Simulation Research on Indoor Environment and Energy Consumption of Multiple Radiant Heating Modes

Chenyu Huang, Nianping Li, A. Yongga, Lizhi Huang, Chenzhang Yuan and Yongsi Wang

Abstract This study aims to compare characteristics of indoor environment and energy consumption of multiple radiant heating modes as well as their combination in winter. A simulation software, EnergyPlus, was used in this study. An office room model based on a real room which was located in Changsha, China, was established. Several radiant heating models with different radiant surfaces and their combinations were selected for simulation. Besides, two conventional heating modes were selected as comparisons, i.e. split air conditioning system and fan coil + fresh air system. In order to compare energy consumption of different systems under a similar condition, PMV = 0 was set as the indoor set-point of all heating systems in this study. A detailed analysis on all heating systems was conducted on the winter heating design day. The obtained results indicated that the system of radiant ceilings, side walls and floor is the best combination. This study provides references of selecting different radiant heating modes for thermal comfort and energy efficiency in winter.

Keywords Radiant heating mode · Indoor environment · Energy consumption

1 Introduction

Compared with traditional air conditioning systems, radiant heating system forms have obvious advantages in saving energy and improving indoor thermal comfort. Radiant surfaces can be placed on ceilings, floors or side walls to create different radiant heating methods. In recent years, researchers have conducted extensive research on the heat transfer performance and indoor thermal environment of different radiant heating surface positions and their combinations [1, 2]. The optimal energy consumption prediction control strategy for radiant floor heating systems had been proposed [3]. The effects of capillary ceiling radiation and wall radiation on indoor comfort had been considered by Airpak software [4].

C. Huang · N. Li (✉) · A. Yongga · L. Huang · C. Yuan · Y. Wang
College of Civil Engineering, Hunan University, Changsha, Hunan, China
e-mail: linianping@126.com

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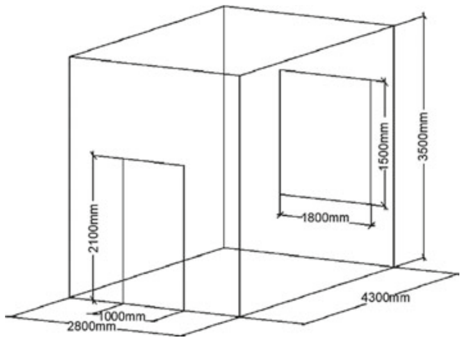

Fig. 1 Building model

Until now, research is mostly limited to the study of single-radiation heating modes or just an analysis of the indoor thermal environment with different radiating surface combinations and does not consider energy consumption when achieving a comfortable indoor environment. There are few studies on the comprehensive analysis of thermal comfort and energy consumption in the case of different radiation heating modes and their combinations.

This paper uses EnergyPlus software to simulate and compare the indoor thermal comfort and energy consumption of the split air conditioning system, fan coil plus fresh air system and fan coil plus fresh air combined with different radiant heating systems. It provides a reference for the comprehensive consideration of thermal comfort and energy consumption and the design of multi-radiation heating environment.

2 Building Model

An office room model based on a real room which was located in Changsha, China, was established. The room size was 4300 mm × 2800 mm × 3500 mm. The walls were all external walls, and an outer door was set on the south outer wall, and the size of the door was 1000 mm × 2100 mm; an exterior window was set on the north outer wall, the size of the window was 1500 mm × 1800 mm, the roof of the room was in contact with the outdoor air, and the floor of the room was in contact with the ground. The building model is shown in Fig. 1.

3 Air Conditioning Models

The air conditioning model included three models of split air conditioning model. The specific operating modes and the position of the radiant panel of each air conditioning model are shown in Table 1.

