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<td><strong>Author(s)</strong></td>
<td>Gao, Song; Li, Yang; Zhao, Min; Wang, Yuang; Yang, Xiaohu; Yang, Chun; Jin, Liwen</td>
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Design method of radiant cooling area based on the relationship between human thermal comfort and thermal balance

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Abstract

The radiant cooling air conditioning system has been widely applied, due to its features of better thermal comfort and efficient energy-saving. Most of the research on radiant cooling air conditioning system tends to concentrate on its cooling performance and energy-saving potential. However, the design methods of radiant cooling air conditioning system to guide its engineering application are rare. On the basis of the simplified human thermal balance equation and the linear relationship between the sensible heat loss and human thermal comfort achieved in our previous studies, the cooling performance of cooled surface is analyzed and then the method for determining the area of cooled surface is proposed in this paper. The numerical model is validated by experimental data and the calculation methods of cooled area are investigated with different boundary conditions. In addition, the PMV values in different heights and around human body are analyzed in detail. The results show that the calculation methods on account of the features of cooled surface could accurately predict the cooled area to maintain human thermal comfort under different conditions. Therefore, it is possible to determine the area of cooled surface in view of the relationship between human thermal comfort and thermal balance. This study could provide the guidelines for both the assessment of human thermal comfort and the system design of radiant cooling air conditioning system.

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1. Introduction

Radiant cooling air-conditioning system has been increasingly prevailed, thanks to its advantages of better thermal comfort and efficient energy-saving provision. Compared to conventional convective air conditioning system, the directly radiant heat exchange between human body and cooled surface makes people feel more comfortable [1]. In addition, the decreases of radiant temperature asymmetry and air temperature gradients could be the reasons for the better human thermal comfort under radiant cooling air conditioning system [2]. To have a better knowledge of the features of radiant cooling systems, a great deal of research on it has been done already.

K. Nagano [3] researched on the control conditions of radiant cooling ceiling for human body in supine position with Predicted Mean Vote (PMV), and the results show that direct cooling effect by radiation could be achieved with less energy than convective system. S.G. Hodder [4] found that the vertical radiant temperature asymmetry has an insignificant effect on the overall thermal comfort of the seated occupants subject to the hybrid system composed of cooling ceiling and displacement ventilation system. Koichi Kitagawa [5] investigated the effect of humidity and small air movement on human thermal comfort under a radiant cooling ceiling by subjective experiments, and it is concluded that the most comfortable sensation vote is obtained when people feel slightly cool. D.L. Loveday [6] verified the feasibility of the design standard BS EN ISO7730 established based on the experimental studies on conventional convective system for radiant cooling system. In addition, some studies pointed out that the traditional design criteria, such as these based on dry-bulb temperature and operative temperature, are insufficient and the effect of radiation heat transfer on human thermal comfort should be considered when it comes to radiant cooling system [7-8].

As discussed above, it could be learned that the existing studies on radiant cooling system focused on either its cooling performance or the effects of environmental factors on human thermal comfort. However, the research on the design methods of radiant cooling system is rare. With the aim to establish the method determining the area of cooled surface, both the characteristics of human thermal comfort subject to radiant cooling system and the cooling performance of cooled surface are investigated in detail in this study.

2. Simplification of the PMV model

The widely acknowledged Fanger’s PMV model based on personal and environmental variables is accurate for thermal comfort assessment of occupants in near-sedentary and stationary conditions [9]. Fanger [10] correlated the PMV to the difference between the actual heat loss and the required heat loss for thermal comfort from human body by Eq. (1):

\[
PMV = [0.303\exp(-0.036M) + 0.028]L
\]

where \( M \) is the metabolic heat production, and \( L \) is the human thermal load, defined as the difference between internal heat production and heat loss to the environment for a person hypothetically kept thermal comfort. The human thermal comfort level is affected by environmental conditions and human thermal balance. Due to the characteristics of radiant cooling system, the PMV model was reasonably simplified for near-sedentary human body in our previous studies, as shown in Eq. (2) [11]:

\[
PMV = -0.0406Q + 1.5117
\]

where \( Q \) is the total sensible heat loss from human body, consist of radiative and convective heat losses, \( \text{W} \cdot \text{m}^{-2} \). In addition, it has been concluded that the human thermal comfort subject to radiant cooling system could be directly evaluated from human sensible heat loss instead of complicated environmental factors [12]. So, based on Eq. (2), the methods to determine air-conditioning load and cooled surface area of radiant cooling system are investigated in this study.
3. Methods

