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Survey of Thermal Environmental Deviation in Offices

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Abstract

This study proposes a new thermal comfort index for evaluating radiant air-conditioning systems. The characteristics of thermal environmental distribution are examined in three offices with differing air-conditioning systems. Thermal environment showed very uniform distribution for radiant cooling and floor-supply displacement HVAC system when compared to standard convective air-conditioning. Subsequently, this paper introduces a new thermal comfort index that utilizes provided temperature and required temperature.

Keywords – thermal environment; thermal acceptability; thermal comfort; provided temperature; required temperature

1. Introduction

Conventional air-conditioning systems aim to provide comfortable and thermally uniform environments by preventing temporal and spatial variations in the thermal environment. However, conventional convective air-conditioning systems may create air drafts and non-uniform thermal environments, resulting in discomfort. In contrast, radiant cooling systems are expected to improve thermal comfort, since they do not create potentially uncomfortable air drafts. However, as yet, there is no index for evaluating the thermal comfort of radiant cooling systems. Evaluation by means of conventional thermal comfort indices involves considering a single person in a room as being representative of a group of people with common characteristics. In a survey of thermal environment acceptability conducted by the authors, workers who were sensitive to cold frequently expressed discomfort in offices with convective air-conditioning systems. In contrast, offices with radiant cooling systems produced few complaints from sensitive workers. Moreover, with convective air-conditioning, even if the average thermal environment was categorized as comfortable, workers who are sensitive to cold complained of discomfort when sitting beneath an air vent or at a cold spot in the actual working space. Therefore, evaluation of thermal environment should be conducted from the perspective of such individuals.

Two indices are typically used to evaluate thermal comfort: predicted mean value (PMV), and standard effective temperature (SET*). However, these indices cannot evaluate the advantages of using radiant cooling systems over convective air-conditioning systems, because they are unsuitable for evaluating the uniformity of the indoor thermal environment.

Radiant air-conditioning systems have recently attracted much attention. However, such systems are yet to gain widespread popularity because it is not clear to what degree they increase thermal comfort. Therefore, the authors consider that the development of a new thermal comfort index will contribute to the widespread adoption of radiant air-conditioning. This study proposes a new thermal comfort index for evaluating uniform, high-quality indoor thermal environments (e.g., using radiant air-conditioning) and non-uniform, unsteady thermal environments (e.g., convective air-conditioning).

2. Outline of measurement

Planar thermal deviation was measured during summer, in three offices that have adopted different air-conditioning systems. The conditions for each measurement location are shown in Table 1. Office T employs a floor-supply displacement HVAC (heating, ventilation, and air conditioning) system, controlled by temperature and humidity [(1)]. Office C employs a system that separates latent and sensible heats, based on radiant and desiccant air conditioning. Temperature is managed by air conditioning, based on a radiation ceiling panel, and humidity is supplied from a floor-supply displacement ventilation system by a desiccant. Office A employs a common convective air-conditioning system. The device used to measure thermal environment (see Table 2) can record air temperature, globe temperature, relative humidity, and air speed. Moreover, a physical activity meter and a questionnaire survey were used to measure metabolic rate and clothing insulation for 10 workers in office C and 11 workers in office A. The floorplan and measurement locations for each office are shown in Fig. 1.

Table 1. Conditions for each measurement location

Office name	T	C	A
Location	Tokyo, Japan	Tokyo, Japan	Tokyo, Japan
Term	August 18 to 19, 2015	August 26 to 27, 2015	July 23 to 24, 2015
Air-conditioning system	Floor-supply displacement HVAC system	Radiant air-conditioning system + Floor-supply displacement ventilation system	Convective air-conditioning system

Table 2. Thermal environmental measurement device

Thermal environmental measurement device	
Appearance	 
Installation	Personal desk
Measurement interval	Air temperature : 5 min, Globe temperature : 5 min, Relative humidity : 5 min, Air speed : 1 min

