Improving the indoor thermal environment with ceiling radiant terminals

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ABSTRACT

A CFD (computational Fluid Dynamics) simulation model of the porous ceiling radiant air-conditioning system was established to study the influence of the ceiling temperature and envelope temperature (including the temperature of the walls and the floor of a room) on the thermal environment in the room equipped with such a system. The results showed that, for the summer condition, higher ceiling temperatures would result in higher indoor air temperature and higher Predicted Percentage Dissatisfied (PPD), which meant potential discomfort of occupants in the room. For the winter condition, however, a higher ceiling temperature within 28°C would result in a lower PPD, thus improved the thermal comfort. Considering the energy-conservation, the thermal comfort could be assured if the ceiling temperature was not more than 28°C. As for the effect of envelope temperature, the result showed that the increase in the envelope temperature during summer could result in a higher indoor air temperature, but the thermal comfort of occupants could still be ensured under such condition. Considering both the thermal comfort and the energy-conservation, a ceiling temperature of 18°C (underside surface temperature of the ceiling) and an envelope temperature between 26°C and 32°C were proved appropriate for the summer. Similarly, based on the simulation results, a ceiling temperature of 26°C, and an envelope temperature between 8°C and 11°C were found appropriate for the winter. The results indicated that for the porous ceiling radiant air-conditioning system, ceiling temperature should be controlled to increase the ratio of radiant heat transfer in the summer, and the envelope temperature should be lowered to improve the energy-conservation of the system. In the winter, the heat transfer by radiation of the porous ceiling would account for a larger ratio, therefore the system showed good heating capacity and energy-conservation performance in winter.

KEYWORDS

radiant air-conditioning; thermal environment; air temperature; PPD index

INTRODUCTION

It has been reported that the energy consumption on buildings in China accounts for nearly 40% of the total social energy cost, among which the energy consumption on heating and air-conditioning accounts for 20% approximately. Moreover, over 90% of the buildings in China are heavy energy-consumption ones, the energy consumption of which on heating and air-conditioning per square meters reaches up to 3 times that found in other developed countries. Therefore, it is important to reduce the energy consumption on heating and air-conditioning in buildings by developing new technologies.

The porous ceiling radiant air-conditioning system is one kind of new energy-saving technologies in buildings. The heating and cooling of the system are realized by convection heat transfer of the air flowing into the room through holes in the ceiling, and radiation heat transfer of the porous ceiling. The ratio of these heat transfer can be adjusted according to the local climate. The system is characteristic of energy-conservation and comfortableness comparing to the traditional air conditioning system, in addition it can avoid condensation problem in the room.

Based on the heat transfer theory and the analysis of the porous ceiling radiant air-conditioning system, as well as our previous research, a simulation model was established to study the thermal environment of a room equipped with the system.

METHODS

Numerical simulation with CFD was adopted to study the thermal environment of a reading room in a university in south China. The dimensions of the reading room are 3400mm in length, 2000mm in width and 3000mm in height (shown in Figure 1a). The key component of the radiant air conditioning system is the energy storage area that is installed at the top of the room. This area is a cavity with 3 air inlets at one side and 3 air outlets at the other side. Meanwhile, the bottom of this area is the porous ceiling that allows the air to flow through and enter the room. Consequently, both convective and radiant heat transfer are included in this system. The air flow and heat transfer process are depicted in Fig 1b.

The energy storage area has a height of 300mm. There are 3 inlets (230mm in length and 120mm in height) at the south side and 5 outlets (230mm in length and 120mm in height) at the north side of the energy storage area. The porous ceiling consists of 14 smaller ceilings (600mm in length and 600mm in width) and 1 piece with fluorescent lamp panel. The model is shown below.

a)

b)

