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Effect of humidity and small air movement on thermal comfort under a radiant cooling ceiling by subjective experiments

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Abstract

Radiant air-conditioning systems are expected to be more comfortable and superior energy-saving systems than convective air conditioning ones generally used. There are some studies on radiant cooling systems. However, they were seldom put to practical use because of dew point problem in Japan. The objective of this study is to investigate the thermal comfort of local parts of the body and the whole body, in particular, including the effects of humidity (45% rh, 65% rh, 85% rh) and small air movements, by subjective experiments under a radiant cooling system. The experiments have been performed by using radiant cooling panels in a climate chamber. Subjects were seated on a chair under the radiant cooling panels, and voted their thermal sensation and comfortable sensation. The following results were obtained. Even in the radiant cooling system, the influence of humidity and small air movement on thermal sensation votes of the whole body could be correctly estimated by using a standard new effective temperature (SET*) within one scale error of thermal sensation. Small air movement with the radiant cooling system had a possibility of improving the comfortable sensation votes in the radiant cooling.

Keywords: Humidity; Thermal comfort; Radiant cooling

1. Introduction

Radiant air conditioning systems are expected to be more comfortable and superior energy-saving systems than convective air conditioning systems generally used [1]. This is because radiant air conditioning systems can create an indoor environment, which has smaller vertical temperature differences and almost no air movement field, to be able to prevent local thermal discomfort. In addition, radiant air conditioning systems can be operated under smaller temperature differences between the heat source temperature and the room air temperature, which leads to superior energy-saving performance in heat pump systems.

Electric floor carpets and electric heaters are widely used as radiant heating systems in Japan. In recent years, floor heating systems using electrical heaters and circulating hot water systems are also in practical use. On the other hand, some studies have been carried out in the radiant cooling systems. However, radiant cooling systems are seldom in practical use in Japan because of the technical problem of condensation and lack of design information concerning thermal comfort. In particular, radiant cooling systems are seldom applied to Japanese housing.

Some studies have discussed thermal comfort and energy-saving performance in the radiant cooling systems. Fanger et al. [2] examined a comfort limit for radiant asymmetry, which is caused by cool or warm ceilings and a cool or warm vertical wall, by subjective experiments and using a thermal manikin. As a result, they obtained comfort limit lines for radiant asymmetry conditions. The ISO standard 7730 [3] used this result as a basis on the thermal comfort limit condition caused by radiant asymmetry.

Fitzner [4] reported that the combined system with radiant ceiling cooling and displacement ventilation created successfully comfortable thermal environment, whose characteristics were draftless and small temperature distributions in the occupied zone, by experimental studies. Feustel [5] examined several office air conditioning systems applied in European and American countries from a view of air conditioning load and he reported that the radiant cooling systems were expected to be superior with regard to energy-saving performance.

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In Japan, a ceiling cooling and heating system for office air conditioning was reported to have been reduced 10% and 30% energy consumption in cooling and heating, respectively. Satoh and Murakami [6] studied the thermal environment created by a convective system with a radiant cooling panel, and they reported that the combined system reduced draft in the zone occupied by their experiments. Takahashi and Murakami [7] also reported that boundary conditions of radiant panels and windows were important factors in the numerical analysis. Murakami et al. [8] discussed the radiant effect on the ceiling cooled or heated by detached air flow.

In these studies, effects of air temperature and radiant panel temperature on thermal comfort were discussed. However, effects of humidity and air velocity were seldom discussed. Radiant air conditioning systems usually utilize building thermal capacity as thermal storage and they are continuously used. However, in Japan, air conditioning systems are generally operated only while the occupants are in the room. This custom needs large-capacity air conditioning systems for rapid start-up. Radiant air conditioning systems have disadvantages in this start-up performance and the dehumidifying problem, when compared to convective air conditioning systems. The air conditioning system, which composes both radiant and convective systems, improves this performance in the start-up conditions, and the system is a candidate of the most suitable air conditioning systems for housing.

We studied thermal comfort in the radiant cooling ceiling panels by using experimental panels similar to those of Fanger et al. [2], however, taking reciprocal radiant effects of floor into consideration [9]. Fanger et al. [2] discussed radiant asymmetry effects on thermal comfort and they carried out their subjective experiments for several panel temperatures by keeping thermal neutral conditions. That is, panel temperatures were gradually lowered and room air temperatures were set up gradually higher during the experiment. On the other hand, we were interested in conditions for thermal comfort in the real operating conditions for radiant cooling ceiling systems. Subjective experiments were carried out to evaluate thermal comfort under the radiant cooling system which had effects of reciprocal radiant heat exchanges. In this study, the radiant system cooled the air temperature and the floor below the panels near the subjects. We discussed the effects of humidity and small air movement on thermal comfort in the radiant cooling system, by using a similar experimental facility [2,9].

