Analysis of Indoor Thermal and Humidity Environment of Radiant Cooling Coupled with Attached Jet System

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Abstract: The radiant cooling combined with attached jet air supply system is a temperature and humidity independent control system. Radiant cooling panels are used to bear the indoor sensible heat load, and the attached jet air supply is used to bear the indoor humidity load. Numerical simulation method is used to study the changes of indoor relative humidity and dehumidification efficiency of radiant cooling panels installed on ceiling and wall, as well as the advantages and disadvantages of all three systems taking into consideration the radiant cooling coupled with wall attached jet air supply with deflectors in terms of comfort. The results show that the attached jet has good adhesion to the cooling panel and will not leads to condensation; the dehumidification efficiency of wall attached jet is relatively poor; at the height of 0.1m, the thermal comfort of wall radiant cooling system is the best; at the height of 0.7m, the wall radiant cooling system with deflector is the best; in the working range of 1.1 ~ 2.4m, the wall radiant cooling system is better than the ceiling radiant cooling system with or without deflector.
Keywords: Radiant cooling, Dehumidification, PMV

1 Introduction

China is a large consumer of energy in the world. According to relevant data, China's energy consumption of buildings (including energy, materials, water and the occupation of cultivated land) accounts for 21.5% of the national energy consumption[1].In order to achieve energy conservation and emission reduction, reduce energy consumption and finally realize sustainable development, we can start from reducing air conditioning energy consumption, so as to research and develop new methods for cooling and reducing air conditioning energy consumption.

Radiant cooling combined with attached jet air supply can improve comfort level on the basis of reducing noise, reduce energy consumption compared with traditional central air conditioning, and effectively reduce environmental pollution[2-5]. A cold source of about 16 ~ 20℃ can be used for refrigeration and only a heat source of 30 ~ 40℃ is required for heating. It is suitable for the development and application of renewable energy such as solar energy, wind energy and geothermal energy, which greatly reduces energy consumption. According to relevant data, radiant air conditioning can save energy consumption by 28 ~ 40%[6-7]. Wenzeng Shen[8] studied roof radiant cooling with attached jet composite of the indoor thermal environment and air conditioning systems. YasinKhan[9] proved that the radiant cooling system integrated with dedicated outdoor air system is a viable alternative to traditional all air system. H Karlsson and A Zarrella et al.[10-11] studied the transient operation of the embedded underwater floor heating system and recorded the specific experimental data of radiation condensation, which showed that latent heat load and high indoor humidity ratio lead to condensation on the surface of the radiant panel. In order to avoid the condensation, the humidity ratio should be reduced by increasing the corresponding equipment. Shin[12], etc. through simulation, discussed the method of improving cold energy of roof radiant cooling system, and pointed out that open roof radiant cooling system with air circulator reduced the level of indoor air temperature and freezing temperature difference, making it possible to operate in relatively high chilled water temperature, improve the refrigerating capacity, and reduce the energy consumption and the risk of condensation. Previous scholars have little research on the radiation location of radiation system as well as the indoor environment. This paper uses numerical simulation to study the parameters of indoor thermal and humidity environment in three conditions, including radiant panels installed on the ceiling, on the wall, and on the wall with deflectors. And advantages and disadvantages of all three forms are compared in terms of indoor dehumidification efficiency, comfort, etc.

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2 Physical model

2.1 Geometric model establishment

Build a physical model with L × W × H = 5.8 m × 3.3 m × 3.3 m, in which the west wall is the inner wall, and the rest except the floor are built with color steel laminboard of the same material to form the peripheral protection of the air conditioning room, with a thickness of 0.05m and a heat transfer coefficient of 0.763W/(m^2·K).

2.2 Room parameter setting

2.2.1 Temperature, humidity and humidity ratio of air supply

In this simulation, a radiant panel is used to bear all indoor sensible heat load, and the fresh air only meets the requirement of indoor dehumidification. Therefore, the jet air supply temperature is also 27℃, the relative humidity of air supply is 43.28%, and the outlet jet velocity is 1.144m/s.

2.2.2 Temperature of radiant cooling panels

In this paper, the average temperature of 18℃ is taken as the surface simulation value of radiation cold plate, and the detailed boundary conditions are shown in Table 1.