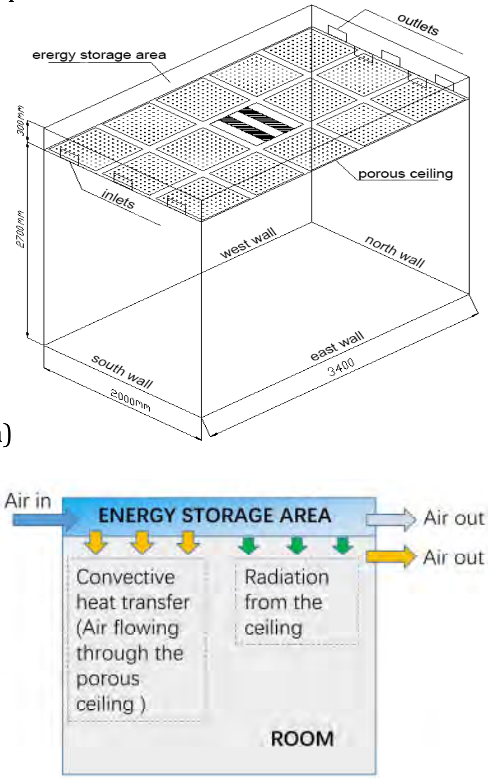


Figure 1 Diagrammatic sketch of the room with porous ceiling radiant air-conditioning system (a: structure of the air-conditioning system; b: air flow and heat transfer process of the system)

The boundary conditions of the model were determined according to the theories and features of the system. The open porosity and the aperture of the ceiling were 2.14% and 1cm, respectively. The supply air temperature was 10 °C in summer and 35 °C in winter. By controlling the supply air flow rate, the ceiling temperature could be controlled at 16°C, 18°C and 20°C at summer condition, and 24°C, 26°C and 28°C at winter condition. As for the heat gain from the walls of the room, the constant wall temperature boundary condition was adopted to simplify the simulation. The wall and floor temperature used in the simulation was the mean inner surface temperature of each surface from 9:00 to 17:00, which was measured by our team before the simulation. As for the heat gain from the lamp at the centre of the ceiling, we ignored it because its heat dissipation is much less than that of the ceiling.

Table 1. The temperature of the inner surface of the room (°C)

	North wall	South wall	West wall	East wall	Floor
Summer	29	27	27	26	25
Winter	11	13.5	12.5	14	15

Considering the PPD (predicted percentage of dissatisfied) index provides an estimate of how many occupants in a space would feel dissatisfied by the thermal conditions, we selected it as an indicator of thermal comfort performance of the room. During the simulation, we have assigned the clothing insulation of 0.5clo at summer and 1.5clo at winter condition, respectively. And the metabolic rate was set to 1met (58w/m^2) that corresponding to the rest status of the human body. The initial relatively humidity was set to be 60% that was a neutral indoor humidity, and the air velocity was the calculated value through the porous ceiling. Based on these 6 parameters, we obtained the PPD values.

RESULTS

By conducting the simulation, effects of the ceiling temperature and envelope temperature on thermal environment (air temperature distribution and PPD index) of the reading room were analyzed. The vertical plane X=1 (in width direction) in the centre of the room was selected as the typical plane to study. The air temperature showing in Fig. 2, 3, 6 and 7 were given in the format of Kelvin Temperature.

The effects of ceiling temperature

Air temperature distribution

For summer condition, the simulation was carried out when the ceiling temperatures were 16°C, 18°C and 20°C. The results showed that the air temperature in the room increased when the ceiling temperature increased. The mean air temperature near the porous ceiling was found to increase by 2.9°C when the ceiling temperature increases from 16°C to 20°C. Similarly, the mean air temperature increase in the working area was found to be 2.4°C. The air temperature distribution under 3 different ceiling temperatures was shown in Figure 2. In addition, temperature stratification was observed in Figure 2. However, air temperature in the working area was comparatively uniform. Therefore, for summer condition, a temperature increase of the porous ceiling could result in a reduction in cooling capacity of the air-conditioning system and air temperature increase in the room.