2. Experimental methods

2.1. Experimental facilities

The experiments took place in an environmental chamber (dimensions 4.0 × 4.0 × 2.5 m) at the Air-Conditioners and Appliances Engineering Laboratory of Toshiba as shown in Fig. 1. The environmental chamber consisted of walls whose inner wall temperature was controlled by using a circulating water system and panel heaters. The radiant panel, which was shown in Fig. 2, was situated in the center of the chamber above the subjects to examine thermal comfort in the radiant cooling. The radiant panel form was similar to previous studies [2,9]. Two panels were situated horizontally above the subject, 1.8 m above the floor. To increase the angle factor from the subject, two extra vertical panels were placed, as shown in Fig. 2. Each panel radiator was painted black and its surface temperature was controlled by circulating water and its back side was insulated with 50 mm polyurethane foam.

The air temperature in the chamber (a measured point was shown in Fig. 1), which was controlled by using both an air conditioning system and a wall surface temperature-controlled system, was maintained constant during the experiment. The experiment of Fanger et al. [2] was carried out in the air-ventilated chamber by keeping thermal neutrality while radiant panel temperature was gradually lowered and room air was gradually heated throughout the experiment. The floor surface temperature was also kept at

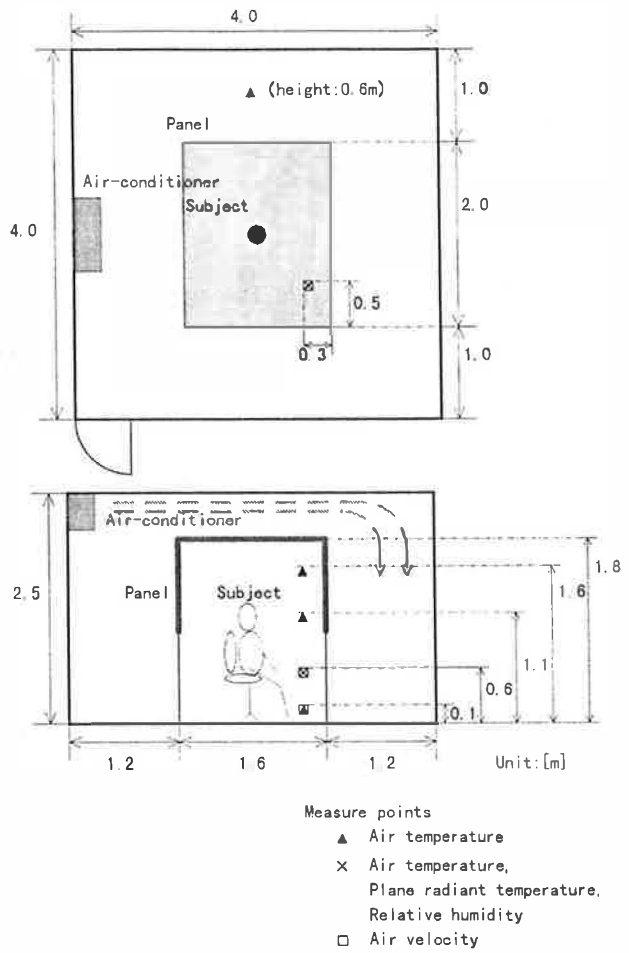

Fig. 1. Experimental chamber.

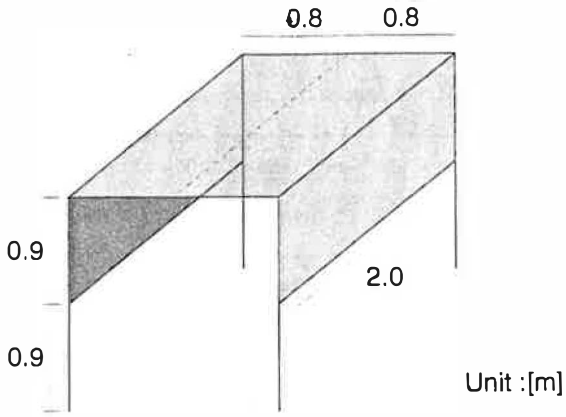

Fig. 2. Radiation panel.

almost the same level as air temperature. Therefore, the subjective experiment took place in the highly uniform artificial thermal environment. On the other hand, we have carried out subjective experiments in the natural conditions created by actual radiant ceiling panels.

Measuring points for physical conditions were also shown in Fig. 1. Air temperature was measured by using a thermocouple (Type T, 0.2 mm diameter) connected to the hybrid recorder. The environmental data to compute the standard new effective temperature (SET*) [10] were measured by the indoor climate analyzer (B&K Type 1213). All data were also recorded in the personal computer.