3.1. Estimation methods of cooling capacity

The total heat gain of cooled surface is the summation of radiation and convective heat fluxes. The heat exchange by radiation and convection could be calculated by following equations [13]:

\[ R = h_r(AUST - T_p) \]  (3)
\[ C = h_c(T_a - T_p) \]  (4)
\[ h_c = 2.13(T_a - T_p)^{0.31} \]  (5)

where \( R \) and \( C \) are the radiation and convective heat gains of cooled surface \((W \cdot m^{-2})\), respectively; \( h_r \) and \( h_c \) are the radiation and convective heat transfer coefficients \((W \cdot m^{-2} \cdot K^{-1})\), respectively; \( T_p \) and \( T_a \) are the mean cooled surface temperature and air temperature \((^\circ C)\), respectively; AUST, the area weighted average temperature \((^\circ C)\), could be calculated by Eq. (6) [13]:

\[ \text{AUST} \approx T_a - dz \]  (6)

where \( d \) and \( z \) are both correction factors, and their product is less than 1. So, in this study, AUST is approximately equal to \( T_a \). In addition, the radiation heat transfer coefficient, \( h_r \), could be considered as constant, 5.6 \( W \cdot m^{-2} \cdot K^{-1} \) [14].

3.2. Calculation methods of cooling load and cooled area

Based on Eq. (2), it could be seen that for near-sedentary occupant with standard body surface area of 1.8 \( m^2 \), the required sensible heat loss for thermal comfort \((PMV = 0)\) is about 67 \( W \). In addition, the latent load isn’t considered in this study, and the air supply temperature and relative humidity are the same as those of indoor air. So the cooling load could be calculated by following equation:

\[ S = Q_1 + Q_2 + Q_3 \]  (7)

where \( S \) is the total sensible cooling load, \( W \); \( Q_1 \), the cooling load gained from human body, is dependent on the number of occupants, \( W \); \( Q_2 \) is the heat gain through building envelopes, \( W \); \( Q_3 \) is the heat production of equipments, \( W \). Thus, based on Eq. (3), Eq. (4) and Eq. (7), the area could be determined by Eq. (8):

\[ A = \frac{S}{R + C} \]  (8)

where \( A \) is the area of cooled surface, \( m^2 \).

3.3. Numerical scheme

Airpak\textsuperscript{\textregistered}, one of the most convenient softwares simulating indoor environment, is adopted in this paper. Both the indoor zero equation turbulence model and the discrete ordinate model are used. The room model with dimensions of 4.72 \( m \times 3.55 m \times 2.75 m \) is shown in Fig. 1.

In order to simulate the typical operating conditions of the hybrid system composed of cooling ceiling and displacement ventilation system, the air supply temperature, relative humidity and velocity are set as 26\(^\circ\)C, 50\% and
0.21 m·s⁻¹, respectively. Only the south wall is taken as exterior wall and all the simulated conditions are summarized in Table 1.

![Fig.1. CFD model](image)

Table 1 Summary of simulated conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
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<td>18</td>
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<tr>
<td>Q₁ (W)</td>
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<td>67</td>
<td>134</td>
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<td>0</td>
<td>0</td>
<td>148</td>
<td>268</td>
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<tr>
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<td>4.68</td>
<td>5.84</td>
<td>7.33</td>
<td>10.67</td>
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4. Results and discussion

4.1. Validation of numerical scheme

The validation is focused on the air temperature difference between the experimental data and numerical results on three positions along z direction of the test room, at heights of 0.1 m, 1.1 m and 1.7 m, respectively. To present the validation results concisely, only the difference value is showed here, i.e., the maximum relative error is 1.2% and the average relative error for the three analyzed points is only 0.8%.

4.2. Analysis of calculation methods determining the cooled area

The numerical data show that the PMV distributions of different cases are similar to each other, so only the PMV distributions of Case 1 are shown in Fig. 2. Figure 2 shows that the PMV in different heights are uniformly distributed and its values are all in the required range for human thermal comfort. In addition, the PMV around human body is also investigated.

In order to evaluate the accuracy of calculation methods determining the cooled area, the PMV values around human body are investigated. As shown in Fig. 3, these analyzed points with different colors are at the horizontal distance of 0.1 m from human body and distributed in different heights of 0.1 m, 1.1 m and 1.7 m, respectively. Obviously, almost all the PMV values are between -0.15 and 0.15, approximately equal to zero, which validate the reliability of the methods determining the cooled area.
Fig. 2. The PMV distributions in different heights of Case 1.

Fig. 3. The PMV values around human body.

5. Conclusions

In this study, the method for determining the cooled area on the radiant cooling air conditioning system is established based on the simplified human thermal balance equation and the linear relationship between the sensible heat loss and human thermal comfort acquired by our previous studies. The numerical model is validated by experimental data and the calculation methods of cooled area are investigated with different boundary conditions. In
addition, the PMV values in different heights and around human body are investigated in detail. The PMV data show that the calculation methods determining the cooled area established in this paper could be reliable. Based on the calculation methods, it is beneficial to improve the design process and load calculation method for radiant cooling air conditioning system.

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