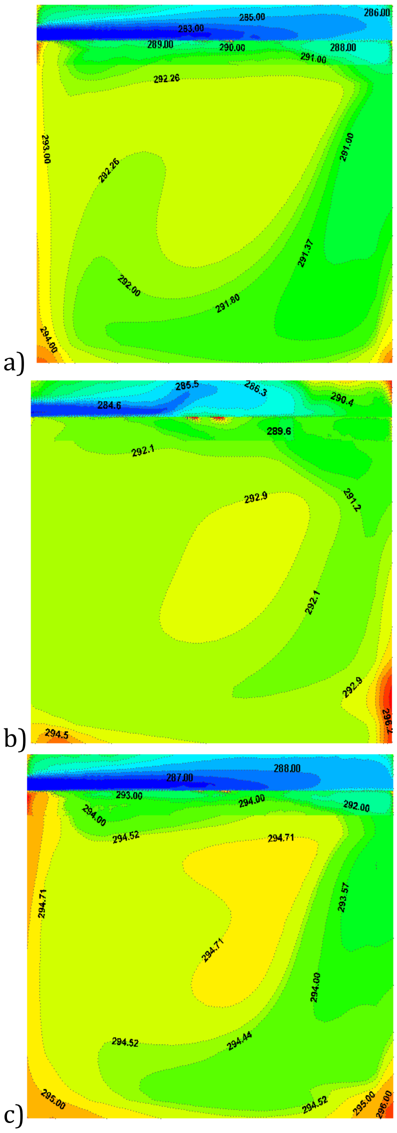


Figure 2 Air temperature distribution in summer under different ceiling temperatures. When ceiling temperature is a) 16°C, b) 18°C and c) 20°C

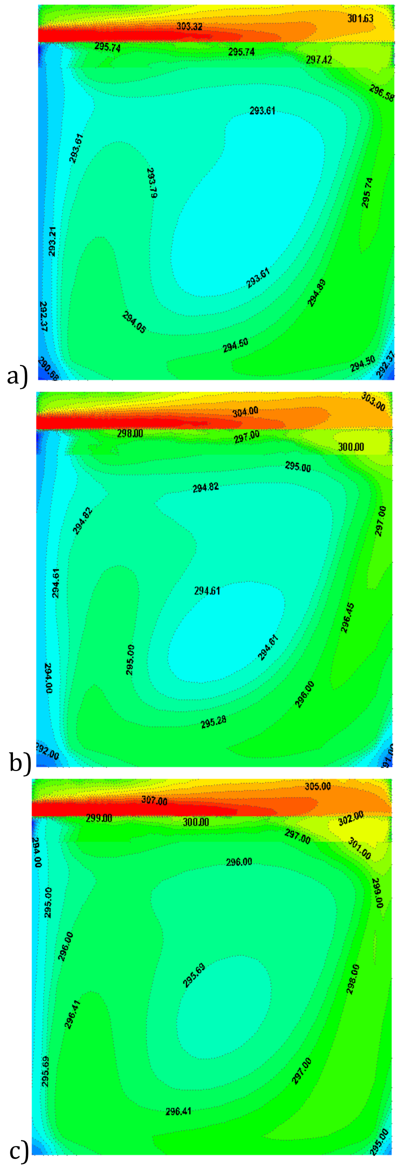


Figure 3 Air temperature distribution in winter under different ceiling temperatures. When ceiling temperature is a) 24°C, b) 26°C and c) 28°C.

For winter condition, the simulation results were shown in Figure 3. The mean air temperature in the room was found to increase when the ceiling temperature increased. The mean air temperature near the ceiling increased by 2.2 °C, while the mean air temperature in the working area increased by 2.5°C when the ceiling temperature increased from 24 °C to 26°C. The temperature stratification was observed in figure 3. However, the hot air in winter tends to move upward, therefore the temperature distribution in the room was more uniform than that in summer, especially in the working area. The results suggested that for winter condition, an increase in ceiling temperature could improve the heating capacity of the system and increase the indoor air temperature in the room.

PPD index

For summer condition, the PPD index that related to human thermal comfort in the room was shown in Figure 4. As the ceiling temperature increased from 16°C to 20°C, the mean PPD values were 5.8%, 7.2% and 16.2%, which suggested that the thermal environment of the room degraded gradually. However, the PPD value was under 10%, a critical value for human thermal comfort evaluation, when the ceiling temperature was 16°C and 18°C. Only if the ceiling temperature was 20°C, the PPD value would be more than 10%, which indicated that the thermal environment in the room was not comfortable.