Table 1 Air conditioning model table

Model number	Model category
1	Split air conditioner
2	Fan coil plus fresh air system
3	Fan coil plus fresh air system + floor radiation
4	Fan coil plus fresh air system + ceiling radiation
5	Fan coil plus fresh air system + side walls radiation
6	Fan coil plus fresh air system + floor + ceiling
7	Fan coil plus fresh air system + floor + side walls
8	Fan coil plus fresh air system + ceiling + side walls
9	Fan coil plus fresh air system + ceiling + floor + side walls

3.1 Boundary Conditions and Parameter Settings

The building envelopes were made of insulating materials. The heat transfer coefficient of the outer wall was 1.1 W/(m^2 K), the roof was 1.53 W/(m^2 K), and outer window was 3.3 W/(m^2 K). The indoor heat source was mainly composed of personnel, lighting and laptops. The number of people in the room was 2, the per capita fresh air volume was 30 m^3/h, and the thermal resistance of clothing was 1clo. The metabolic rate of the human body was 70 W/m^2, the mechanical efficiency of human activity was 0, the lighting load was 9 W/m^2, and the equipment load was 15 W/m^2. The radiation laying area was the same in different fan coils plus fresh air combined with radiant heating composite system models. The average outdoor dry bulb temperature of the running day of the system was −1.9 °C. The running time of the systems was set as 8:00 to 18:00 on the winter heating design day.

3.2 Multiple Air Conditioner Models

Air conditioner model chose the Zone HVAC: Packaged Terminal Air Conditioner module as a control group for this thermal comfort and energy simulation. Fan coil plus fresh air system model used the Zone HVAC: Four Pipe Fan Coil module. The outlet temperature of the hot water unit was 50 °C. Fan coil plus fresh air combined with radiant heating system model used the Zone HVAC: Low Temperature Radiant: Variable Flow module and the Zone HVAC: Four Pipe Fan Coil module. And, the system used two water units: a high temperature (HT) hot water unit that supplied hot water for the fan coil system and a low temperature (LT) hot water unit that supplied hot water for the radiant panel. The outlet temperature of the low temperature hot water unit was 30 °C. Radiant heating controlled indoor thermal comfort by adjusting the flow rate of water supply and backwater according to the change of indoor load.

3.3 Control Method

Used the Zone HVAC: Thermostat: Thermal Comfort module for thermal comfort control of the system. The module used the Fanger's PMV indicator to control the thermal comfort and system energy consumption of the room personnel by controlling the PMV value of the room personnel. The operating control conditions set by the system were PMV = 0.

4 Result of Thermal Comfort

Thermal comfort is the state of consciousness that the human body is satisfied with the thermal environment. The thermal comfort index uses the PMV-PPD indicator in ISO7730 to evaluate the comfort of the room [5]. The PMV-PPD indicator was established by Professor Fanger on the basis of the thermal comfort equation. PMV represents the average evaluation of the staff's prediction of the thermal environment, which represents the feelings of the vast majority of people in the same environment. PPD indicates the percentage of people who are not satisfied with the prediction of the thermal environment. There are many factors that affect thermal comfort, including floor temperature, radiation inhomogeneity and operating temperature.

4.1 Floor Temperature

The comfortable floor temperature is the floor temperature when the barefoot standing on the floor is not satisfied with the complaint ratio below 15%, and whether the floor temperature is too high or too low, it will cause dissatisfaction among the indoor staff. According to the ISO7730 standard, the comfort temperature of the floor temperature is 19–29 °C.

Figure 2 shows a plot of floor temperature versus time for nine different system models. Compared with model 1 and 2, the floor temperature had a faster rise after air conditioning operation for model 3–9. And, they could achieve the comfortable temperature of the floor temperature during the operation period. Among them, the floor temperature of model 3 rose the fastest, meeting the comfort index of PMV-PPD at 9:05. From 18:00 to 2 h after the air conditioner was turned off, the floor temperatures of model 1 and 2 remained basically the same, and the floor temperature

