were exposed only under comfortable conditions, it would be difficult to find out a regression equation between temperature and thermal sensation. In the field studies, one or several thermal comfort parameters were often lacking. A change in thermal insulation of 0.2 clo will change the preferred ambient temperature by 2.7 F (1.5°C) for a seated person (Olesen and Nielsen 1982). In the field studies, it is very difficult to estimate the exact values of thermal insulation of clothing worn by building occupants. Verbal scales expressed in different languages might make differences. Further careful investigation is needed for application of test chamber data to a real world environment.

Evaporative Heat Loss and Skin Wettedness

Figure 2 shows the evaporative heat loss from the skin surface near the thermally neutral zone for Japanese, namely, around 73 - 79 F (23 - 26°C), 60% rh. This can be interpreted as insensible heat loss by skin diffusion, which turned out to be 3.2 Btu/h•ft² - 3.8 Btu/h•ft² (10 W/m² - 12 W/m²). Significant differences were found in the values between males and females in high temperatures. The calculated values at an air temperature of 77 F (25° C), 60% rh, by Fanger's equation (1970, Equation 9a) and the equation in ASHRAE Fundamentals (1981, Equation 22) for skin diffusion were 3.5 Btu/h•ft² (11 W/m²) in both cases and agreed well with the present experimental results.

Figure 3 shows skin wettedness calculated from evaporative heat loss. Three curves in Figure 3 were derived from the computer program of SET (Gagge et al. 1973). At air temperatures of 73 F (23°C) and 77 F (25°C), the values of experimental skin wettedness are around 0.06 and agree well with those obtained by SET. However, at high temperatures, results are much smaller than those predicted by SET (e.g., at 84 F (29°C), 60% rh, present result: 0.13, SET: 0.21). It was considered that at a high temperature, Japanese sweat less than Americans. Osada postulated (1982) that people who live in hot climates sweat less until a certain temperature is reached, but above that, sweat more than those who live in a cold climate when exposed to the same conditions. Hori et al. (1978) concluded that subjects who were born and reared in a hot and humid region were superior to those who were born and reared in a temperate region in the efficiency of sweat for cooling bodies. Ellis (1953) also found similar results in Singapore.

Comfort Sensation Votes

The comfort sensation vote (Gagge's scale, namely, "comfortable," "slightly uncomfortable," "uncomfortable," and "very uncomfortable") was obtained simultaneously with the thermal sensation vote and acceptability in order to more closely investigate subjective effects of humidity on thermal comfort. Hensel (1981) distinguished between thermal comfort and temperature sensation, indicating that both kinds of experience could be separated phenomenologically and physiologically and that temperature sensation was related to rational experience but thermal comfort to emotional or affective experience. Gagge et al. (1967) used separate scales for comfort and temperature sensation.

Figure 4 shows the percentage of subjects who answered "uncomfortable" (namely, "very uncomfortable," "uncomfortable," or "slightly uncomfortable") versus modified temperature. Since the comfort sensation vote may not have the same width of category, probit analysis was used (Finney 1980). A regression line was obtained only from the results at 40% rh and 60% rh. The subjects felt more uncomfortable at 80% rh than at 40% rh and 60% rh, which was statistically significant (5% level). At high relative humidity, modified temperature was not a good index of comfort sensation. Comfort sensation seems somewhat different from thermal sensation at high relative humidity.

There are several ways of achieving thermally comfortable conditions by increasing or decreasing air velocity, air temperature, and humidity. Present results suggest dehumidification toward a moderate relative humidity range in the humid regions such as Japan and East Asia during the summer season, because it would reduce not only the percentage of "unacceptable" assessments but also those of "uncomfortable."

EFFECTS OF AIR MOVEMENT ON THERMAL COMFORT DURING THE SUMMER SEASON

EXPERIMENTAL METHODS

Subjects and Clothing

Sixty-four college-age persons (thirty-two females and thirty-two males) were used as subjects. All were volunteers and were paid for participating. Each subject was exposed under only one experiment for three hours. Only persons in good health were allowed to participate, no subject whose armpit temperature was above 99 F (37.0°C) being permitted to participate. Antropometric data for subjects are listed in Table 2. All subjects were clothed in cotton half-sleeve shirts, trousers, underwear, and socks. In addition, the subjects wore light slippers. The clo-value of the uniform was 0.5 clo (Olesen et al. 1982).

Experimental Facilities and Conditions

The experiment took place in a university's environmental test chamber. In the test chamber (dimensions 10.2 ft x 9.0 ft x 7.4 ft (3.1 m x 2.75 m x 2.25 m)), conditioned air is supplied from the entire front wall and returned through the rear grille (Kimura and Tanabe 1985). To get higher air movement, a wind box was used in the chamber as shown in Figure 5. Table 3 shows experimental conditions. Air velocity was automatically controlled by microcomputer and thyristor system. All temperatures and humidities were automatically registered every five minutes by means of a data recording system outside the chamber. The mean radiant temperature equaled the air temperature. Tests were made with six mean air velocities changed from 26 fpm (0.13 m/s) to 326 fpm (1.63 m/s) in the occupied zone, as shown in the bottom lines of Table 3. The whole experiment took place during the same hours of different days, either 12:00-15:00 or 16:30-19:30, in the test chamber during summer 1986 in Tokyo.

Experimental Procedure

Figure 6 shows the experimental plan. The subjects stayed in the anteroom for 30 minutes. Each subject was asked to answer to the basic thermal questionnaire recommended by the committee on thermal sensation, SHASE 1979, and then to enter into the chamber. The subject was seated on a chair as shown in Figure 5. Two subjects were exposed at the same time. During the first hour, air velocity in the chamber was maintained at 26 fpm (0.13 m/s). During the following five 20-minute periods, the subjects were exposed to five different air movements (shown in Table 3) at andom to avoid the effects of order. This was controlled by changing the air velocity in steps. During the last period, the subjects were asked every two minutes to report whether air velocity was "higher," "just right," or "lower" than it should have been by pushing a button of the question box. Until they reported "just right" more than three times, air velocity was changed. Forty-five minutes from the beginning, the subjects were asked every five minutes to indicate their thermal sensation, comfort sensation, and acceptability against the given air movement as shown in Figure 7.

During the experiment the subject was kept occupied in reading (sedentary) and was prohibited from eating, drinking, and smoking while the test was in progress.

Physiological Measurement

The skin temperatures of each subject were measured with three sensors attached to the skin of arm, upper chest, and leg by surgical tape. Mean skin temperature was calculated from the weighted average of these three temperatures. Weight coefficients of arm, upper chests, and leg were 0.14, 0.50, and 0.36 respectively (Burton 1935).

RESULTS

In the analyses of thermal sensation, comfort sensation, and acceptability of air movement and skin temperatures, mean values were calculated from the final two observed values during each exposure, when it was assumed nearly steady-state conditions were reached. Mean values were thus calculated from the measurements taken 55 and 60 minutes after the beginning of the initial period with 26 fpm (0.13 m/s) air velocity and those taken 15 and 20 minutes after the beginning of each of the following 20-minute periods.

Thermal Sensation

Analysis was performed to determine the relationship between mean thermal sensation vote and modified temperature from the total of 768 observations. As air velocity in the occupied zone was changed from 26 fpm (0.13 m/s) to 326 fpm (1.63 m/s) and relative humidity was set at 50% rh or 80% rh, all experimental combinations of ambient temperature, relative humidity, and air velocities were first converted to modified temperature (MT) as a parameter for data analysis.

Figure 8 shows the plots of thermal sensation vote against modified temperature. Each point represents the mean of the votes of 16 subjects. The dotted line shows the results by Tanabe et al. (1987) under low air movement. It was found that at higher air velocity, air movement brought much more cooling effects than the result predicted by PMV represented by the chain line. Figure 9 shows the linear relationship between the thermal sensation vote and modified temperature with mean air velocity below 100 fpm (0.5 m/s), which agrees fairly well with the previous results of the authors (1987). It would mean that the thermal sensation vote under 100 fpm (0.5 m/s) air velocity has a linear relation close to Fanger's thermal load.