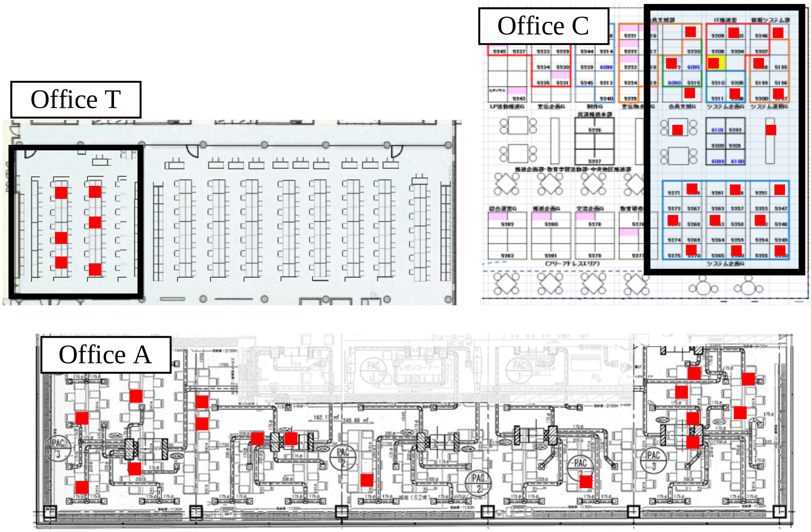

Fig. 1 Floor plan and thermal measurement points for each office

3. Measurement Results

3.1 Thermal environments of offices

Figure 2 shows the data measured in three offices during operational hours in comparison with ASHRAE Standard 55-2013 for indoor thermal environment. The dashed red lines indicate the area within the comfortable temperature–humidity range in summer. Temperature and humidity were higher than usual, due to brownout restrictions set in the aftermath of the Great East Japan Earthquake of March 2011. Office A (convectional air-conditioning) showed a wide thermal distribution compared with office T (floor-supply displacement HVAC) and office C (radiant air-conditioning).

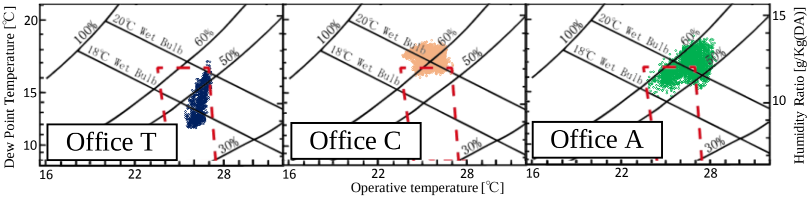

Fig. 2 Indoor thermal environments of each office during operational hours.

3.2 Air speed

Fig. 3 shows chronological changes of air speed at each measurement point. In office A, the operational status of the convective air-conditioning system was clearly in accordance with chronological changes in air speed. Fig. 4 shows a boxplot of air speed at each office. In office A, air speed showed a wide distribution of 0.06 m/s to 0.15 m/s. These results also confirmed that there was a noticeable difference between maximum and minimum air speed. In contrast, in the case of the floor-supply displacement HVAC system at office T and the radiant air-conditioning system at office C, the air speed was highly consistent, with minimal variation (<0.1 m/s). Moreover, this minimal variation in air speed was therefore perceived as being calm, compared to that of the convective air-conditioning system.

The percentage of occupants dissatisfied due to draft, draft rating (DR (%)), can be predicted by the following equation:

$$\mathrm{DR} = (34 - t_a)(v_a - 0.05)^{0.62}(0.37 \cdot v_a \cdot T_v + 3.14) \qquad (1)$$

where

t_a : Air temperature [°C]
v_a : Air speed [m/s]
t_v : Turbulence intensity of the flow [%]

Fig. 5 shows a DR at each measurement point during operational hours. The DR value was less than 15% at each measurement point. DR values tended to be high in office A. However, the DR index is unsuitable for evaluating the thermal comfort of the overall indoor environment.

