A Study on Probabilistic Thermal Acceptability Evaluation

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Abstract

This study aims to establish a new thermal comfort index for evaluating air-conditioning systems, and introduces a new thermal comfort index for the provided and required temperatures. The authors performed comparison verification experiments on the temperature distribution of radiant air-conditioning and convective air-conditioning systems. The results showed the temperature provided by the convective air-conditioning system to have a wide distribution, unlike that of the radiant air-conditioning system. Based on these results, the authors propose a probabilistic thermal acceptability evaluation using the concepts of “provided temperature” and “required temperature”. The authors consider this evaluation method to be applicable for non-steady thermal environments as well as uniform high quality indoor thermal environments using radiant air-conditioning systems, and personalized air-conditioning systems.

Keywords: Thermal acceptability, Thermal comfort, Provided temperature, Required temperature, Evaluation method

1 Introduction

Radiant cooling systems do not create an uncomfortable air draft, unlike conventional convective air-conditioning systems. Therefore, such systems are expected to improve thermal comfort. However, an index evaluation method for assessing the thermal comfort of radiant cooling systems has not yet been established. Evaluation using the conventional thermal comfort indices considers the comfort of an individual staying in a room to be the same as that of a group of people with common characteristics. However, some individuals complain that when they sit under the air outlet, or at the cold spot in an actual working space, they do not feel the thermal environment to be comfortable. Therefore, the thermal environment should be evaluated from the point of view of such individuals. Moreover, conventional indices are used for the evaluation of a steady environment. Therefore, they are not suitable for use in the evaluation of thermal comfort in non-uniform unsteady environments of personal air-conditioning systems.

2 Concept of provided temperature and required temperature

This study deals with each case 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”. The concept of provided temperature and required temperature are further elaborated as follows:
(1) **Provided temperature**
Provided temperature is a quantitative index of the indoor thermal environment. Provided temperature is defined as the temperature of an imaginary 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. However, provided temperature is derived from four elements of the environment because the authors want to regard provided temperature as the pure indoor physical thermal environment. Therefore, the authors consider that provided temperature is an index similar to equivalent temperature. Equivalent temperature is defined as the temperature of a uniform enclosure in which a human body loses heat at the same rate as it would in the actual environment.

(2) **Required temperature**
Required temperature is defined as the provided temperature at which a person in a room feels neutral in terms of thermal sensation. Therefore, the required temperature is derived from the metabolic rate and clothing insulation of the person staying in the room.

3 **Comparison verification of the provided temperature distribution of a radiant air-conditioning system and a convective air-conditioning system**

3.1 **Summary of measurement**
This measurement aimed to compare the characteristics of the indoor thermal environment between a radiant air-conditioning system and a convective air-conditioning system, using provided temperature as an index. Moreover, this measurement was performed in order to gain fundamental data toward establishment of this new index.

This measurement was taken in an environmental test chamber where it was possible to set the temperature to the same level in both the radiant air-conditioning system and the convective air-conditioning system. In this experiment, the authors measured a detailed distribution of the indoor thermal environment in these test chambers. The conditions for each measurement are shown in Table 1. The summary of results in the environmental test chamber is shown in Fig. 1. A photograph of the supply opening used for the conventional air-conditioning system is shown in Fig. 2. In the case of the convective air-conditioning system, a deflection plate was attached to an anemostat type diffuser. This experiment reproduced airflow characteristics in the common office room by using a line diffuser. In the case of the radiant air-conditioning system, cold water was supplied to a radiant ceiling panel. Outside air was introduced through a floor-supply displacement ventilation system.

<table>
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<tr>
<th>Table 1. Conditions for each measurement</th>
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<tr>
<td>Air-conditioning system</td>
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<tr>
<td>Preset temperature</td>
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<td>Air volume</td>
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<td>Sampling points</td>
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3.2 Sampling points
The summary of sampling points is shown in Fig. 3 and Fig. 4. Air temperature and air speed on FL+1100 mm were measured at 90 points (600 mm) apart. The chamber was left to stabilize for 3 hours before measurements were taken. Measurements of air speed used a trestle with an 8-point non-directional probe hot-wire anemometer. These measurements were taken while the trestle was moving for a duration of 1 min at 5 s intervals.
3.3 Results of the experiment

(1) Planar distribution of air speed

Figures 5 and 6 show the planar distribution of the average scalar value air speed in the environmental test chamber for each air-conditioning system. Table 2 shows the maximum, minimum, and average in the planar distribution of the air speed for each air-conditioning system. In the case of the convective air-conditioning system, the average air speed was 0.14 [m/s]. These results also confirmed there was a noticeable difference in air speed between the maximum and minimum. In contrast, in the radiant air-conditioning system, difference in the air speed distribution was low. Moreover, the average air speed was 0.06 [m/s]. Therefore, the radiant air-conditioning system can provide a more stable environment compared to the convective air-conditioning system.
Figure 5. Planar distribution of air speed in the case of convective air-conditioning system