Table 1. Parameters of simulated boundary conditions

Boundary	Boundary condition
Window	Constant heat flux 13W/m^2
Energy saving light	Constant heat flux 9W/ m^2
Personnel	Radiation temperature 30℃,convective heat transfer coefficient $h_c = 1.48\Delta T^{0.25}$
Computer	Constant wall temperature boundary 30℃
Air supply outlet	Speed V=1.144m/s,Temperature T=27℃
Return air outlet	Natural outflow
Wall	Adiabatic boundary

3 Analysis of simulation results

3.1 Roof attachment effect

The radiant cooling of the top plate is combined with attached jet air supply. The low-temperature radiant plate is arranged on the top of the room to radiate heat exchange with the indoor high-temperature wall to reduce the indoor temperature. The jet air outlet is arranged on one side of the radiant plate to adhere to the radiant cooling panel. Observe the air supply deviation caused by gravity during the attachment process of jet air supply, and the results are shown in Fig. 1.

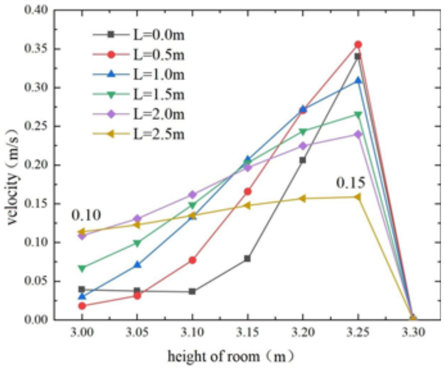


Fig. 1. Speed change at each position within 3 ~ 3.3m height

In Fig. 1, within 3 ~ 3.3m, the velocity of the jet passing through the supply air increases first and then decreases. The smaller the attachment length L is, the higher the initial velocity is, and there is no obvious vertical deviation. When L = 0m, the velocity value starts to rise from 3.1m. When L ≥ 0.5m, the velocity value starts to rise from 3m under the influence of the sinking air supply jet affected by gravity. When L = 2.5m, the air supply is attached. Affected by the sinking air supply jet affected by gravity, the velocity value slowly increases from 0.1m/s to 0.15m/s in the height range of 3 ~ 3.2m, and remains unchanged at the height of 3.2 ~ 3.25m.

At the height of 3.25 ~ 3.3m, the velocity value decreases significantly at each length of the cold plate attachment, indicating that the main flow section of the air supply jet is located in this air supply section. Considering that the height of the center of the jet air supply outlet is 3.27m, it indicates that after the cold plate attachment is completed, the vertical offset is 0.02m ≤ ΔH ≤ 0.07m, meaning good adhesion to cold plate.

3.2 Relative humidity distribution on the surface of roof radiant panel

When the high temperature and high humidity air contacts with the low temperature wall, the air temperature is easy to reduce to the dew point temperature and condense. In order to avoid condensation, the attached jet is used to isolate the surface of the radiant cooling panel from the indoor high temperature and high humidity air. The relative humidity changes of different attachment lengths L at different heights are shown in Fig. 2.

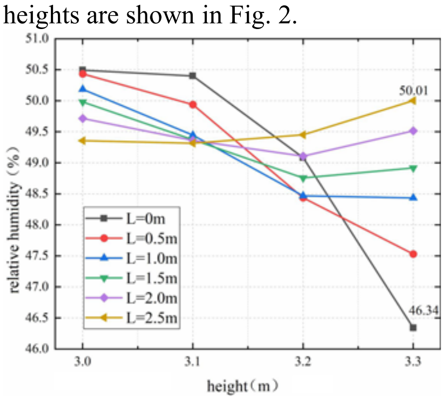


Fig. 2. Change of relative humidity under cold plate

According to Fig. 2, when the temperature of air supply is 27 ℃, the humidity ratio of the air supply meeting the indoor dehumidification is 9.7318g / kg, and the relative humidity of the air supply is RH=43.28%. When the air supply starts to attach the cold plate, that is, when the attachment distance is L = 0m, with the increase of height, affected by the processed dry air supply jet, the lowest relative humidity at the wall of the radiant cooling panel is rhmin = 46.34%. When the attachment distance increases to L = 1m, with the increase of the attachment distance, on the one hand, the dry jet air supply exchanges heat and moisture with the indoor high humidity air. On the other hand, due to the influence of the cold plate, the temperature decreases, resulting in the gradual increase of the relative humidity near the wall. As the attachment distance increases from L = 0m to L = 2.5m, that is, the attachment jet completes the attachment to the radiant cooling panel, the relative humidity at the wall of the cold plate increases from 46.34% to 50.01%, without condensation.