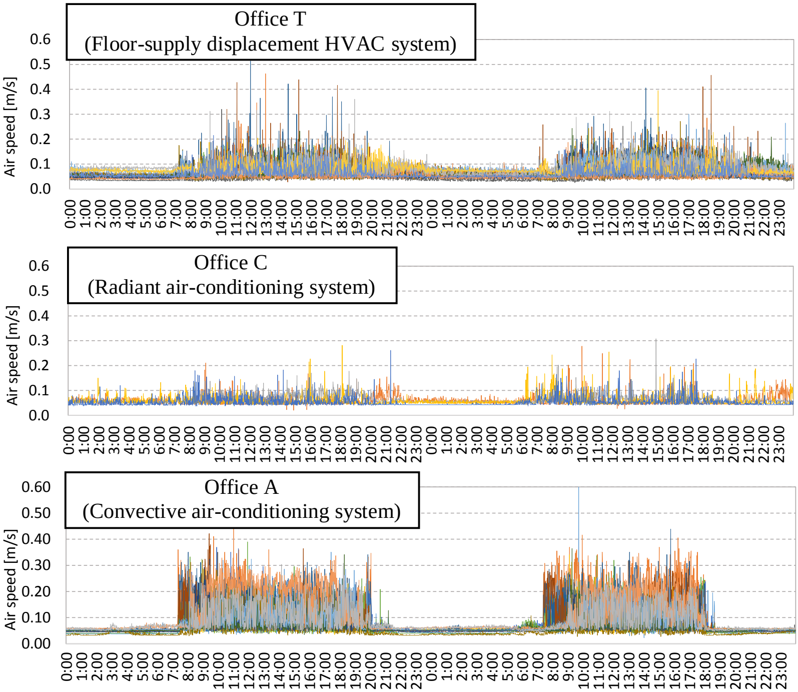

Fig. 3 Chronological change of air speed

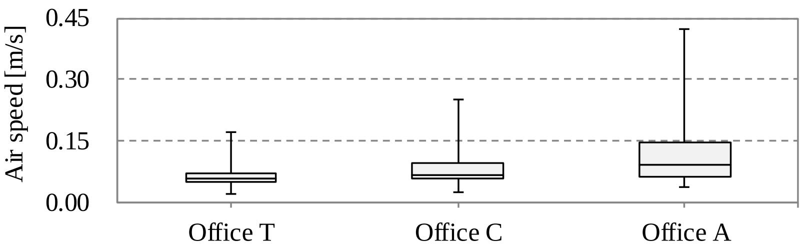

Fig. 4 Boxplot of air speed

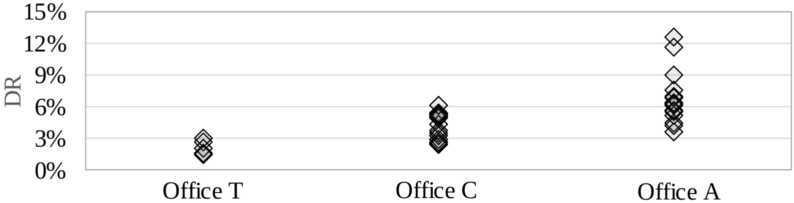

Fig. 5 DR value at each measurement point during operational hours

3.3 Air temperature and equivalent temperature

Figure 6 shows the occurrence frequency of various air temperatures, and equivalent temperature by Bedford. Equation 2 shows the calculation for equivalent temperature, based on the Bedford method.

$$t_{eq} = 0.522t_a + 0.478t_r - 0.21\sqrt{v_{ar}}(37.8 - t_a) \qquad (2)$$

where

t_{eq}	: Equivalent temperature by Bedford	[°C]
t_a	: Air temperature	[°C]
t_r	: Mean radiant temperature	[°C]
v_a	: Air speed	[m/s]

The radiant air-conditioning system and the floor-supply displacement HVAC system achieve narrow distribution of equivalent temperature, and hence provide uniform thermal environments compared to the convective air-conditioning system. Moreover, it was confirmed a difference between equivalent temperature and air temperature. Therefore, it is considered difficult to gain a precise understanding of thermal distribution from the conventional evaluation, primarily using air temperature.

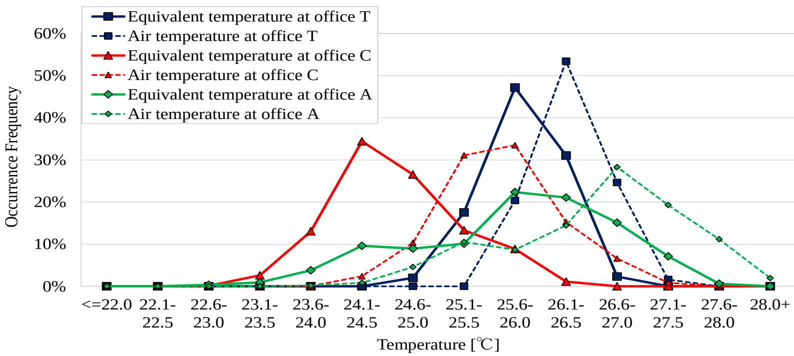

Fig. 6 Occurrence frequency of air temperature and equivalent temperature

4. Evaluating thermal environmental acceptability using a P–R chart

4.1 Concept of provided temperature, required temperature, and P–R chart

Based on the observed deviations in planar thermal environment in the three offices employing differing air-conditioning systems, the authors developed a new method for evaluating thermal environmental acceptability, termed a P–R chart. Each case is examined individually when accounting for the human problems of physiological quality and physical quantity in the indoor thermal environment. A few basic suppositions are necessary in order to discuss these concepts. The authors named the index of physical properties of the indoor thermal environment “provided temperature”, and the index of human physiological needs “required temperature”, hence the proposed index is termed a P–R chart. The concepts are elaborated as follows:

Provided temperature

Provided temperature is a quantitative index of indoor thermal environment, defined as the temperature of a hypothetical uniform thermal environment equivalent to the real environment. The conventional index of thermal comfort is derived from air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. In contrast, provided temperature is derived from four environmental parameters, intended to reflect the pure indoor physical thermal environment. We therefore consider provided temperature to be similar to equivalent temperature.

Required temperature

Required temperature is defined as the provided temperature at which a person in the room perceives a neutral thermal sensation. Therefore, required temperature is derived from the metabolic rate and clothing insulation of the person.

P–R chart

The proposed index employs “provided temperature” and “required temperature”, and is hence termed a P–R chart. In this concept, the values used are all assumed. Conceptual diagrams are shown in Fig. 7. This approach applies probabilistic evaluation to thermal acceptability. The thermally neutral line (shown in white on the charts) indicates the points where provided temperature and required temperature are equivalent. Therefore, a person whose thermal preference is represented by the white line feels that the thermal environment is acceptable (neither too hot nor too cold). In contrast, we considered a case where 20% of workers preferred low temperature because their metabolic rate and clothing insulation were high. If it is assumed that provided temperature in the indoor thermal environment is 20% skewed to the hot side, in evaluating the indoor thermal environment using this concept, we can probabilistically determine that 4% of workers feel that the thermal environment is too hot.

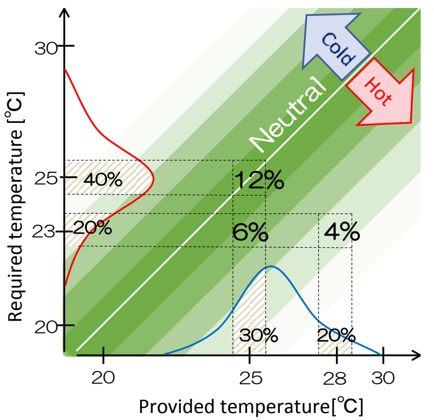

Fig. 7 Conceptual diagram of P–R chart

4.2 Results of P–R chart

Fig. 8 shows the occurrence frequency of the metabolic rates of the workers from office A and C. Metabolic rates were concentrated within the range 1.0 met to 1.6 met. As shown in Fig. 9, clothing insulation among workers in offices C and A was concentrated within the range 0.50 clo to 0.60 clo. Japanese Government policy encourages workers to dress lightly during the summer months to reduce reliance on air-conditioning.

Fig. 10 shows a P–R chart for each office. The evaluation of provided temperature distribution used Bedford's technique for evaluating equivalent temperature (Equation 1) on a trial basis. On the other hand, in accordance with the theory of PMV, the required temperature assumed that the value of air temperature and MRT are equivalent, that a person placed in the uniform thermal environmental room feels a neutral thermal sensation. Therefore, the required temperature distribution was calculated from measured metabolic rate and clothing insulation, and assuming 0.1 m/s air speed and 50% relative humidity. Office T (floor-supply displacement HVAC) shows greater probability of acceptable thermal environment (on the thermal neutral line) compared to office A (convective air-conditioning), because the provided temperature range is narrow. On the other hand, in office C (radiant air-conditioning), there was high likelihood of worker discomfort because although the provided temperature range was narrower, it was concentrated on the cold side. Therefore, in the case of the radiant air-conditioning system, it is considered that worker complaints will decrease if personal air-conditioning systems are provided, thereby allowing workers to adjust the provided temperature to their individual preferences.