For winter condition, the PPD values were found to be 8.5%, 5.2% and 5% respectively, when the ceiling temperature increased from 24°C to 28°C (shown in Figure 5). Therefore, the PPD value decreased as the ceiling temperature increased, and it was always less than 10%. The results suggested that the thermal environment of the room would be improved when the ceiling temperature increased.

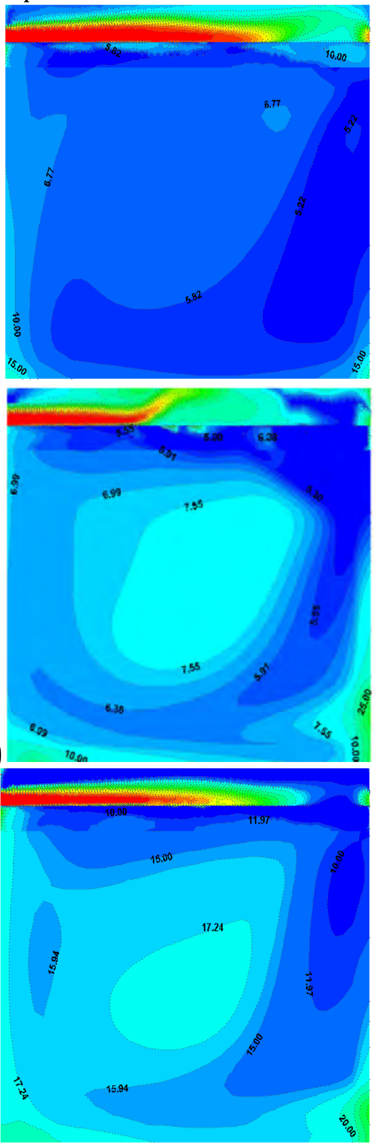
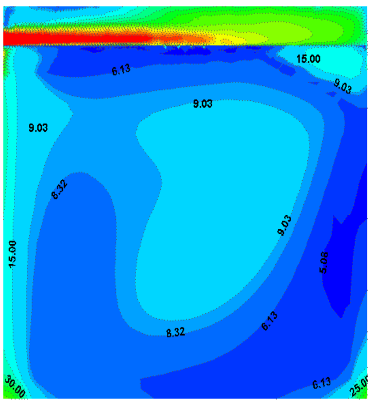


Figure 4 PPD index in summer under different ceiling temperatures. When ceiling temperature is a) 16°C, b) 18°C and c) 20°C.



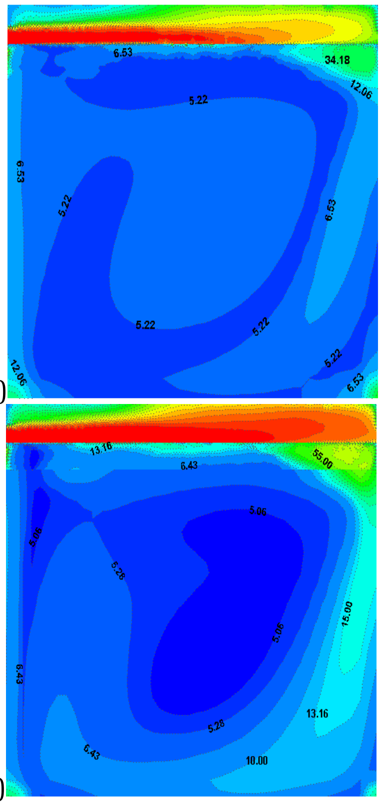


Figure5 PPD index in winter under different ceiling temperatures. When ceiling temperature is a) 24°C, b) 26°C and c) 28°C)

The effects of the envelope temperature

In order to study the effects of the envelope temperature on the thermal environment of the room, the ceiling temperature was set to 18°C and the envelope temperatures were 26°C, 29°C and 32°C in summer condition. In winter condition, the ceiling temperature was set to 26°C, and the envelope temperatures were 8°C, 11°C and 14°C. The plane X=1 (in width direction) in the centre of the room was selected again as the typical plane to study.