Experimental conditions for humidity and small air movement were controlled by a humidifier and the air conditioning system, which included re-heat exchanger, to keep the experimental conditions near subjects. The air-conditioner was operated to make a circulating flow shown in Fig. 1.

2.2. Experimental conditions

The experimental conditions, which were classified into three groups (Experiments I, II and III) were shown in Tables 1–3, respectively.

Experiment I was aimed to examine the effect of humidity on thermal comfort in the radiant cooling. Relative humidity was set up in the experimental chamber to three levels; 85% rh, 65% rh and 45% rh (hereafter, called high humidity, medium humidity and low humidity conditions, respectively). In the beginning of the experiments, the panel temperature and air temperature were kept at the same level, and the panel temperature was gradually lowered. One example of the measured panel temperature was shown in Fig. 3. The horizontal line of this figure means a time progress represented by the number of voting. The panel temperature changed quickly in higher temperature conditions. However, the panel temperature was gradually lowered in the lower temperature conditions because of cooling capacity shortage in the cool and hot water circulating equipment. Each subject was tested in one humidity condition selected from the three.

Experiment II examined the effect of small air movement on thermal comfort in the radiant cooling. A room air-conditioner, which was located in the wall as shown in Fig. 1, was operated to create approximately 0.1 m/s air velocity near the waist of subjects. Louvers in the diffuser were set up to adjust a flow direction to horizontal and a wider vertical angle. Air flow came to the subject after passing the space between the radiant panel and the ceiling and wall of the chamber, as shown in Fig. 1. Subject experiments were carried out in the following conditions: (1) approximately 0.3 m/s air velocity on the 0.1–0.2 m height from the floor and 0.1 m/s air velocity on the 0.6 m height; (2) approximately uniform 0.1 m/s air velocity. The panel temperature was gradually lowered as the same way as Experiment I.

Experiment III was aimed to examine the effect of small air movement fluctuations to thermal comfort in the radiant cooling. The radiant panel temperature was maintained constant 25°C throughout the subjective experiment. Air movement conditions including ON/OFF (approximately 0.1 m/s while ON) and random change (0.1–0.3 m/s) were tested. An example of measured air velocity in the random condition was shown in Fig. 4.

In the Experiments II and III, a soft music was used to prevent subjects from realizing air movement by a fan noise.

Table 1
Experimental conditions (Experiment I)

Air temperature	27°C
Relative humidity	45% (low), 65% (middle), 85 (high)%
Air velocity	still air
Clothing	0.7 clo (short-sleeved shirt, pants, shoes including chair)
Activity level	1.0 met (sedentary)
Panel temperature	27, 25, 21, 17°C

Table 2
Experimental conditions (Experiment II)

Air temperature	27°C
Relative humidity	65% (middle), 85% (high), 65% (middle)
Air velocity	0.1 m/s (local 0.3 m/s), 0.1 m/s (uniform)
Clothing	the same as step 1
Activity level	the same as step 1
Panel temperature	27, 25, 21, 17°C

Table 3
Experimental conditions (Experiment III)

Air temperature	27°C
Relative humidity	65%
Clothing	the same as step 1
Activity level	the same as step 1
Air velocity	0.1 m/s (ON/OFF), 0.1–0.3 m/s
Panel temperature	25°C

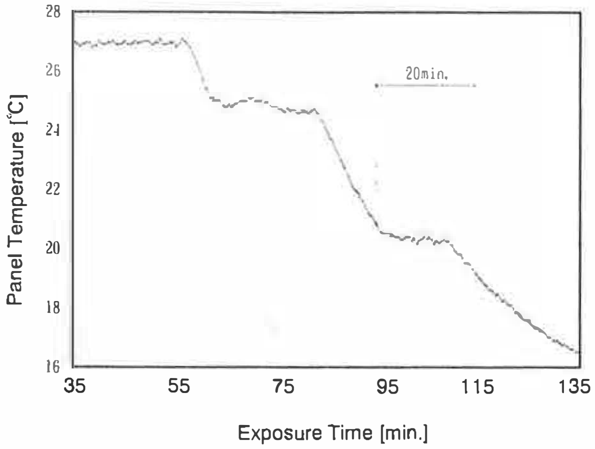

Fig. 3. Example of panel temperature during the experimental session.

2.3. Experimental procedure

The experimental process is shown in Fig. 5. At first, a subject measured his temperature in the chamber, and only subjects whose temperature was below 37°C participated in the experiment. Table 4 indicated the anthropometric data in each experimental condition. All subjects were employees of Toshiba. During the experiment, the subject was seated in an OA chair and was kept occupied by reading. Eating, drinking and smoking were prohibited while the experiment was in progress. The skin temperatures of each subject were measured by means of thermocouple taped to the skin by surgical tape.