Figure 10 shows the relation between thermal sensation vote and standard effective temperature (Gagge et al. 1973). It can be seen that, even for higher air velocity, standard effective temperature still has a linear relation to thermal sensation vote. The correlation coefficient between standard effective temperature and mean thermal sensation was 0.894.

Mean Skin Temperature

A regression analysis was performed to determine the relationship between mean skin temperature and modified temperature. Figure 11 shows the mean skin temperature versus modified temperature. Each point represents the mean of 16 subjects. It was found that mean skin temperature has a good relationship to modified temperature and agreed well with our previous results under low air velocities. Mean skin temperature corresponding to the neutral thermal sensation vote turned out about 34.0°C.

Percentage of Subjects Sensing Air Movement and Uncomfortable

In the winter season or in an air-conditioned space, too high air velocity might cause draught. Draught is defined as an unwanted local cooling of the human body caused by air movement (Fanger and Christensen 1986). But under hot and humid conditions, air movement will provide cool environment. In this experiment, each subject was asked whether he/she felt any air movement and, if yes, whether this air movement was uncomfortable or not. Figure 12 shows the percentage of subjects sensing air movement. The percentage of subjects who found air movement uncomfortable was less than 5% for all experimental conditions. The percentage of subjects who sensed air movement increased with an increase in air velocity, about 50% of the subjects sensing air movement at air velocity of 50 fpm (0.25 m/s). Compared with the results of draught studies (Fanger and Christensen 1986; Bergulund and Fobelets 1987), the percentage of subjects who found conditions uncomfortable in the present experiment was quite small, and it seemed to have no relation to the intensity of air movement. It appeared that subjects wanted air movement under hot and humid conditions. When people are in conditions that are nearly thermally neutral or cold, an increase in air movement will not only cause draught but also make them colder. On the other hand, under hot circumstances, higher air movement causing draught provides beneficial cooling to building occupants because of greater heat loss from their bodies.

Preferred air velocity

Table 4 shows the air velocities preferred by the subjects. The preferred air velocity at 80.6 F MT (27°C MT) / 50% rh was 200 fpm (1.0 m/s); at 84.2 F MT (29°C MT) / 50% rh, 240 fpm (1.2 m/s); at 84.2 F MT (29°C MT) / 50% rh, 280 fpm (1.4 m/s); and at 87.8 F MT (31°C MT) / 50% rh, 320 fpm (1.6 m/s). There was no significant difference in preferred air velocity between sexes (5% level). The mean thermal sensation under preferred air velocity conditions was -0.5, which indicated that the subjects preferred slightly cool conditions.

DISCUSSION

Why Cannot Fanger's PMV Model Predict Subjective Thermal Comfort at Higher Air Velocities?

Though PMV has a linear relation to the thermal sensation vote for mean air velocity below 100 fpm (0.5 m/s), it seems that Fanger's PMV model is not suitable for predicting thermal sensation at higher air velocity. In Fanger's thermal load, L, or PMV, no evaporative heat loss term is included besides skin diffusion and latent respiration heat loss under sedentary activity. The terms of skin diffusion and latent respiration heat loss by Fanger (Equation 9a, 11a (1970)) are not expressed as a function of air velocity. On the other hand, evaporative heat loss from skin surface in SET by Gagge et al. (1973) is expressed to be proportional to maximum evaporative heat loss, Emax, which includes a convective heat transfer term. Evaporative heat loss from the skin surface near the thermally neutral zone (0.6 clo, 50% rh), interpreted as insensible heat loss by skin diffusion, is around 3.5 Btu/h•ft^2 (11 W/m^2) in both equations of PMV and SET under 20 fpm (0.1m/s) mean air velocity. While for a mean air velocity of 200 fpm (1.0 m/s), skin diffusion calculated by PMV equation is 3.5 Btu/h•ft^2 (11 W/m^2), equal to the value under 200 fpm (1.0 m/s) mean air velocity, that by SET equation is 7.0 Btu/h•ft^2 (22 W/m^2). Fanger's thermal load, L, is expressed with the deviation from the neutral conditions. At high air velocities, even under thermally neutral conditions, evaporative heat loss from the skin surface is increased, but in Fanger's PMV model, this incremental heat loss is neglected. Thermal insulation of clothing might be decreased due to increasing of air velocity. These might be the reason that even under the thermally neutral zone PMV would give predictions warmer than our present results under higher air velocity conditions.

Since, besides the above reason, mean skin temperature and skin wettedness become higher at high temperatures than under neutral conditions, it is considered that air movement has many more cooling effects than predicted by PMV model. As the mean air velocities in general air-conditioned spaces are below 0.5 m/s (Isoda et al. 1979, 1980; Kobayashi 1980) and nearly thermally comfortable conditions are achieved there, it would be possible to evaluate the thermal environment in air-conditioned buildings by the PMV Model. But under hot and humid conditions in naturally ventilated spaces or in places where fans are used, the PMV model may be not suitable for predicting thermal comfort.

CONCLUSIONS

During a summer season, 172 Japanese college-age subjects were exposed under sedentary activity for three hours to 11 different thermal conditions in a climate chamber. Analyses from a total of 516 observations leads the following conclusions:

1. The neutral temperature for sedentary Japanese clothed at 0.6 clo is 79.4 F (26.3°C). Japanese subjects preferred temperature 1.1 F (0.6°C) higher than Danish subjects and 1.4 F (0.7°C) higher than Americans, but these differences were not significant. These results supported the previous experimental data in test chambers made by Nevins et al. (1966), Rohles and Nevins (1973), and Fanger (1970 and 1973) (Figure 1 and Table 1).

2. The differences of the neutral temperatures between the field and test chamber studies by some researchers were pointed out. Further careful investigation is needed to apply the test chamber data to actual environment.

3. Evaporative heat loss from the skin surface under conditions of low air velocity at the thermally neutral zone was 3.2 - 3.8 Btu/h•ft² (10 - 12 W/m²), which was similar to that predicted by SET or PMV. But skin wettedness for Japanese was lower than predicted by SET at high temperatures (Figures 2, 3).

4. High relative humidity was observed to be associated with a high percentage of "uncomfortable" feelings. At high relative humidity, thermal comfort seems somewhat different from thermal sensation (Figure 4).

During the summer season, 64 college-age subjects were exposed under four different thermal conditions and six different air velocities. Analyses from a total of 768 observations lead to the following conclusions:

1. Present results show that thermal sensations at higher air velocity than 100 fpm (0.5 m/s) were much lower than those of PMV and our previous experimental results under low air velocity (Figures 8, 9).

2. Standard Effective Temperature is regarded as more suitable for predicting thermal sensations at high air velocities than the PMV Model, especially under hot and humid conditions (Figure 10).

3. Mean skin temperature has a good relationship to the modified temperature and our previous experimental results under low air velocity (Figure 11).

4. In a hot and humid environment, the percentage of subjects who found air movement uncomfortable was quite small compared with those in thermally neutral conditions (Figure 12).

5. Preferred air velocity by subjects at 80.6 F MT (27°C MT) / 50% rh was 100 fpm (1.0 m/s); at 84.2 F MT (29°C MT) / 50% rh, 240 fpm (1.2 m/s); at 84.2 F MT (29°C MT) / 80% rh, 280 fpm (1.4 m/s); and at 87.8 F MT (31°C MT) / 50% rh, 320 fpm (1.6 m/s). It was found that subjects who felt the thermal environment slightly cool were -0.5 in the thermal sensation vote under preferred air velocity conditions (Table 4).

REFERENCES

ASHRAE. 1981. ASHRAE handbook -- 1981 fundamentals, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. pp. 8.1-8.34.

Ballantyne, E.R.; Barned, J.R.; and Spencer, J.W. 1967. "Environment assessment of acclimatized Caucasian subjects at Port Moresby, Papua." 3rd Australian Building Research Congress DBR Reprint, No. 400.

Ballantyne, E.R., and Spencer, J.W. 1972. "Climate and comfort in a humid tropical area." Build International, pp. 214-219.