Air temperature distribution

The simulation results were shown in Figure 6. For summer condition, according to Figure 6, the mean air temperature in the room increased when the envelope temperature increased. But the air temperature change near the porous ceiling was more significant than that in the working area. The mean air temperature near the ceiling was reduced by 2.3°C, while the temperature in the working area was increased by 1.9°C. The differences in temperature change lay in the increase of the thermal load in the room caused by the temperature increase of the building envelop. In addition, the temperature stratification near the ceiling was more significant than in the working area. The reason for the thermal load in the room was due to the radiation heat transfer, therefore the temperature changed more rapidly near the porous ceiling.

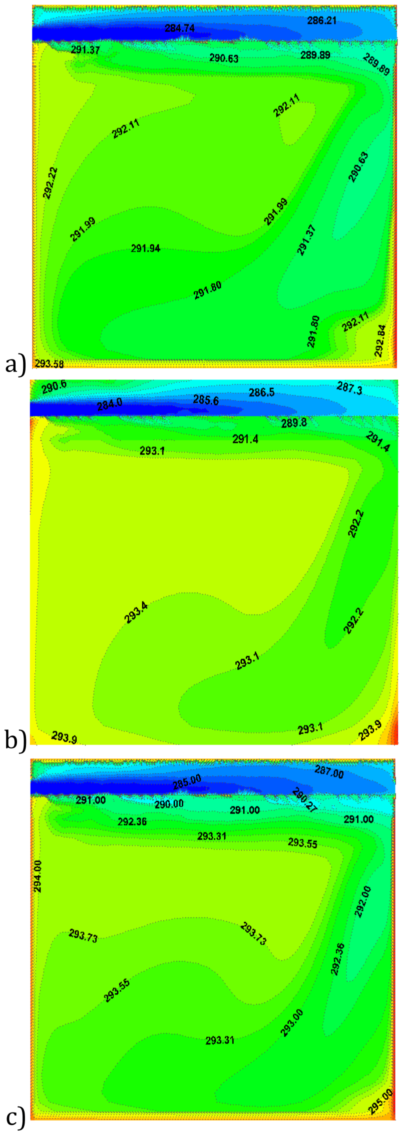


Figure 6 Air temperature distribution in summer under different envelope temperatures. When ceiling temperature is a) 26°C, b) 29°C and c) 32°C)

For winter condition, the simulation results were shown in Figure 7. According to figure 7, as the envelope temperature increased from 8°C to 14°C, the mean air temperature near the ceiling decreased by 1.6°C, while the mean air temperature in the working area increased by 1.6°C. The reason for the decline the air temperature near the ceiling is due to the reduced radiation heat transfer because of the reduced temperature differences between the ceiling and the envelope. However, the thermal load in the room was increased as a result of the temperature increase of the envelope, therefore the mean air temperature in the working area was increased.

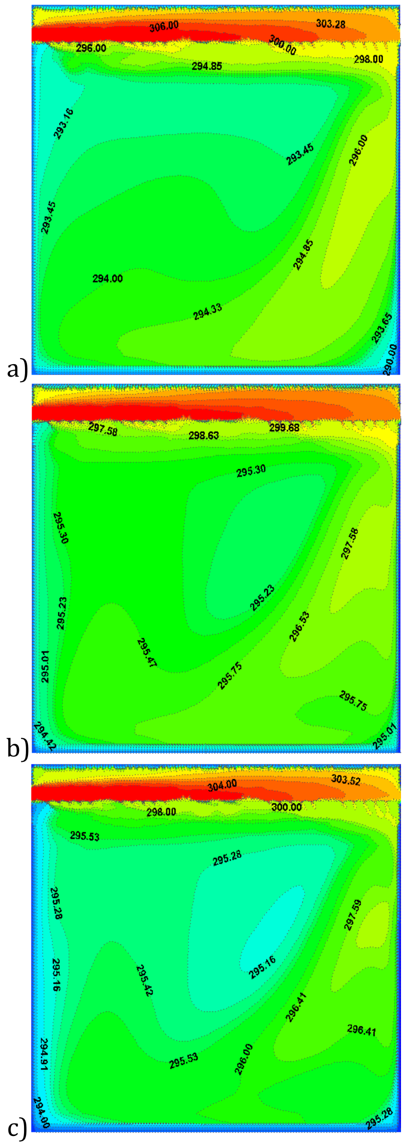


Figure 7 Air temperature distribution in winter under different envelope temperatures. When ceiling temperature is a) 8°C, b) 11°C and c) 14°C)