During the 40 min of the start of the experiment, the room temperature and panel temperature were set equally to maintain a steady thermal sensation on the subject. In the following four periods, the panel temperature was gradually lowered to the values shown in Tables 1 and 2, in Experiments I and II. The subject stayed for 2.25 h in the chamber. Air temperature, including vertical distributions under the panel, humidity and air velocity were registered every minute by the measurement system in

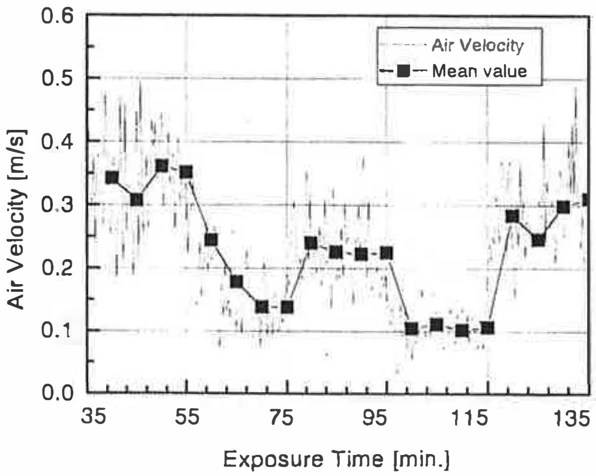

Fig. 4. Air velocity fluctuations measured during the experiment (Experiment III).

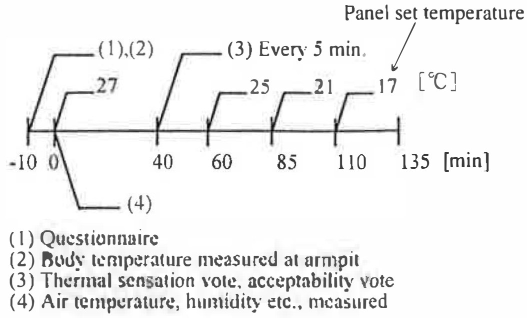

Fig. 5. Experimental procedure.

Experiments I and II, and once every 20 s in Experiment III, to evaluate fluctuations of air velocity environment correctly.

The subject was asked every 5 min during the experiment about the thermal sensation and comfortable sensation of the local parts of the body and the whole body, following the voting scales shown in Fig. 6 throughout Experiments I, II and III. Intermittent values of each question were permitted. In the case of Experiment III, a question concerning the air movement was added to examine the effect of air movement.

All voting data were utilized to analyze thermal comfort sensation and comfortable sensation in each experiment condition. Environmental conditions were evaluated by averaging data measured during 5 min before each vote. For example, the fluctuated air velocity was evaluated as values connected by a line shown in Fig. 4.

3. Results

3.1. Analysis concerning the influence of humidity

First of all, the effect on humidity was discussed from the results obtained in Experiment I. Three different hu-

Table 4
Anthropometric data for subjects

Experiment	Condition	Number			Age
		Male	Female	Total	
I	45% rh	3	2	5	30.8 ± 3.8
	65% rh	9	2	11	33.2 ± 11.3
	85% rh	5	1	6	29.0 ± 5.7
					31.5 ± 8.9
II	65% rh + wind	5	2	7	29.1 ± 2.6
	85% rh + wind	4	2	6	30.3 ± 6.4
	65% rh + uniform wind	3	2	5	28.0 ± 4.9
					29.2 ± 4.9
III	0.1 m/s ON/OFF	2	2	4	30.0 ± 6.9
	random wind	3	1	4	25.8 ± 2.7
					27.9 ± 5.6
Total	–	34	14	48	30.0 ± 7.3

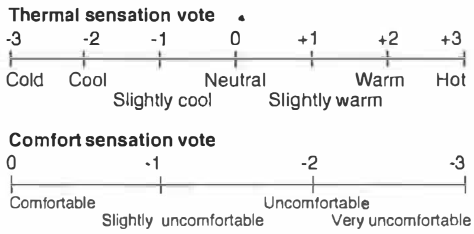

Fig. 6. Voting scales.

midity conditions, approximately 85, 65, 45% rh, (each called by high humidity, medium humidity and low humidity condition) were tested. The relationships between the thermal sensation vote and operative temperature (OT) and SET* were examined. The following measured values: air temperature, mean radiant temperature, air velocity and humidity at one point (in front of the subject, 0.6 m above the floor as shown in Fig. 1), and 0.7 clo for clothing insulation, and 1.0 met in the activity level, were used to obtain the value of SET*.