Ballantyne, E.R.; Hill, R.K.; Spencer, J.W.; and Bartlett, N.R. 1979. "A survey of thermal sensation in Port Moresby Papua New Guinea." No32 Commonwealth Scientific and Industrial Research Organization, Australia, pp. 1-28.

Berglund, L.G. and Fobelets, A.P.R. 1987. "Subjective human response to low-level air currents and asymmetric radiation." ASHRAE Transactions, Vol. 93, Part I.

Burton, A.C. 1935. "The average temperature of the tissues of the body." Journal of Nutrition, Vol. 9, pp. 261-280.

Clark, R.P., and Edholm, O.G. 1985. Man and his thermal environment. Edward Arnold.

Dedear, R.J., and Auliciems, A. 1986. "Validation of the predicted mean vote model of thermal comfort in six Australian field studies." ASHRAE Transactions, Vol. 91, Part 2B.

Ellis, E.P. 1952. "Thermal comfort in warm, humid atmospheres." Journal of Hygiene, Vol. 50, pp. 415-432.

Ellis, E.P. 1953. "Thermal comfort in warm and humid atmospheres." Journal of Hygiene, Vol. 51, pp. 386-403.

Fanger, P.O. 1970. Thermal comfort. Danish Technical Press.

Fanger, P.O. 1973. "Conditions for thermal comfort - A review." Proc. of the CIB Commission W45 (Human Requirements) Symposium : Thermal Comfort and Moderate Heat Stress, Building Research Station, London, September 1972, Published by HMSO, pp. 3-15.

Fanger, P. O., and Langkilde, G. 1975. "Interindividual differences in ambient temperatures preferred by seated persons." ASHRAE Transactions, Vol. 81, Part 2, pp. 140-147.

Fanger, P.O., and Christensen, N.K. 1986. "Perception of draught in ventilated spaces." Ergonomics, Vol. 29, No. 2, pp. 215-235.

Finney, D.J. 1980. Probit analysis. Chambridge University Press.

Foo, S., and Phoon, W. 1986. "The thermal environment of Singapore offices." Proc. of the tenth symposium on man-thermal environment system, Tokyo, pp. 86-92.

Frisancho, A.R. 1981. Human adaptation. The University of Michigan press.

Gagge, A.P.; Stolwijk, J.A.J.; and Hardy, J.D. 1967. "Comfort and thermal sensations and associated physiological responses at various ambient temperatures." Environmental Research 1, pp. 1-20.

Gagge, A.P.; Nishi, Y.; and Gonzales, R.R. 1973. "Standard Effective Temperature - A single temperature index of temperature sensation and thermal discomfort." Proc of the CIB Commission W45 (Human Requirements) Symposium, Thermal Comfort and Moderate Heat Stress, Building Research Station, London, September 1972, Published by HMSO, pp. 229-250.

Guilford, J.P. 1971. Psychometric method. McGraw-Hill.

Hensel, H. 1981. Thermoreception and temperature regulation. Monographs of the physiological society, No. 38, Academic press.

Hori, S.; Tsujita, J.; Tanaka, N.; and Mayuzumi, M. 1978. "Studies on heat tolerance of subtropical natives after migration to a temperate zone." International Journal of Biometeorology, Vol. 22, No. 2, pp. 82-93.

Humphreys, M.A. 1978. "Field studies of thermal comfort compared and applied (CP 76/75)." BRE Building Research Series Vol. 4 Energy, Heating and Thermal Comfort, Construction Press, pp. 237-265.

Isoda, N.; Minamino, O.; Inoue, T.; Ito, T.; and Fujii, S. 1979. and 1980. "Field study on thermal comfort and insulation of clothing in offices Part 1 - Part 10." Proc. of Annual Meeting, Architectural Institute of Japan, pp. 125-128, 561-564, 141-152, 659-670 (in Japanese).

Kimura, K., and Tanabe, S. " Design of Waseda University environmental test chamber and its performance characteristics." Proc. of CLIMA 2000, Ed. by P.O. Fanger, Vol. 4, Indoor Climate (Copenhagen), pp. 121-126.

Kobayashi, Y. 1981. "Field study on subjective thermal comfort in air-conditioning spaces." Ed. by A. Nakayama, Thermal Physiology, pp. 585-612 (in Japanese).

Miura, T.; Morioka, M.; Kimura K.; Akutu, A.; Hydo, S.; Osawa, H.; Tihara, Y.; and Okazima, T. 1960. "Experimental studies on the optimum temperature of room cooling in summer in relation to the outdoor temperature." Journal, Science of Labour, Vol. 36-6, pp. 283-336 (in Japanese).

Miura, T.; Kimura, K.; Akutsu, A.; Sato, T.; Morioka, M.; Kogi, K.; Takagi, K.; Masuda, T.; and Nishibe, T. 1962. "Experimental studies on the optimum temperature of room cooling for lightly clothed men in summer in relation to the outdoor temperature (Part 2)." Journal, of Science of Labour, Vol. 38-4, pp. 198-214 (in Japanese).

Miura, T.; Kimura, K.; Tominaga, Y.; Akutsu, A.; and Suzuki, Y. 1963. "Experimental studies on the optimum temperature of room cooling in summer for lightly clothed men in relation to the outdoor temperature (Part 3)." Journal, Science of Labour, Vol. 39-8, pp. 403-422 (in Japanese).

Naruse, T.; Minamino, O.; Inoue, T.; Ohta, K.; Shiota, U.; Kajii, H.; and Fujii, S. 1978, 1979. "Experimental study on thermal environment and sensation in the test chamber (Part 1 - 5)." Proc. of annual meeting, Architectural Institute of Japan, pp. 589-596 (in Japanese).

Nevins, R.G.; Rohles, F.H.; Springer, W.; and Feyerherm, A.M. 1966. "Temperature-humidity chart for thermal comfort of seated persons." ASHRAE Transactions, Vol. 72, pp. 283-291.

Ogawa, S.; Osada, Y.; Yamamoto, H.; Hosokawa, T.; Kuno, Y.; Yoshida, K.; Isoda, N.; Kobayashi, Y.; and Kanemitsu, K. 1974. "Experimental study on the optimal thermal condition." Bulletin, Institute of Public Health, Vol. 23-2, pp. 72-87 (in Japanese).

Ogawa, S.; Osada, Y.; Kuno, Y.; and Yoshida, K. 1975. "On the seasonal difference of optimum thermal condition." Bulletin, Institute of Public Health, Vol. 24-4, pp. 221-231 (in Japanese).

Olesen, B.W. and Nielsen, R. 1983. "Thermal insulation of clothing measured on a movable thermal manikin and on human subjects." Research No. 7206/00/914 IIIrd ECSC Program in ergonomics.

Olesen, B.W.; Sliwinska, E.; Madsen, T.L.; and Fanger, P.O. 1982. "Effect of body posture and activity on the thermal insulation of clothing: Measurements by a movable thermal manikin." ASHRAE Transactions, Vol. 88, pp. 791-805.

Osada, Y. 1982. Environmental psychology, Chapter 1. New architectural series, Vol.11, Shokokusha, pp. 3-76 (in Japanese).

Rohles, F.H., and Nevins, R.G. 1971. "The nature of thermal comfort for sedentary man." ASHRAE Transactions, Vol. 77, pp. 239-246.

SHASE, Committee on Thermal Sensation 1979. "Standarized questionnaire of investigating subjective thermal comfort and their personal history." Journal of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, Vol. 53, No. 8, pp. 778-779 (in Japanese).

Tanabe, S., and Kimura, K. 1986. "Pilot experiment on thermal comfort requirements for adults during summer season in Japan." Transaction of AIJ, Journal of Architecture, Planning and Environmental Engineering, Vol. 368, pp. 545-550 (in Japanese with English summary).

Tanabe, S.; Kimura, K.; and Hara, T. 1987 "Thermal comfort requirements during the summer season in Japan." ASHRAE Transactions, Vol. 93, Part 1.

Wyndham, C.H. 1963. "Thermal comfort in the hot and humid tropics of Australia." British Journal of Industrial Medicine, Vol. 20, pp. 110-117.