Figure 6. Planar distribution of air speed in a radiant air-conditioning system

Table 2. Results of air speed

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<th>Convective air-conditioning system</th>
<th>Radiant air-conditioning system</th>
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<tbody>
<tr>
<td>Maximum [m/s]</td>
<td>0.40</td>
<td>0.15</td>
</tr>
<tr>
<td>Minimum [m/s]</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Average [m/s]</td>
<td>0.14</td>
<td>0.06</td>
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(2) Provided temperature
For the evaluation of the provided temperature, the authors used Bedford’s technique for evaluating equivalent temperature (Equation 1) on a trial basis. This can be easily calculated from the indoor physical thermal environment. Further, while we know the importance of the measurement of radiant temperature, it was not possible to measure it because of time constraints. Therefore, the mean radiant temperature is given as air temperature.

\[
te_{eq} = 0.522t_a + 0.478t_r - 0.21\sqrt{v_{ar}(37.8 - t_a)} \quad (1)
\]
where

\[
\begin{align*}
t_{eq} & : \text{Equivalent temperature by Bedford} \quad [\degree C] \\
t_a & : \text{Air temperature} \quad [\degree C] \\
tr & : \text{Mean radiant temperature} \quad [\degree C] \\
v_a & : \text{Air speed} \quad [\text{m/s}]
\end{align*}
\]

Figure 7 shows the occurrence frequency of the provided temperature and air temperature in each air-conditioning system. The equivalent temperature was used to determine the provided temperature, confirming a noticeable difference between provided temperature and air temperature in the case of convective air-conditioning systems. Therefore, it is difficult to precisely understand thermal environmental distribution using the conventional evaluation, which relies mainly on air temperature. Moreover, the radiant air-conditioning system appeared to create a uniform thermal environment compared to the convective air-conditioning system because the distribution of provided temperature was narrow. However, Bedford’s equation is open to the criticism that it treats convection as measured from the body core temperature (37.8 °C) rather than from the mean surface temperature of the clothed body, which can be much lower. In addition, the convective part of the equation rests on a multiple regression equation whose accuracy is questionable, to say the least. Further consideration will be needed to confirm any findings about the provided temperature.

![Figure 7. Occurrence frequency of the provided temperature and air temperature](image)

### 4 Evaluating thermal environmental acceptability using a P-R chart

The authors designed a new means of evaluating thermal environmental acceptability based on the results from comparison verification of the provided temperature distribution between the two air-conditioning systems. The authors named this a P-R chart, after “provided temperature” and “required temperature”. In this concept, all the values used are assumed. The conceptual diagrams are shown in Fig. 8 to Fig. 10. This theory applies...
probabilistic evaluation to thermal environmental acceptability. The thermal neutral line, which appears white on the charts, shows the points where provided temperature and required temperature are the same. Therefore, anyone on the white line area feels neither too hot nor too cold, meaning that they feel the thermal environment is acceptable. On the other hand, for example, we considered a case where 20% of the workers had a low required temperature because their metabolic rate and clothing insulation were high. If it is assumed that provided temperature in the indoor thermal environment is 20% maldistributed on the hot side, in evaluating the indoor thermal environment using this concept, we can probabilistically determine that 4% of the workers feel that the thermal environment is too hot. Moreover, in the case of an indoor thermal environment using a radiant air-conditioning system, the probability of worker complaints decreases, because the maldistribution of provided temperature becomes lower. In addition, if workers can use personal air-conditioning systems, worker complaints decrease further, because workers can adjust the individual provided temperature.

Two indices are typically used to evaluate thermal comfort: the 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 these indices are unsuitable to evaluate the uniformity of the indoor thermal environment. Moreover, they are not suitable for the evaluation of the thermal comfort of personal air-conditioning systems. However, it is believed that the aforementioned P-R chart can be used in thermal comfort evaluation for all air-conditioning systems. Radiant air-conditioning systems and personal air-conditioning systems are attracting attention now. However, these air-conditioning systems are not popular yet, because it is not clear to what degree do they increase the thermal comfort. Therefore, the development of the P-R chart will contribute to the widespread use of these air-conditioning systems.

![Conceptual diagram of P-R chart (Convective air-conditioning system)](figure8.png)

Figure 8. Conceptual diagram of P-R chart (Convective air-conditioning system)
Figure 9. Conceptual diagram of P-R chart (Radiant air-conditioning system)

Figure 10. Conceptual diagram of P-R chart
(Radiant air-conditioning system + personal air-conditioning system)
5 Conclusions
This study aims to establish a new thermal comfort index for evaluating air-conditioning systems, and introduces a new thermal comfort index for provided temperature and required temperature. The results are summarized as follows:

1) The authors performed comparison verification experiments of the provided temperature distribution of a radiant air-conditioning system and a convective air-conditioning system.

2) In the case of the convective air-conditioning system, the average air speed was 0.14 [m/s]. It was also confirmed that there was a noticeable difference between maximum and minimum air speed. In contrast, in the case of the radiant air-conditioning system, the air speed distribution was low and the average air speed was 0.06 [m/s].

3) The narrow distribution of provided temperature indicated that the radiant air-conditioning system created a uniform thermal environment compared to the convective air-conditioning system.

4) The authors designed a means of evaluating thermal environmental acceptability based on the results from comparison verification of the provided temperature distribution of radiant air-conditioning systems and convective air-conditioning systems. The authors consider that this is an applicable method for evaluating non-steady thermal environments as well as uniform high-quality indoor thermal environments using radiant air-conditioning systems and personal air-conditioning systems.

References