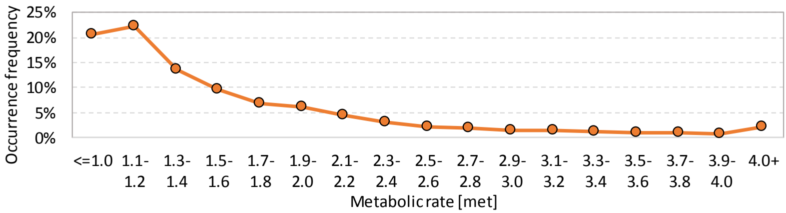

Fig. 8 Occurrence frequency of metabolic rate

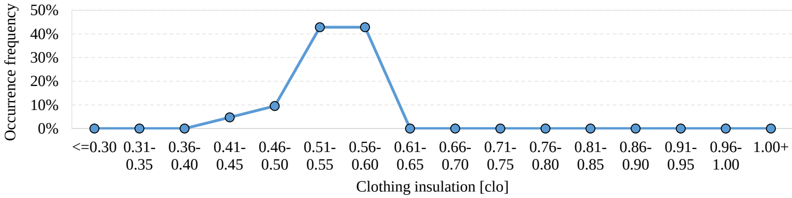

Fig. 9 Occurrence frequency of clothing insulation

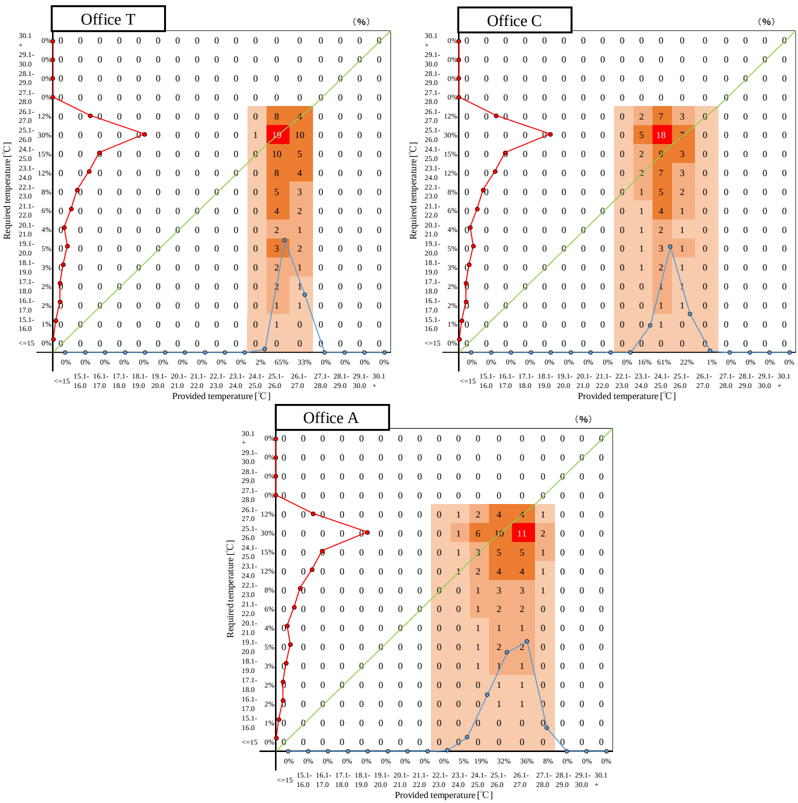

Fig. 10 Results of P–R chart

5. Conclusions

This study proposes a new thermal comfort index for evaluating air-conditioning systems, and introduces a new thermal comfort index for provided temperature and required temperature. Deviations of planar thermal environment were measured during summer, in three offices with differing air-conditioning systems. The results are summarized as follows:

1) In the case of the convective air-conditioning system, the findings confirmed a noticeable difference between maximum and minimum air speed. In contrast, air speed distributions were narrow for radiant air-conditioning and floor-supply displacement HVAC.
2) The narrow distribution of equivalent temperature indicated that radiant air-conditioning and floor-supply displacement HVAC created uniform thermal environments compared to the convective air-conditioning system.
3) The authors designed a new means of evaluating thermal environmental acceptability, termed a P–R chart. The floor-supply displacement HVAC was associated with low incidence of thermal discomfort compared to the convective air-conditioning system, because the provided temperature range is narrow.
4) For radiant air-conditioning, there was high probability of worker discomfort despite the lower maldistribution of provided temperature, because provided temperature was concentrated on the cold side. Therefore, in buildings with radiant air-conditioning, the use of supplementary personal air-conditioning systems would permit adjustments to the individual provided temperature, thereby reducing worker complaints.

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Supplementary note

(1) Cold drafts and non-uniform thermal environment do not occur, because the air speed is very slow and passes through the floor carpet.