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TABLE 1a.
Regression Equations and Neutral Temperature for Different Groups of Subjects (Tanabe et al. 1987)

	Number	Regression Equation	Neutral Temperature (F)
College-age Japanese			
Female - Male	172	Y= −11.21 + 0.1916 F	79.4
Female	84	Y= −12.33 + 0.2035 F	80.3
Male	88	Y= −10.08 + 0.1794 F	78.5
College-age Danish [1]			
Female - Male	128	Y= − 9.26 + 0.1693 F	78.3
Female	64	Y= −12.91 + 0.2171 F	77.9
Male	64	Y= − 5.60 + 0.1217 F	78.9
College-age American [2]			
Female - Male	720	Y= −10.63 + 0.1876 F	78.0
Female	360	Y= −12.32 + 0.2075 F	78.6
Male	360	Y= − 8.94 + 0.1677 F	77.2

1 (Fanger 1970) 2 (Nevins et al. 1966)

TABLE 1b.
Regression Equations and Neutral Temperature for Different Groups of Subjects (Tanabe et al. 1987)

	Number	Regression Equation	Neutral Temperature (°C)
College-age Japanese			
Female - Male	172	Y= −5.080 + 0.3448 T	26.3
Female	84	Y= −5.821 + 0.3663 T	26.8
Male	88	Y= −4.337 + 0.3130 T	25.8
College-age Danish [1]			
Female - Male	128	Y= −3.836 + 0.3048 T	25.7
Female	64	Y= −5.963 + 0.3907 T	25.5
Male	64	Y= −1.709 + 0.2190 T	26.1
College-age American [2]			
Female - Male	720	Y= −4.625 + 0.3376 T	25.6
Female	360	Y= −5.678 + 0.3735 T	25.9
Male	360	Y= −3.574 + 0.3019 T	25.1

1 (Fanger 1970) 2 (Nevins et al. 1966)

TABLE 2a.
Antropometric Data for the Subjects

Group	Sex	Number	Age (year)	Height (ft)	Weight (lb)	Body Surface Area[2] (ft^2)	Ponderal Index ($kg^{0.33} \cdot m^{-1}$)
College -age	Female	32	20.8 ±1.7[1]	5.22 ±0.16	116 ±11.2	16.6 ±0.97	2.35 ±0.08
	Male	32	21.3 ±1.5	5.61 ±0.20	141 ±21.8	18.9 ±1.61	2.34 ±0.08
	Female +Male	64	21.0 ±1.6	5.41 ±0.26	129 ±21.4	17.8 ±1.72	2.35 ±0.08

1. Standard Deviation
2. Calculated by Takahira's Equation $A = 72.46\ W^{0.425} \cdot H^{0.725}$

TABLE 2b.
Antropometric Data for the Subjects

Group	Sex	Number	Age (year)	Height (m)	Weight (kg)	Body Surface Area[2] (m^2)	Ponderal Index ($kg^{0.33} \cdot m^{-1}$)
College -age	Female	32	20.8 ±1.7[1]	1.59 ±0.05	52.7 ± 5.1	1.54 ±0.09	2.35 ±0.08
	Male	32	21.3 ±1.5	1.71 ±0.06	64.1 ± 9.9	1.76 ±0.15	2.34 ±0.08
	Female +Male	64	21.0 ±1.6	1.65 ±0.08	58.5 ± 9.7	1.65 ±0.16	2.35 ±0.08

1. Standard Deviation
2. Calculated by Takahira's Equation $A = 72.46\ W^{0.425} \cdot H^{0.725}$

TABLE 3a.
Experimental Conditions

Subject	College-age Female 32 Male 32 Total 64					
Exposure Time	3 hours					
Clothing	0.5 clo					
Activity	1 met (Sedentary)					
MT	81	84	84	88		
Air Temperature (F)	82	85	84	88		
Humidity %rh	50	50	80	50		
	Mean Radiant Temperature equaled Air Temperature					
Air Movement: Mean Air Velocity (fpm)	26	87	140	203	264	321
Air Movement: TI	0.47	0.30	0.31	—	—	—

TABLE 3b.
Experimental Conditions

Subject	College-age Female 32 Male 32 Total 64					
Exposure Time	3 hours					
Clothing	0.5 clo					
Activity	1 met (Sedentary)					
MT	27	29	29	31		
Air Temperature (°C)	27.8	29.6	28.8	31.3		
Humidity %rh	50	50	80	50		
	Mean Radiant Temperature equaled Air Temperature					

Air Movement	Mean Air Velocity (m/s)	0.13	0.44	0.71	1.03	1.34	1.63
	TI	0.47	0.30	0.31	—	—	—

TI : Turbulence Intensity V(SD)/$\bar{V}$

V(SD) : Standard Deviation of Air Velocity (fpm)

$\bar{V}$: Mean Air Velocity (fpm)

MT : Modified Temperature (F)

V(SD) : Standard Deviation of Air Velocity (m/s)

$\bar{V}$: Mean Air Velocity (m/s)

MT : Modified Temperature (°C)

TABLE 4a.
Preferred Air Velocities
by the Subjects

	Female	Male	Female & Male
81 F 50% rh	197	195	195
84 F 50% rh	266	224	244
84 F 80% rh	289	246	268
88 F 50% rh	295	325	311

(fpm)

TABLE 4b.
Preferred Air Velocities
by the Subjects

	Female	Male	Female & Male
27℃ 50% rh	1.00	0.99	0.99
29℃ 50% rh	1.35	1.14	1.24
29℃ 80% rh	1.47	1.25	1.36
31℃ 50% rh	1.50	1.65	1.58

(m/s)

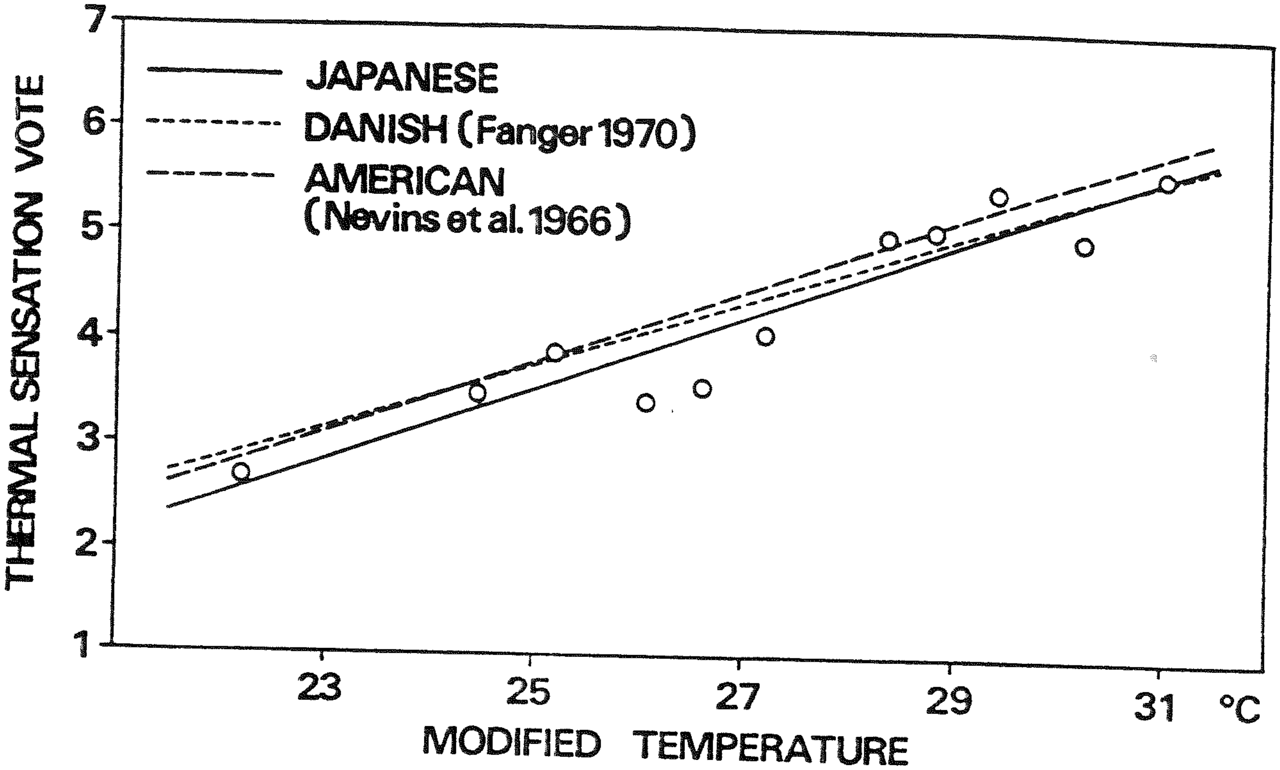

Figure 1. Mean thermal sensation vote vs. modified temperature Japanese college-age subjects (Tanabe et al. 1987). Each point represents the mean of 16 or 15 subjects. The solid curve is the regression line for individual votes (n = 172). For comparison, see the dotted curve for American college-age subjects and the broken curve for Danish college-age subjects.