3.3 Dehumidification efficiency

The indoor air distribution formed by the corresponding attached jet air supply is also different due to the different installation positions of the radiant cooling panel. Under the same indoor humidity source, the dehumidification capacity is also different. And the differences of indoor dehumidification capacity under different air supply air distribution with the same initial indoor humidity are explored. Under the initial indoor temperature of 30℃ and relative humidity of 60%, the average indoor relative humidity changes of the three systems with the treatment time during the system operation for 0 ~ 2,500s is shown in Fig. 3.

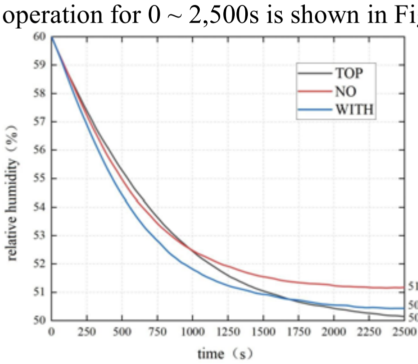


Fig. 3. Variation of indoor relative humidity with time

It can be seen from Fig. 3 that since the air supply directly enters the human body's moisture production work area, the wall attached air supply with deflector has better dehumidification efficiency and final stable value of indoor relative humidity than the simple wall attached air supply. Finally, the difference between the two relative humidity balance values is about 0.74%.

Due to the time difference between the rise of high temperature and high humidity air and the contact with the top dry air, the relative humidity value is slightly higher than the other two forms in 0 ~ 1,000s. The relative humidity value gradually decreases in 1,000 ~ 2,500s. Finally, the indoor relative humidity value is lower than the other two forms at 50.14%, which is the closest to 50% of the design state.

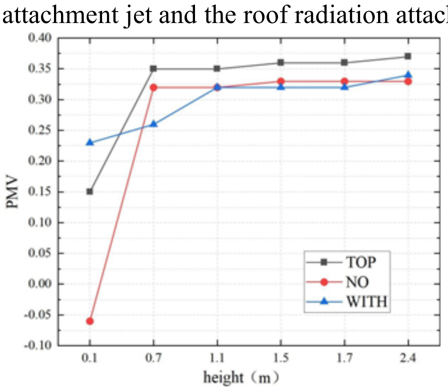
3.4 Comfort Index of Human Body PMV-PPD

Due to the differences of the existing standards in applicable buildings, people and other aspects, the requirements for speed, temperature and humidity are different[13-14]. On the basis of integrating various influencing factors, PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied)[15] are used for evaluation, and good values should be -1 ≤ PMV ≤ 1, PPD ≤ 27%.

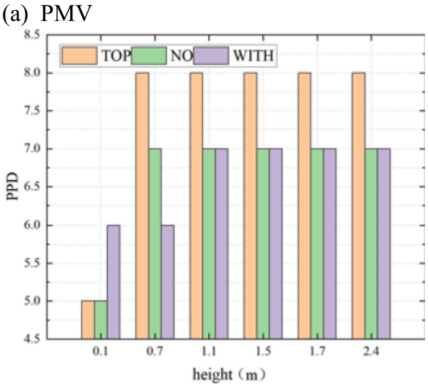
The PMV values of three system forms at different heights of human body are obtained through calculation, and the specific distribution is shown in Fig. 4.

As can be seen from the figure, the PMV values of the three types of radiant cooling attached jet air supply systems are no less than -0.1 and no more than 0.4 in the working range of 0.1 ~ 2.4m. The thermal feeling is moderate and meets the requirements of human comfort, which is different only at different heights.

At the height of 0.1m at the ankle of human body, the thermal comfort of wall radiant cooling and attached jet is the best, followed by roof radiant cooling, while the air supply with deflectors reverses the air supply midway under the influence of the deflector, so that it is not sent to the floor but to the ankle of human body along the floor, leading to a low comfort level. At the center of a sitting human body, a height of 0.7m, under the guidance of the deflector, the low-temperature and low humidity jet air after the attachment is directly sent to the human body working area for heat and humidity treatment, with good comfort level, followed by the wall radiation attachment jet and the roof radiation attachment jet.



(a) PMV



(b) PPD

Fig. 4. PMV-PPD values at different heights

In the lower working area within 0.1 ~ 0.7m, the velocity decay of wall attached jet is reduced, which can better deliver the air supply with low temperature and low humidity. The PMV value is low and has obvious advantages. In the human body area within the height range of 0.7 ~ 1.1m, the deflector can directly send the air supply with low temperature and low humidity to this position, so that the comfort level of wall attached jet air supply with deflector is the best in this range, followed by wall attached jet air supply and roof attached jet.