Fig. 7 showed an example of temperature distributions, which were obtained as environmental data for each final voting, under the radiant panel. Air temperature under the radiant panel was cooled when the radiant panel temperature was lowered. Almost homogeneous temperature distributions were obtained in the vertical direction.

Fig. 8 showed a relation between the OT and the thermal sensation vote of the whole body. It has been confirmed that the higher the humidity, the larger the thermal sensation vote was for the same level of OT.

The relation of the SET* to thermal sensation vote was shown in Fig. 9. In the comparison between Figs. 8 and 9, the differences of three humidity conditions in Fig. 9 were smaller than in Fig. 8. For example, when the OT or the SET* was at 26°C, the difference of thermal sensation vote became approximately 1 from 2 in the high and low humidity conditions.

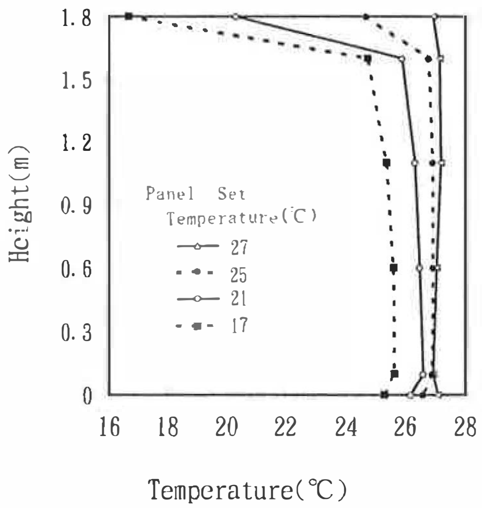

Fig. 7. Vertical temperature distributions under radiant panel.

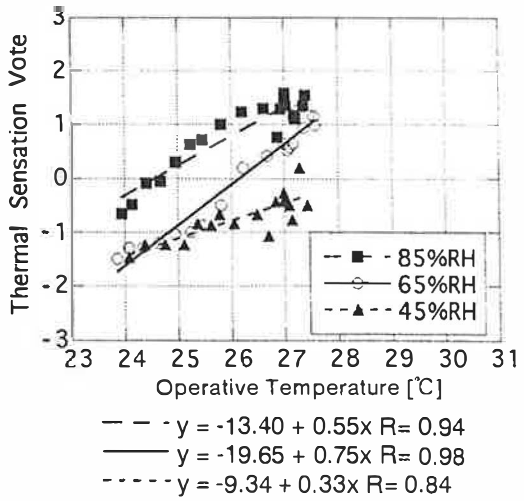

Fig. 8. Relationship between operative temperature and thermal sensation vote for Experiment I.

The thermal sensation vote for all conditions increased with SET*, but the tangent of the regression line obtained in the case of 65% rh was a little larger than in other cases as shown in Fig. 9. The regression line (the relative coefficient 0.87) obtained by all humidity conditions approximated all data within ±1 scale error in the thermal sensation vote. Any statistical difference in the results obtained in three humidity cases was not significant, because of bigger standard errors of sensation votes depending on the personal difference of each subject.

3.2. Analysis concerning the influence of small air movement

The effect of small air movement to thermal comfort in the radiant cooling was discussed in Experiment II. The relations of SET* to the thermal sensation vote of the

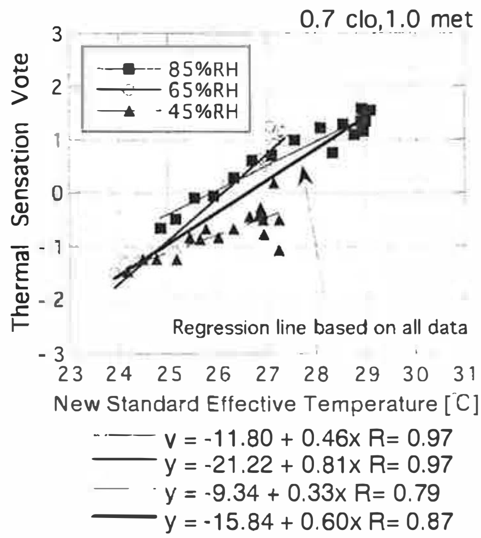

Fig. 9. Relationship between SET* and thermal sensation vote (Experiment I).