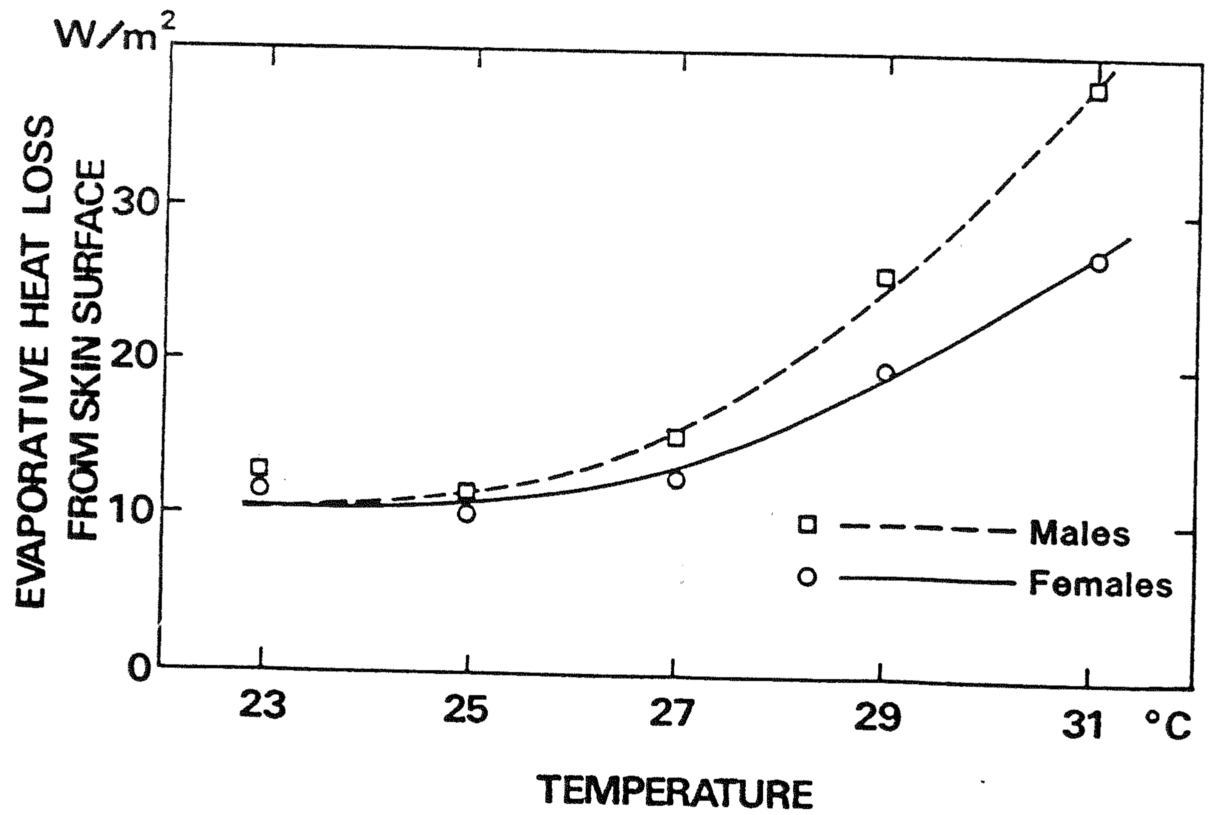

Figure 2. Evaporative heat loss from skin surface at 60% rh. Each point represents the mean of 8 or 7 subjects. (Tanabe et al 1987)

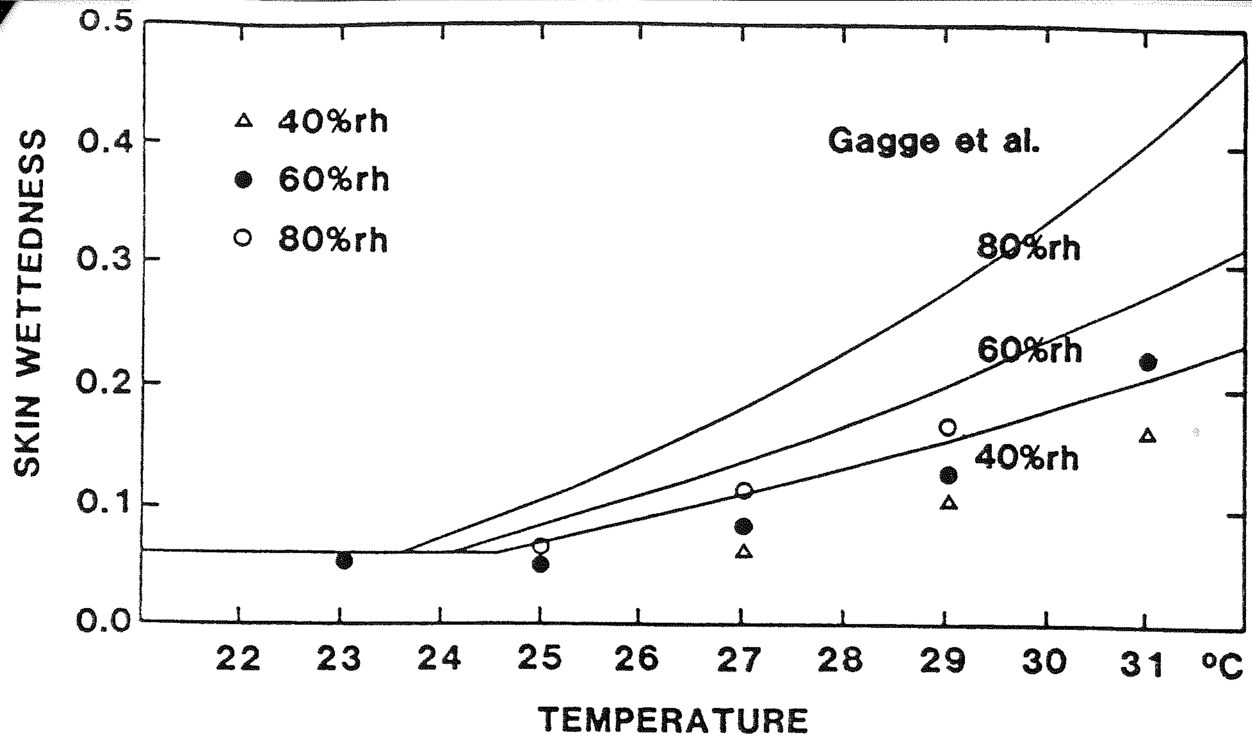

Figure 3. Skin wettedness (Tanabe et al. 1987). Each point is calculated from the mean evaporative heat loss of 16 or 15 subjects. For comparison, see the three curves of skin wettedness at 40% rh, 60% rh, and 80% rh calculated by SET.