PPD index

For the summer condition, there was an increases in the PPD value as the envelope temperature was increased. According to Figure 8, the mean PPD values were found to be 6.1%, 5.9% and 9.7% when the envelope temperature were 26°C, 29°C and 32°C. The PPD index indicated that the thermal environment of the room was acceptable.

For winter condition, when the envelope temperature was 8, 11, 14°C, the mean PPD values were found to be 5.2%, 8.6% and 15.7%. Therefore, the thermal environment in the room changed greatly as the envelope temperature changed. When the envelope temperatures were 8 and 11°C, the PPD value was under 10%, a critical value to evaluate the human thermal comfort in the room. However, when the envelope temperature was 14°C, the PPD value was higher than 10%, which would bring thermal discomfort to the occupants.

The reason was due to the increases in the envelope temperature, the temperature difference between the porous ceiling and the building envelope would then the reduced, and therefore the radiation heat transfer of the system would also be reduced.

a)
b)
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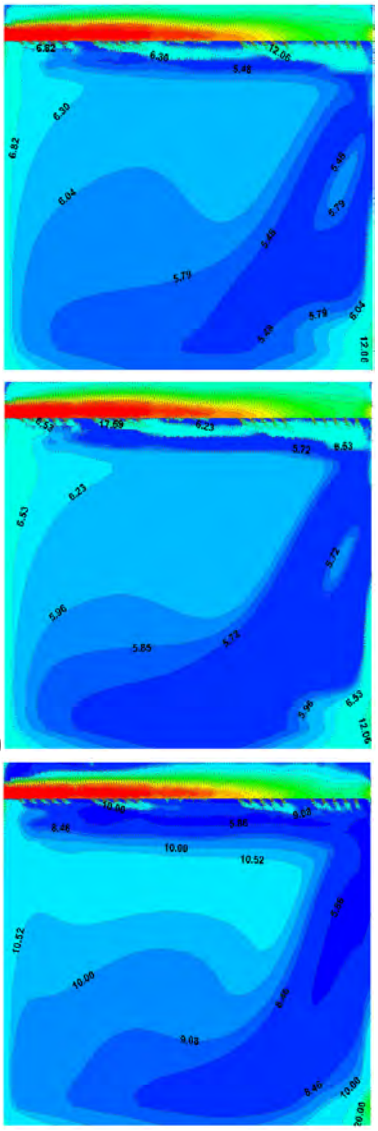

Figure 8 PPD index in summer under different envelope temperatures. When ceiling temperature is a) 26°C, b) 29°C and c) 32°C)

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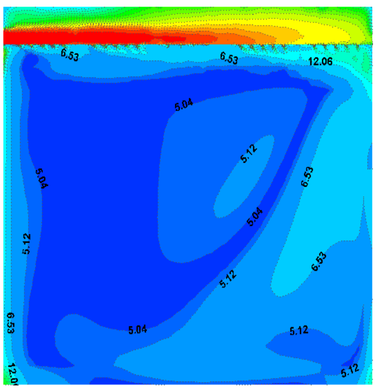