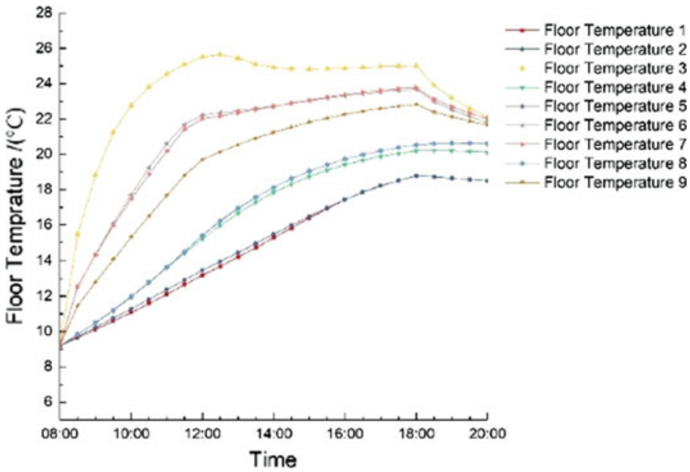

Fig. 2 Variations in floor temperature

of model 3 began to drop rapidly to 22 °C; the floor temperature of model 3–9 could still maintain a comfortable temperature, in which the floor temperature of fan coil + ceiling + floor + side walls radiation system decayed the slowest.

Analysis of the simulation results: the floor surface conducts convection heat transfer with indoor air and radiation heat transfer with other indoor inner surfaces. The composite system of radiant heating directly reduces the single or multiple internal surface temperatures of the room, forming hot surfaces and increasing the radiation heat exchange between the surfaces of the room, so that the floor temperature can reach a comfortable temperature more quickly. The more inner surfaces that form the hot surfaces, the slower the floor temperature will decay after the air conditioning system is turned off and the more comfortable the temperature will be.

4.2 Radiation Inhomogeneity

According to the ISO7730 standard, the asymmetric temperature difference of the heating radiation surface should be less than 5 °C. The smaller the vertical temperature difference of the heating radiation surface, the more comfortable the human body feels. Comparing the vertical and the lateral temperature difference between the east and west wall surfaces with radiant under different system models. The results are shown in Fig. 3.

It can be seen from Fig. 3 that model 3, 4 and 7 had large vertical temperature differences in the initial operation phase of the system, and the maximum vertical temperature difference of model 3 could reach 13.0 °C, which seriously affects the comfort of the room. After 10:00, the vertical temperature difference gradually decreased. The vertical temperature differences of the models 1, 2, 5, 6 and 9 showed

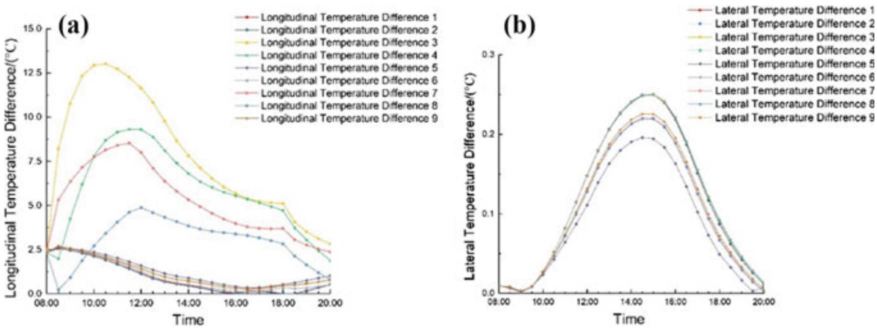

Fig. 3 Variations in vertical and lateral temperature difference

similar trends because no asymmetric radiation surface heating was provided in these five models, and its maximum difference did not exceed 3 °C. And, it can also be seen from Fig. 3 that the lateral temperature difference of all the models was less than 1 °C. Because that all the models had the same open state of the radiant surface of the east and west walls, without the asymmetric single wall radiant heating.

Analysis of simulation results: The use of a radiation system with a separate ceiling or floor raises the temperature of the longitudinal single wall and increases the vertical temperature difference from the floor to the ceiling. The systems of fan coil + side walls radiation, fan coil + ceiling + floor radiation and fan coil + ceiling + floor + side walls radiation have the smallest vertical temperature difference and lateral temperature difference, because they form a heating environment with relatively uniform surface temperature, which can be appropriately reduced the vertical temperature difference of the room and avoid the lateral temperature difference.