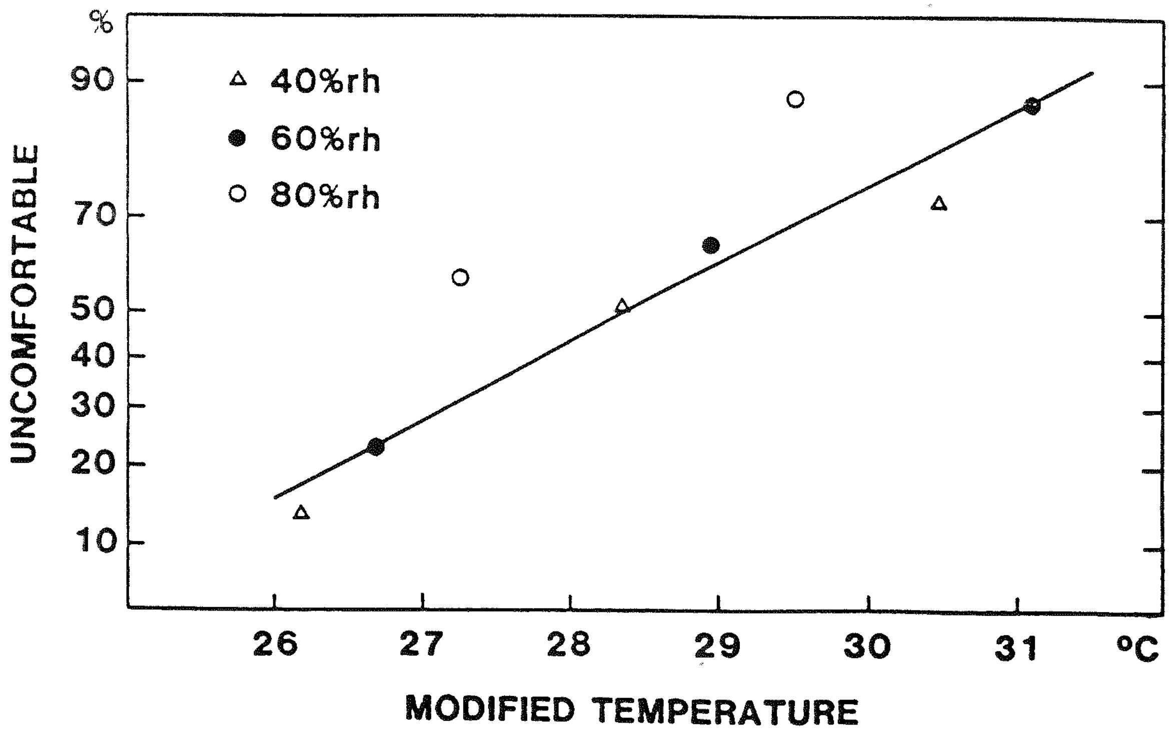

Figure 4. Probit analysis of the subjective responses concerning uncomfortable vs. modified temperature (Tanabe et al. 1987). Percentage of uncomfortable, or slightly uncomfortable. The regression line was calculated only from the results at 40% rh and 60% rh. Each point was calculated from the last three votes of 16 or 15 subjects.

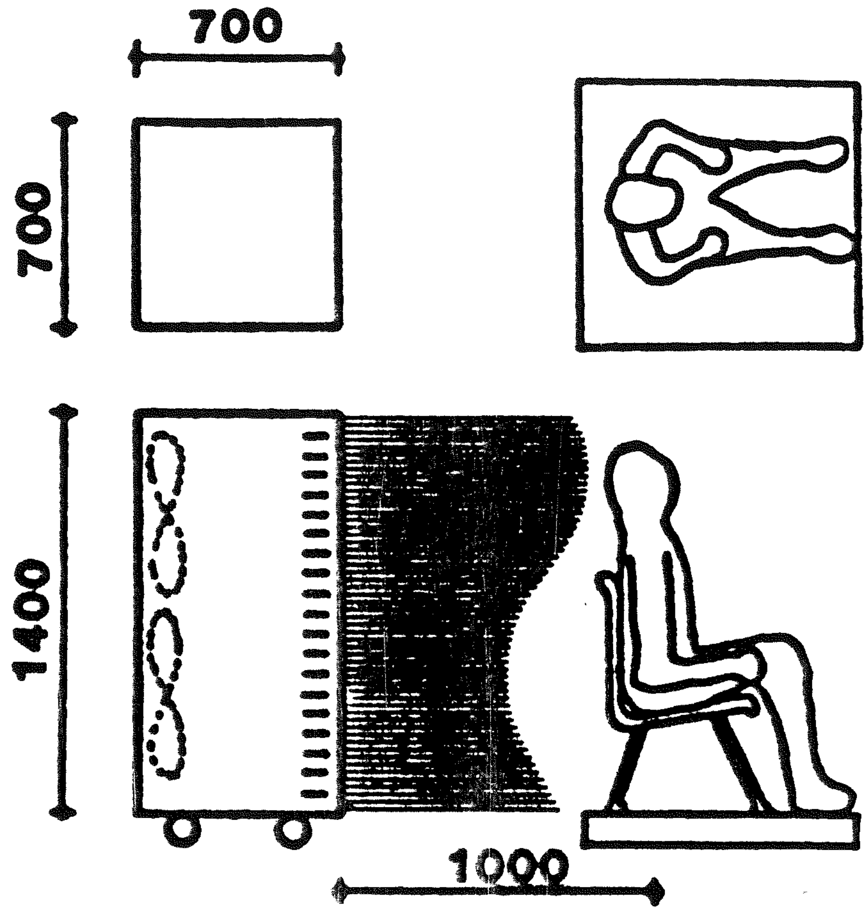

Figure 5. Wind box

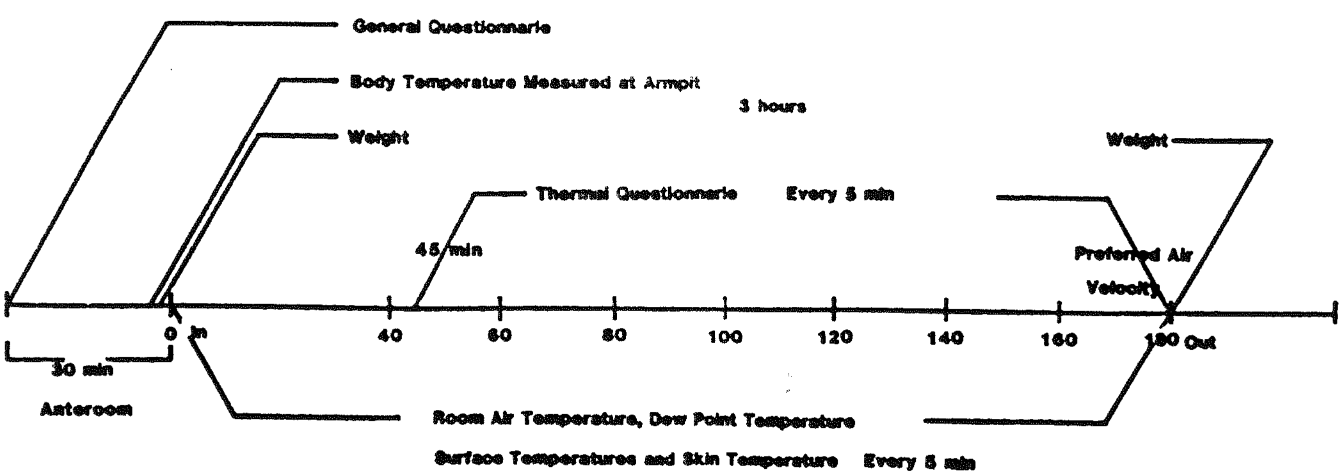

Figure 6. Experimental plan

Time ______________________ No ______________
Name ______________________

1. How do you feel ?

-3	-2	-1	0	-1	-2	-3
cold	cool	slighly cool	neutral	slightly warm	warm	hot

2. Do you feel this thermal environment uncomfortable ?

0	-1	-2	-3
comfortable	slightly uncomfortable	uncomfortable	very uncomfortable

3. Do you feel air movement ?

☐ Yes ☐ No

4.

- If yes, do you find the air movement uncomfortable ?

☐ Yes ☐ No

- Where do you notice the air movement ?