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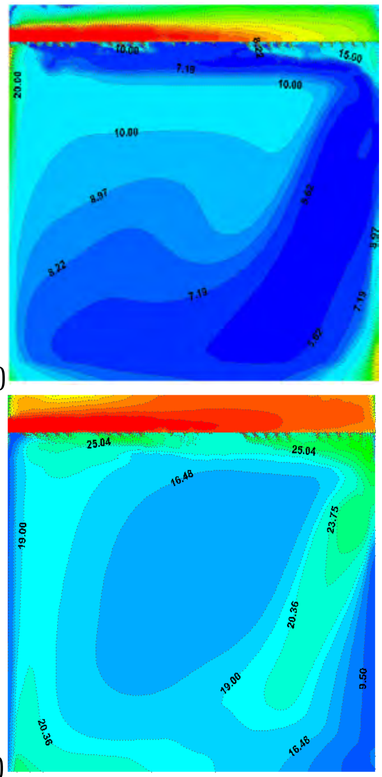

Figure 9 PPD index in winter under different envelope temperatures. When ceiling temperature is a) 8°C, b) 11°C and c) 14°C)

DISCUSSION

Numerical simulation was carried out to study the air temperature distribution and PPD index variation in a reading room equipped with porous ceiling radiant air-conditioning system, under different ceiling temperatures and envelope temperatures. Two interesting findings were obtained according to the simulation results, and a few suggestions were put forward for the practical application of the air-conditioning system.

Provided that the indoor and outdoor thermal load were constant, for summer condition, the air temperature in the room would increase as the ceiling temperature was increased. The PPD index would increase thus the thermal comfort of occupants in the room would deteriorate. The reason was due to the radiant heat transfer of the system would attenuate as a response to the increase in the celling temperature, meanwhile the convection effect would dominate. As a result, the PPD value would increase and the occupants in the room would feel uncomfortable gradually. In practical applications, the ceiling temperature should be not more than 20°C to ensure that thermal comfort of occupants in the room.

For winter condition, the air temperature in the room would increase as the ceiling temperature was increased. However, the PPD index would be reduced and improve the thermal comfort of the occupants; due to the increase in celling temperature which enhance the radiation heat transfer. In practical applications, however, the ceiling temperature should not be too high. The ceiling temperature be not more than 28°C in winter, considering both the thermal comfort of occupants and the energy conservation requirements.

Provided that the cooling capacity of the system were constant, for summer condition, the air temperature in the room would increase as the envelope temperature was increased, while the value of PPD index was within 10% and therefore the thermal environment was acceptable. In practical applications, the envelope temperature should be not less than 26°C and not more than 32°C to ensure both the thermal comfort of occupants and energy conservation, when the ceiling temperature is 18°C.

For winter condition, the thermal comfort of occupants and the energy conservation requirements could be satisfied when the envelope temperatures were between 8°C and 11°C, and the ceiling temperature was 26°C. However, if the envelope temperature was too high, the energy consumption would increase. In addition, the thermal comfort of occupants would also deteriorate as a result of the attenuated radiation heat transfer due to the reduced temperature difference between the ceiling and the envelope.

Finally, the limitation of this study may lie in that the heat gain due to the occupants and possible equipment was not considered. The heat gain brought by the human body consists of the sensible heat and latent heat, among which the latter would change the humidity condition of the room thus may further affect the thermal comfort of the human body. In addition, the heat dissipation due to lighting equipment and computers may also elevate the indoor air temperature thus add more extra load of the system, leading to different thermal comfort. Furthermore, the boundary conditions have been simplified in this study. The wall temperature and floor temperature were provided as the constant wall temperature condition, and the windows were not considered, which would lead to deviation to the actual results. What's more, the recommended wall temperature in winter was obtained simply by PPD index. It was low enough to lead to the condensation on the wall thus deteriorate the quality of the indoor environment. These factor will be considered in our future studies.

CONCLUSION

Porous ceiling radiant air-conditioning system is one kind of air-conditioning system considering both energy conservation and thermal comfort. The holes in the ceiling can provide the convective heat transfer and the ceiling can realize the radiant heat transfer. By adjusting the ratio of convection heat transfer and radiant heat transfer according to the environment, thermal comfort and energy conservation can be realized at the same time.

In practical applications, the ratio of radiant heat transfer of the system should be increased in the summer by controlling the ceiling temperature, to improve the energy conservation performance of the system. In winter, a higher ceiling temperature can reduce the energy consumption and ensure the thermal comfort of occupants. In addition, the envelope temperature should also be taken into consideration in practical applications.

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