4.3 Operating Temperature

Operating temperature is a parameter introduced by considering the combined action of average radiant temperature and indoor air temperature. According to the ISO7730 standard, within the comfort range, the operating temperature should be 20–24 °C. Comparing and analysing the operating temperature changes of each system model in different time periods are shown in Fig. 4.

It can be seen from Fig. 4 that the indoor operating temperature trends of model 1 and 2 were basically consistent, and the operating temperature of the room rose to 20 °C until around 13:55; the indoor operating temperature trends of models 3–9 were consistent, and the operating temperature of the room rose to 20 °C until around 11:15. The operating temperature of radiant models reached the comfortable range more quickly. After the system was shut down at 18:00, the operating temperatures of models 1 and 2 dropped rapidly to the unsatisfactory comfort range, while the operating temperatures of models 3–9 fell slowly. The operating temperatures of

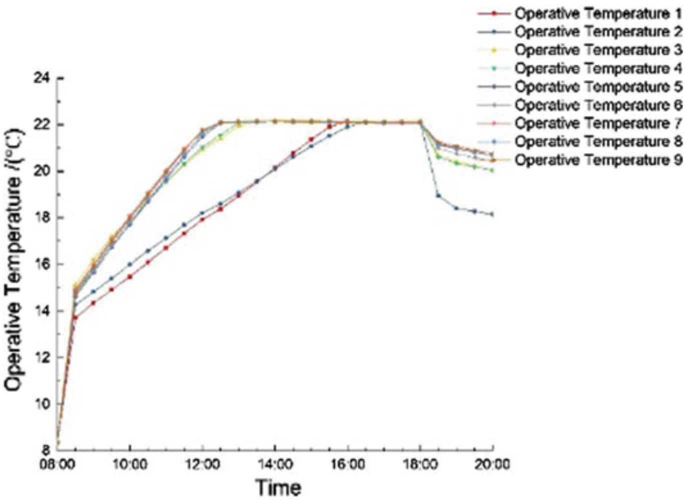

Fig. 4 Variations in operating temperature

model 6 and 9 rose fastest to 20 °C, and the operating temperature remained higher than 20 °C two hours after the system is shut down.

Analysis of simulation results: The operating temperature is determined by the internal surface temperature of the enclosure and the indoor air temperature. The radiant heating system directly raises the temperature of each inner surface, and the operating temperature rises faster; after the system is turned off, the operating temperature drops slowly due to the high internal surface temperature. Among them, the system temperature of fan coil + ceiling + floor + side walls radiation system drops the slowest, and the operating temperature can be maintained in a comfortable range for a longer time.

4.4 PMV-PPD Indicator

According to the ISO7730 standard, the comfort range of the PMV indicator should be −0.5 to +0.5; the corresponding PPD should be no more than 10%. The PMV-PPD index changes of each system model in different time periods were compared and analysed, as shown in Fig. 5.

It can be seen from Fig. 5 that the trend of PPD change was similar to that of PMV. The indoor PMV and PPD reached the comfort range at around 13:30 for model 1 and 2 and at around 11:00 for model 3–9. The PMV value of model 6, 7 and 9 rose to −0.5 the fastest. Within 2 h after the system was shut down, the PMV values of model 1 and 2 decreased rapidly to below −0.5, correspondingly, PPD increased to more than 10%, while the PMV values of models 3–9 remained relatively stable between −0.5 and +0.5, the PPD was also less than 10%. Among them, the PMV