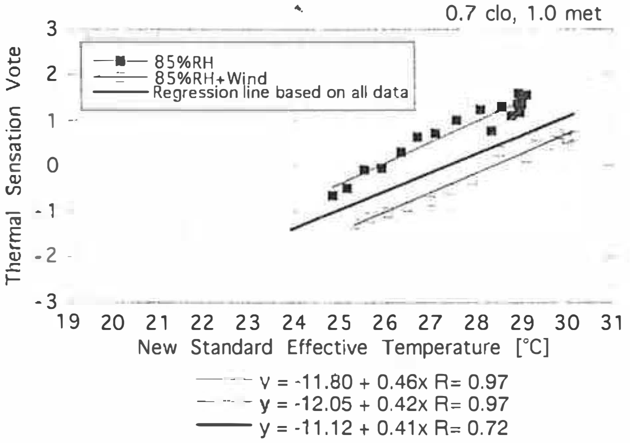

Fig. 10. Relationship between SET* and thermal sensation vote (Experiment II: 85% rh).

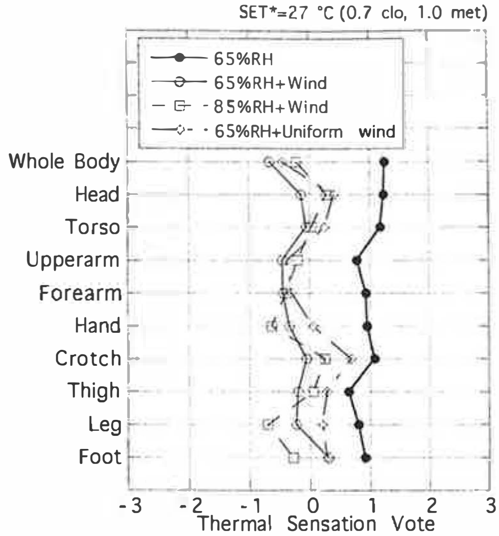

Fig. 12. Local thermal sensation vote.

whole body were shown in Figs. 10 and 11, for 85% rh conditions and 65% rh conditions, respectively. In Fig. 11, symbols (□) indicated the results obtained in the non-uniform velocity condition (approximately 0.1 m/s on the 0.6 m height, 0.3 m/s on the 0.1–0.2 m height), on the other hand, symbols (•) for the homogeneous velocity condition (approximately uniform 0.1 m/s). SET* was computed by using values on the 0.6 m height, even if air velocity was 0.3 m/s on the 0.1 m height.

The results obtained for the both humidity conditions including small air movement had about one scale cooler tendency of thermal sensation for the same level of SET*. The thermal sensation of local parts of the body were compared in Fig. 12 when SET* equalled 27°C. Small air movement (approximately 0.1 m/s) caused cooler thermal sensation than still air conditions in the almost the same level, for all local parts of the body. Only a little cooler tendency appeared in the naked parts of the body, e.g., hands and arms. In all conditions, the thermal sensation for local parts of the body was almost uniform and no local uncomfortable parts were found.

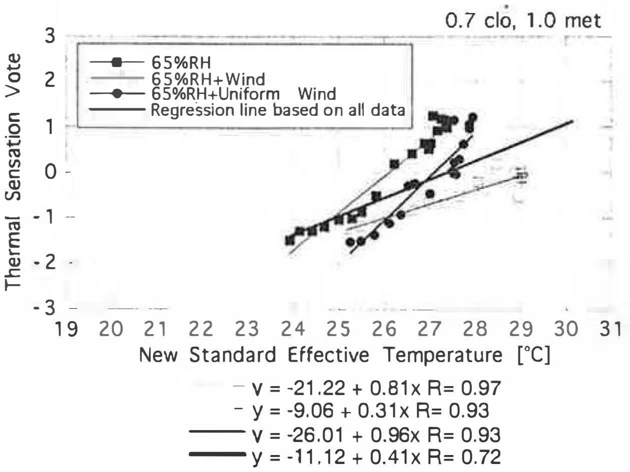

Fig. 11. Relationship between SET* and thermal sensation vote (Experiment II: 65% rh).

Next, we discussed the effects of 0.3 m/s air velocity to thermal sensation on the 0.1–0.2 m height in 85% rh and 65% rh conditions. In the medium humidity conditions shown in Fig. 11, we compared the results of homogeneous velocity cases, indicated by symbols (•), with non-uniform velocity cases, indicated by symbols (□). Homogeneous cases had a little bigger tangency in the regression line, which caused warmer thermal sensation in the larger range of SET*. On the other hand, local thermal sensation in the leg and foot parts of the body was a little cooler in the high humidity condition and a little warmer in the medium humidity than the thermal sensation of the whole body. In the still air medium humidity condition, foot and leg parts were a little cooler than the whole body. Hence, we concluded that the velocity distributions near the floor caused almost no effects on thermal comfort. It should be noted that subjects used shoes during the experiment.