In the working range of 1.1 ~ 2.4m, which is the jet reflux area formed by attached jet, the effect of heat and moisture treatment is good, and the PMV value basically does not change. Only the system form is different and the PMV value is different. The PMV value of the attached jet of radiant cooling on the top plate is maintained between 0.35 and 0.4, and the wall radiant cooling is basically consistent within the height range of 1.1 ~ 2.4m with or without deflector, between 0.3 and 0.35.

At different positions in the height direction, the distribution trend of PPD value is basically the same as that of PMV value. For ceiling radiant cooling attachment jet, PPD = 6 at the height of 0.1m, and PPD = 8 at other heights. For wall radiant cooling without deflector, PPD=6 at the height of 0.1m, and PPD=7 at other heights. For wall radiant cooling with deflectors, PPD=6 at the height of 0.1 and 0.7m, and PPD=7 at other heights. The wall radiant cooling is better than the roof radiant cooling, while the wall radiant cooling is only different at the height of 0.1 ~ 0.7m below the reversing height of the deflector with or without deflector. When it is higher than 0.7m, the wall radiant cooling has no significant difference with or without deflector.

4 Conclusions

According to the installation position of radiant plate and whether there is a deflector for attached jet air supply, the system is divided into three system forms: roof radiant cooling attached jet, wall radiant cooling attached jet and wall radiant cooling combined with attached jet with deflectors. Through numerical simulation, the following conclusions are obtained.

(1) In the process of jet air supply attaching to the cold roof, due to the Coanda Effect, the maximum vertical offset $\Delta h < 0.07$m when the attachment is completed, indicating good adhesion to cold plate. The maximum relative humidity at the wall of the cold plate is 50.01% without condensation.

(2) The PMV values of the three system forms are no less than -0.1 and no more than 0.4 in the working area, which are only different at different heights. At the height of 0.1m, the wall radiation cooling is the best. In the height range of 0.7m ~ 1.1m, the comfort level of the attached jet with deflectors is the best. In the working range of 1.1 ~ 2.4m, the PMV value of roof radiant cooling maintains between 0.35 ~ 0.4, and that of wall radiant cooling maintains between 0.3 ~ 0.35 with or without deflector. The distribution trend of PPD value is basically the same as PMV value at different positions in the height directions.

(3) The relative humidity value of ceiling attached jet air supply is slightly higher than the other two forms within 0 ~ 1,000s, and gradually decreases within 1,000 ~ 2,500s. Finally, the indoor relative humidity value is lower than the other two forms, which is 50.14%, the closest to 50% of the design state.

Acknowledgments

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Reference

1. CABEE. Build. Energy Effic, **49 (2)**, 1 (2021).
2. K.X. Liu, Y. Wang, G. Liu, X. Zhang. J. Tianjin Univ, **51 (5)**, 522 (2018).
3. Q. Si, G.Y. Xu, X.S. Zhang. J. Southeast Univ, **48 (02)**, 213 (2018).
4. M.H. Chen, R. Ji, L.Y. Zeng. Build. Energy Effic, **47 (6)**, 57 (2019).
5. G.C. Gong, J. Liu. J. Hunan Univ., Nat. Sci, **46 (5)**, 148 (2019).
6. G.Q. Zhang, K.N. Fu, F. Zhang, Z.X. Xu, Y.Y. Zhang. J. Hunan Univ, Nat. Sci, **47 (09)**, 158 (2020).
7. C. Z, X.S. Zhang, G.Y. Xu, J.Z. Ji. J. Cent. South Univ, **52 (06)**, 1779 (2021).
8. Wenzeng Shen, Zhaoyi Zhuang,Bin Wang, Guangbin Wang. J. Shandong Jianzhu Univ, **36(03)**, 2021.
9. Yasin Khan, Gaurav Singh, Jyotirmay Mathur, Mahabir Bhandari. ATE, **124**, 2017.
10. Angelo Zarrella, Michele De Carli, Clara Energy CA Management, **85**, 2014.
11. Henrik Karlsson.J. Build Physics, **34**, 2010.
12. Shin MiSu, Choi JiSu, Rhee KyuNam.Energies, **14**, 2020.
13. G. L, Y. Qian, K.X. Liu, T. Nie, W.L. Huang. J. Tianjin Univ, **53 (08)**, 777 (2020).
14. Y.J. Yang, B. Zhang, Y.J. Li, B. Yuan, R. Li, L. Han, G. Wang. J. Southwest Univ., Nat. Sci. Ed, **43 (05)**, 162 (2021).
15. G. Xu, Q.Q. An, J. Yang, Z. Hui. J. Xi'an Univ. Sci. Technol, **41 (01)**, 55 (2021).