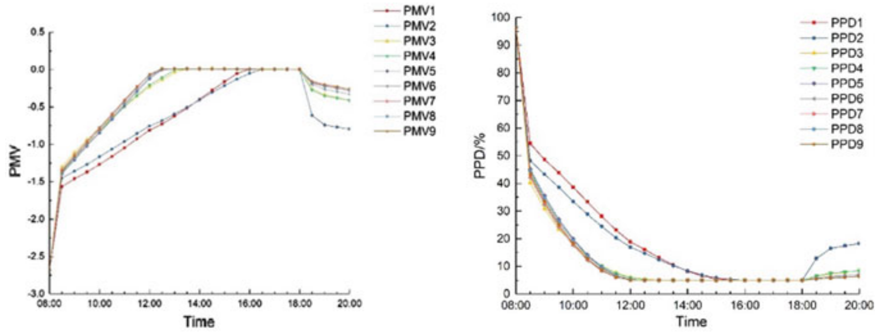

Fig. 5 Variations in PMV and PPD

value and PPD value of fan coil + ceiling + floor + side walls radiation system changed the slowest, so that the indoor thermal comfort was the best.

Analysis of simulation results: The radiant heating system directly raises the temperature of the inner surface of the enclosure structure, and raises the indoor average radiant temperature more quickly, which increases the radiation heat transfer capacity of the human body, enhances the comfort of the human body, and at the same time slows the heat decay.

5 Result of Energy Consumption

When the running time of the system simulation was from 8:00 to 18:00 of the design day, the total power consumption of the system model with similar comfort level was obtained to compare the power consumption of each device, as shown in Table 2.

As can be seen from Table 2, the total power consumption of model 1 was the highest, which was 20.76 kW h. The total energy consumption of model 7 was the lowest, which was 8.94 kW h, followed by model 9, which was 8.96 kW h. Compared with model 1, the energy consumption of hot source and fan in model 2–9 was significantly reduced, but the energy consumption of water pump was increased.

The simulation results show that when the system achieves similar comfort, the power consumption of the split air conditioning system is much higher than other systems. The composite system with radiant heating uses LT water supply and backwater, which improves COP of the hot water unit and thus reduces energy consumption of cold and hot sources. As the load borne by the fan coil is reduced, the energy consumption of the fan coil is reduced. However, the energy consumption of the water pump will be increased due to the use of fan coil and radiant heating, respectively. In general, the system of fan coil + floor + side walls radiation consumes the least power, followed by the system of fan coil + ceiling + floor + side walls radiation.

Table 2 Energy consumption of different models

Energy category	Model number								
	1	2	3	4	5	6	7	8	9
Split air conditioner	20.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fan coil	0.00	0.14	0.11	0.10	0.09	0.09	0.09	0.09	0.09
HT hot water unit	0.00	8.81	6.74	6.53	5.88	5.99	5.78	5.74	5.65
HT cooling water pump	0.00	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
LT hot water unit	0.00	0.00	1.90	2.19	2.73	2.57	2.75	2.87	2.90
LT cooling water pump	0.00	0.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Total energy consumption	20.76	9.17	9.06	9.14	9.02	8.98	8.94	9.01	8.96

6 Conclusion

(1) Comparing the simulation results, it can be concluded that compared with other system models, the fan coil + ceiling + floor + side walls radiation system could quickly reach the control conditions and obtain better floor temperature, vertical temperature difference, lateral temperature difference and operating temperature.
(2) From the point of view of energy consumption, the system consumption of fan coil + floor + side walls radiation was the lowest, compared with the split air conditioner, its energy consumption reduction rate was 56.94%, followed by the system of fan coil + ceiling + floor + side walls radiation, and the reduction rate was 56.85%.
(3) Within two hours after the system was shut down, comparing to the conventional heating system, the composite system could still maintain a comfortable indoor environment due to its strong heat storage. The system of fan coil + ceiling + floor + side walls radiation had the best indoor thermal environment.
(4) Comprehensive comparison, the system of fan coil + ceiling + floor + side walls radiation is the best combination, it provides a most comfortable indoor thermal environment and relatively low energy consumption, which can solve the problem that high heat comfort and low energy consumption cannot be simultaneously satisfied. It provides a reference for the optimal design of thermal comfort and energy consumption and the design of multi-radiation radiant heating system.

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