From Figs. 10 and 11, small air movement caused approximately one scale cooler thermal sensation in the same SET* with the radiant cooling. The regression line (the relative coefficient 0.72), which was obtained by using all data, could estimate all conditions within ±1 scale error of thermal sensation. Any statistical difference in the results obtained in these cases was not significant, because of bigger standard errors of sensation votes depending on the personal difference of each subject.

3.3. Analysis concerning the influence of air velocity fluctuations

The results obtained in Experiment III to examine the effects of air velocity fluctuations to thermal sensation in the radiant cooling were discussed. The relationship be-

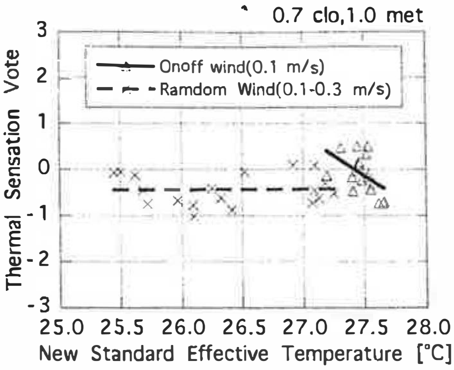

Fig. 13. Relationship between SET* and thermal sensation vote (Experiment III).

tween SET* and thermal sensation vote was indicated in Fig. 13. Even if SET* changed by about 2°, thermal sensation vote had little changes. However, some subjects were reported to feel a small air movement in the case of 0.3 m/s. This result suggested that SET* might have a difficulty in evaluating thermal sensation with air velocity fluctuations shown in Fig. 4.

In addition, it has been confirmed that the most comfortable vote has been obtained not in neutral thermal sensation vote but in thermal sensation vote situated between neutral and slightly cool.

Fig. 14 indicates the relationship between the comfortable sensation vote and thermal sensation vote under many conditions carried out from Experiments I to III. Comfortable sensation votes obtained in the case of including small air movement, especially with velocity changes, had more comfortable sensations than the other cases in the range of almost neutral thermal sensation. In addition, it has been confirmed that the most comfortable vote was obtained not in the neutral thermal sensation vote but in the vote situated about the center of neutral and slightly cool. However, for cooler thermal sensation (less than −1 in the scale of thermal sensation), small air movement showed an opposite effect on comfortable sensation vote. Personal differences were large and the total number of subjects

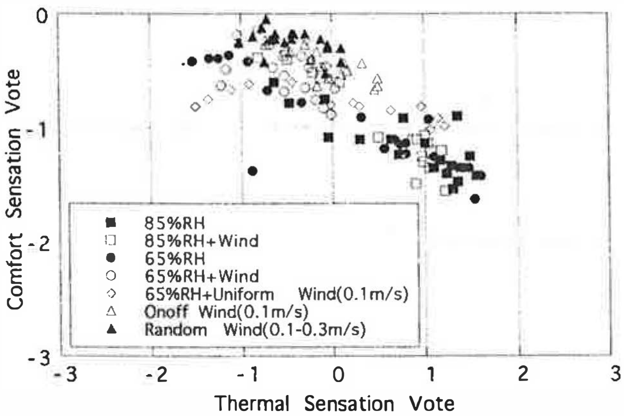

Fig. 14. Relationship between thermal sensation vote and comfortable sensation vote.

was too small, hence, these results could not be found to be significantly different from statistical analysis.

4. Discussion

4.1. Effects of small air movement on computing SET*

The relation between the metabolic rate and thermal sensation vote will be discussed here. In the process of calculating SET*, the convective heat transfer coefficient h_c is evaluated by Eqs. (1)–(3). The first one, h_1, is calculated from the Eq. (1) using the metabolic rate M, and the second one, h_2, is calculated from Eq. (2) using the air velocity v_a. Then, the convective heat transfer coefficient of the human body (h_c) is evaluated as the larger value of the two values, but the minimum value of h_c is 3.0 W/m²°C.

$$h_1 = 5.66 \times (M - 0.85)^{0.39}\ [\mathrm{W/m^2{}^\circ C}], \quad (1)$$

$$h_2 = 8.6 \times v_a^{0.53}\ [\mathrm{W/m^2{}^\circ C}], \quad (2)$$

$$h_c = \max(h_1, h_2)\ [\mathrm{W/m^2{}^\circ C}], \quad (3)$$

(If $h_c < 3$, then $h_c = 3$), M: metabolic rate [met], v_a: air velocity [m/s].