☐ head ☐ neck ☐ hands ☐ feet other places ( )

Figure 7. Voting scales

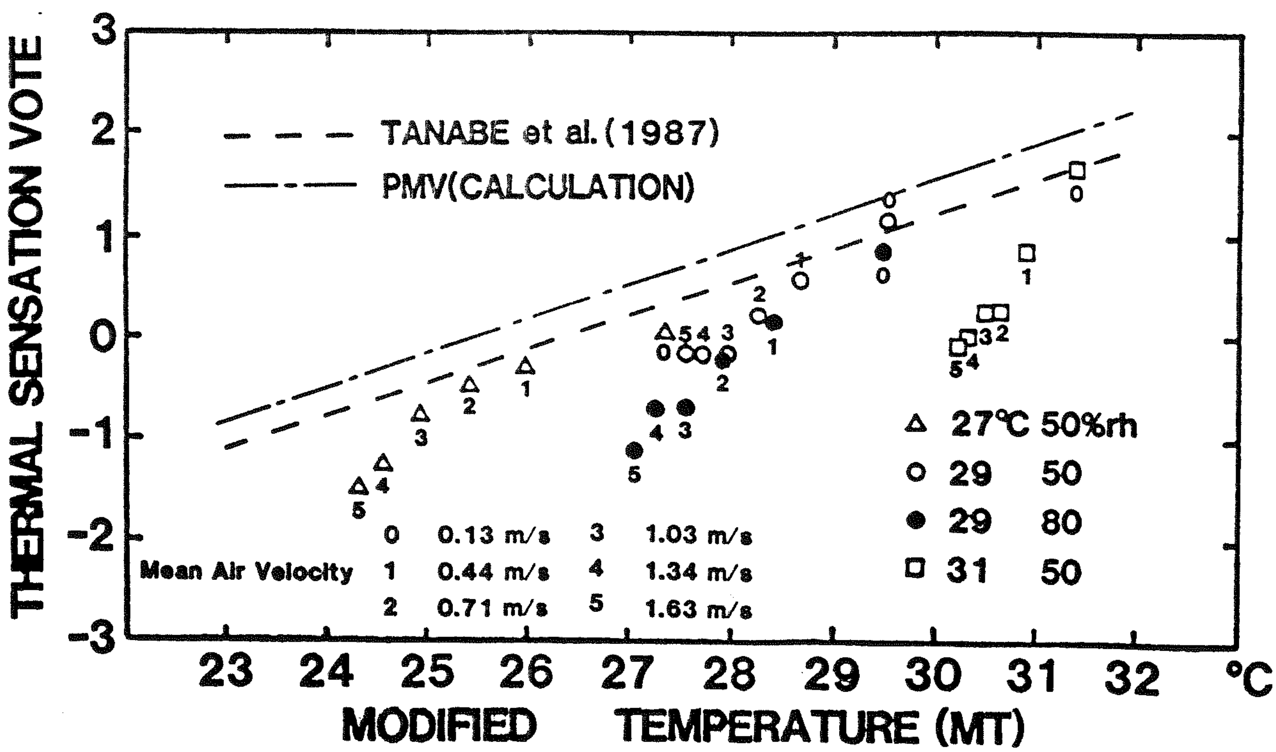

Figure 8. Thermal sensation vs. modified temperature for various air velocities. Each point represents the mean of 16 subjects. For comparison, see the broken curve for Japanese college-age subjects under low air movement (Figure 1 and Tanabe et al. 1987) and the dotted curve calculated by PMV. The numbers attached to symbols are identified with the six different mean air velocities.

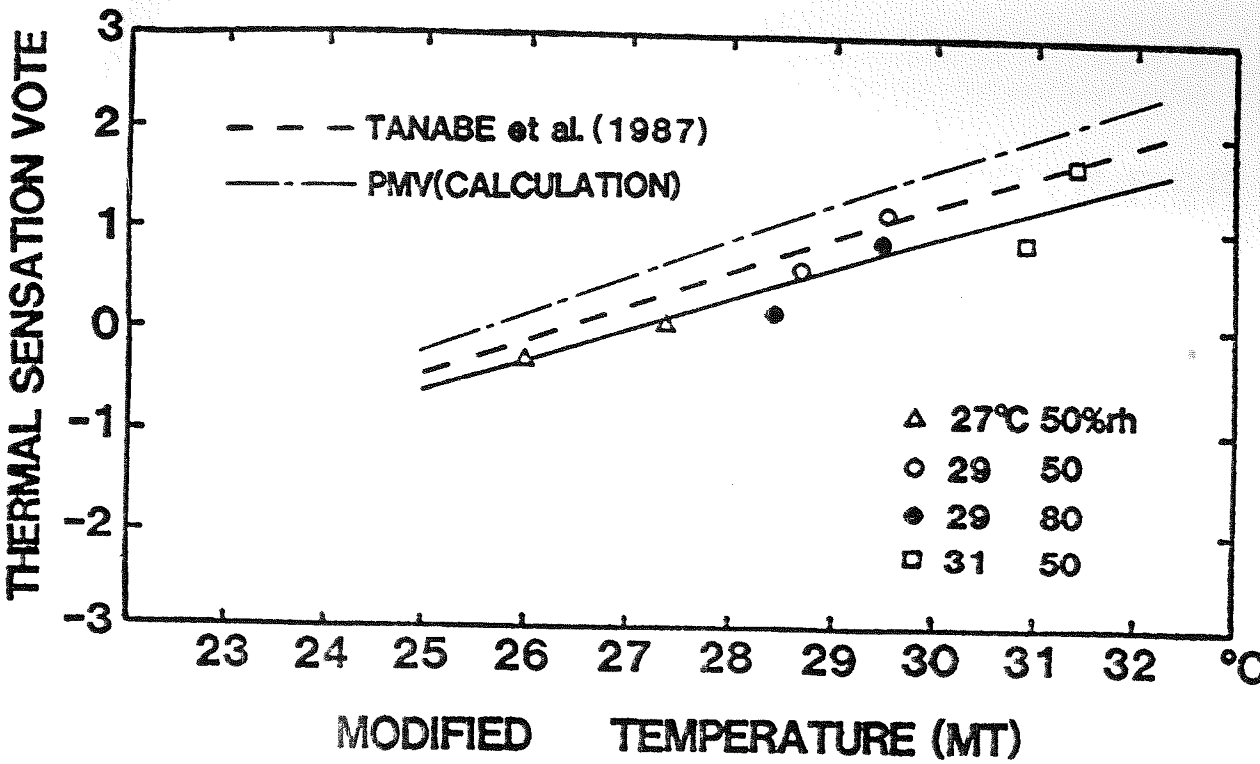

Figure 9. Thermal sensation vs. modified temperature below air velocity of 100 fpm (0.5 m/s). Each point represents the mean of 16 subjects. The solid curve is the regression line for individual votes. For comparison, see the broken curve for Japanese college-age subjects under low air movement (Figure 1 and Tanabe et al. 1987) and the dotted curve calculated by PMV.

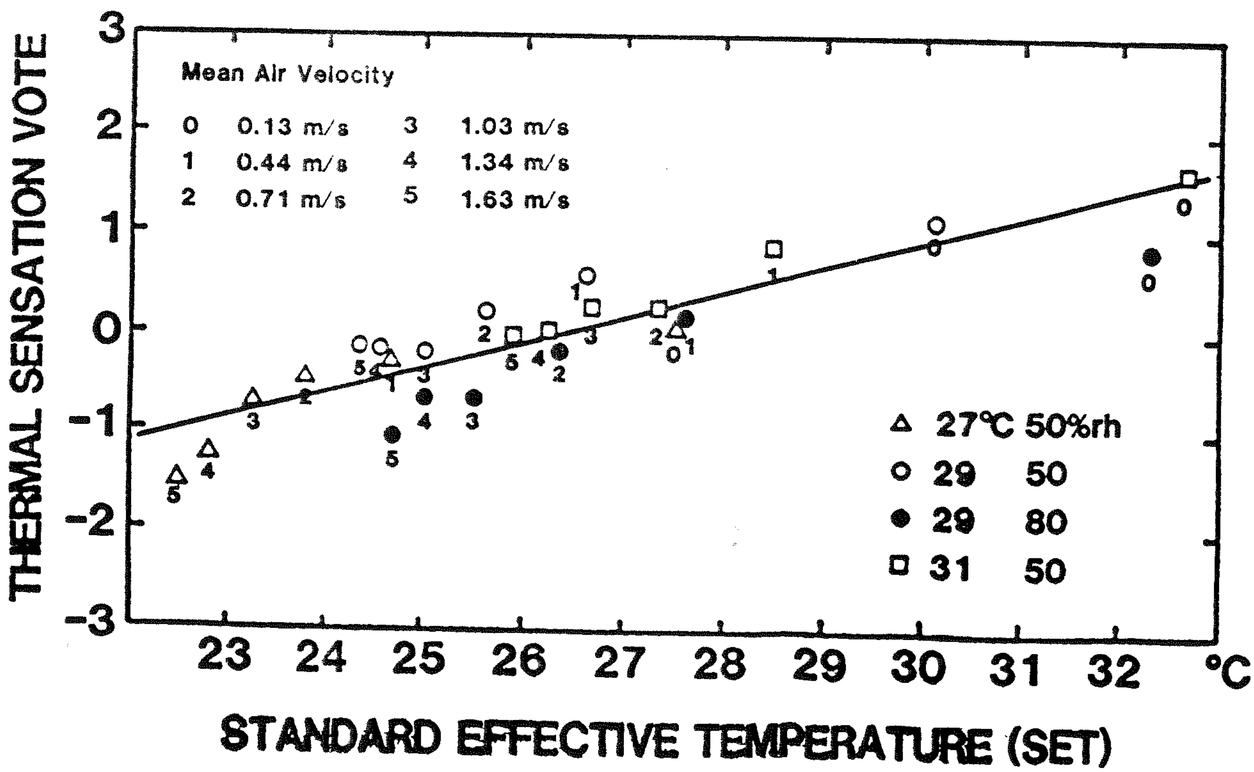

Figure 10. Thermal sensation vs. SET. The solid curve is the regression line for individual votes.

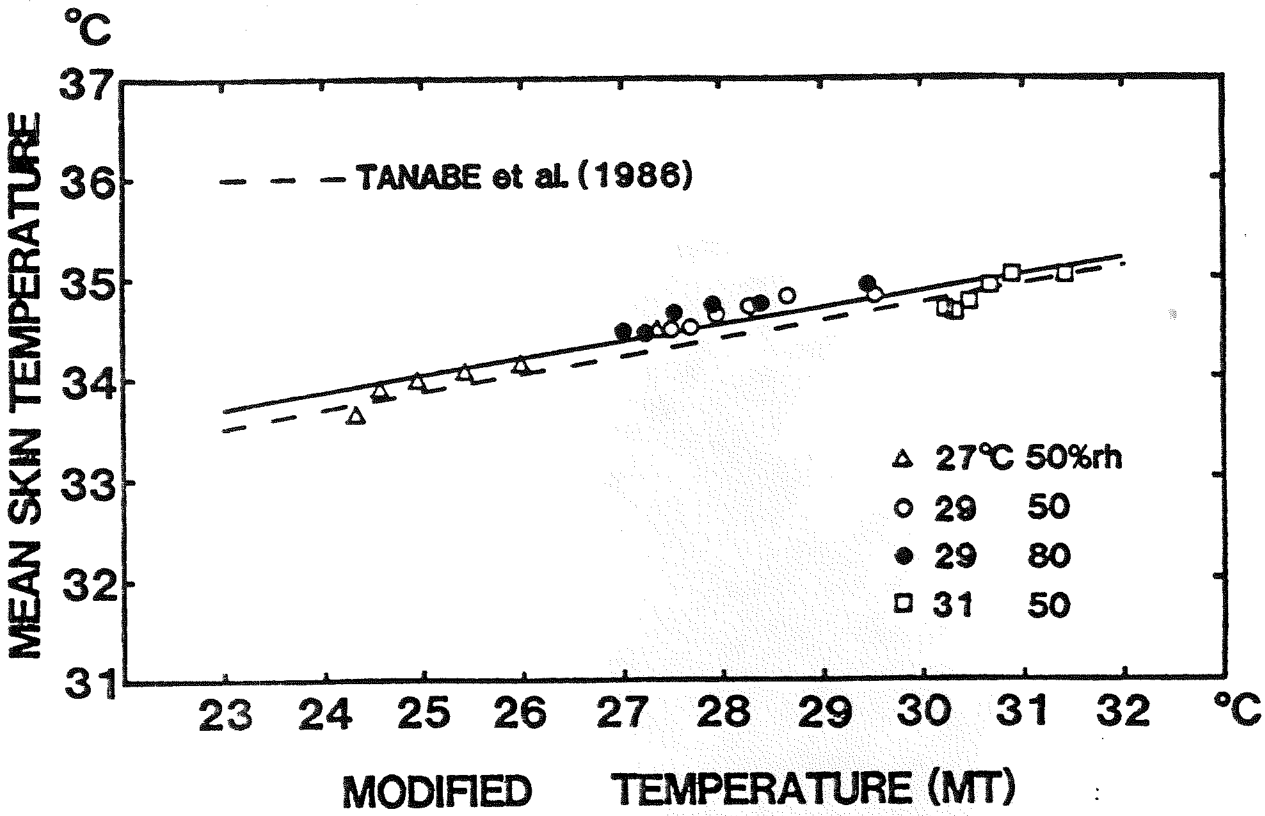

Figure 11. Mean skin temperature vs. modified temperature. Each point represents the mean of 16 subjects. The solid curve is the regression line for individual mean skin temperatures. For comparison, see the broken curve for Japanese college-age subjects under low air movement (Tanabe and Kimura 1986).

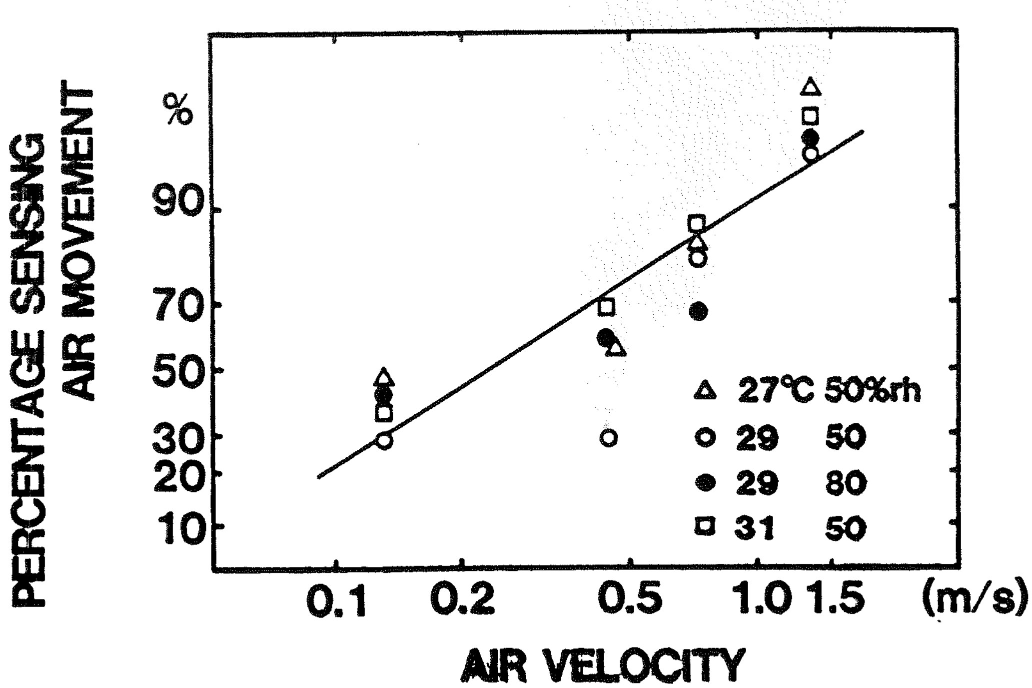

Figure 12. Percentage of subjects sensing air movement after probit analysis