The condition of satisfying h_c equalling 3.0 W/m²°C corresponds to the metabolic rate equalling 1.046 met and the air velocity equalling 0.137 m/s, respectively. Hence, when the metabolic rate is 1.0 met, air movement smaller than or equal to 0.137 m/s has no effect on SET*. On the other hand, in the case of a metabolic rate = 1.2 met, the air movement smaller than or equal to 0.21 m/s has no effect on SET*. It means that if air velocity is smaller than or equal to 0.21 m/s, thermal sensation is the same as that for still air. Fig. 15 shows a relationship between SET* and air velocity, computed in two metabolic rates, 1.0 and 1.2 met, by assuming the following conditions: air temperature and mean radiant temperature equals 27°C, clothing insulation, 0.5 clo and relative humidity, 50%. The modeling in estimating the heat convective coefficient h_c caused the difference in the velocity conditions around 0.14 to

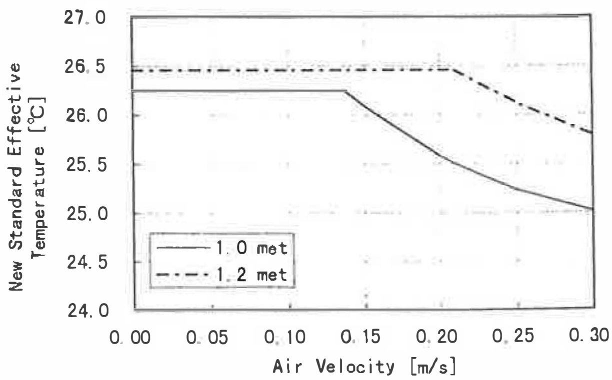

Fig. 15. Effect of air velocity on SET* under different activity levels.

0.21 m/s. The maximum characteristic difference is about 0.5 degree in SET* by selecting different activity levels.

After a numerical simulation is applied to solve the indoor air flow and thermal fields, the predicted mean vote (PMV [11]) and SET* are usually used to evaluate thermal comfort from the air temperature and velocity obtained in the simulation. If we had applied PMV to evaluate thermal sensation instead of SET*, the above-mentioned problem would have never been observed. We need to pay attention to this characteristic in the process of evaluating thermal comfort with SET* for numerical simulation results.

4.2. Steady conditions in the subjective experiment

Here, we discussed the steady state conditions for the radiant cooling in the subjective experiments.

In the previous study investigated by Fanger et al. [2], during the first hour, the panel temperature was maintained equal to the air temperature, each subject was in the experimental chamber to make his metabolism stable. In the following five half-hour periods, the subject was exposed to different conditions created by gradually reducing the radiant panel temperature. Every 5 min during the experiment, the subject was asked about thermal sensation and the ambient temperature was adjusted according to his requests. To analyze the results, the final three values were utilized to evaluate the steady state thermal sensation in all conditions.

By taking their procedure into consideration, we made the experimental procedure indicated in Section 2 and Fig. 5. In our experimental procedure, the first condition was maintained for 60 min. However, the first questionnaire was started after 40 min and the following periods are by 25 min. Every 5 min, the subject answered the questionnaire. Hence, five questionnaire data are collected each for different conditions. If our procedure is compared with that of Fanger, a slightly small interval is applied. This is the reason why our subjects were in the office located near the experimental chamber, so that they were in almost steady state metabolic conditions before starting the subjective experiment.

We have difficulty in changing the panel temperature with a random sequence, because of a large heat capacity of the radiant panel and limitation of the cooling capacity of water circulating system. Hence, we carried out the experiment with a monotonous change in a similar manner to the previous study of Fanger et al. [2]. The panel temperature, which was shown in Fig. 3, changed gradually in the lower panel temperature in our experiments. Effects, which were caused by the monotonous panel temperature change and the gradual panel temperature change in lower range to thermal sensation, should be examined in the future study.

In our experiments concerning the velocity fluctuation, we set up the random sequence as shown in Fig. 4.

5. Conclusion

The influence of humidity and small air movement on the thermal sensation vote and the comfortable sensation vote in the radiant cooling system were evaluated by subjective experiments, and the following results were obtained.

(1) In radiant cooling, the higher the humidity, the warmer the thermal sensation was for the same level of OT, but SET* could more correctly estimate the thermal sensation vote of the whole body within ± 1 scale error of thermal sensation.

(2) Small air movement in the radiant cooling had a tendency to feel approximately one scale cooler than still air conditions in the same level of SET*. Local parts of the body were shifted to the cooler side with almost homogeneous effects.

(3) Thermal sensation votes for the small air movement effects in the radiant cooling were estimated by using SET* within ± 1 scale error of thermal sensation.

(4) Small air movement, especially including velocity change, had a tendency of improving the comfortable sensation vote near neutral thermal sensation, however, reducing the comfortable sensation vote in the cooler conditions whose thermal sensation vote was less than -1.

(5) The most comfortable sensation vote was obtained in the condition whose thermal sensation vote was not neutral but approximately -0.5.

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