Simulation and experimental study of phase change cooling and heating wall radiation air conditioning system

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Abstract. This paper presents a case study of phase change cooling and heating wall radiant (PC-CHWR) air conditioning system application in an energy-saving renovation project in a laboratory in Wuhan, Hubei province in China. To test the thermal performance of the system, the PHOENICS software was utilized to simulate and analyse the indoor thermal environment in the laboratory under both winter and summer operating conditions. In addition, field experiments were also conducted under winter operation condition. By comparing the results between numerical simulation and field experiment, it is found that thermal performance of the PC-CHWR air conditioning system evaluated by these two evaluation methods are quite match. Moreover, the results also show that the PC-CHWR system can meet the cooling and heating load of the building within the acceptable range.

1 Introduction

Building energy-saving technologies have attracted widespread attention as building energy consumption has been increasing globally. Radiant terminal unit and phase change energy storage technology among other energy-saving technologies are studied by researchers and applied by engineers due to their high effectiveness on building energy conservation and advantage on heat load regulation.

Researchers have been conducting studies on phase change energy storage technologies for a long time. Tomlinson and Heberle [1] found that phase change wall panels can significantly reduce energy consumption in solar houses. Peippo et al. [2] tested the thermal performance of a phase change wall room. Athiellitis [3] set up a laboratory to encapsulate 25% butyl stearate phase change material in wall gypsum boards and tested its thermal properties. TIAN et al. [4] smeared the mortar with phase change energy storage ceramsite on the wall to make a phase change energy storage mortar wall and compared its performance with the ordinary mortar wall. Zhang Yangyang et al. [5] added phase change materials to ordinary walls and analysed the changes in temperature fluctuations and heat flow densities of the surface of interior walls under different distribution positions and distribution forms of phase change materials under periodic fluctuations in outdoor temperature. Chen Chao et al. [6] studied the feasibility of using composite phase change wall materials in passive solar houses in Beijing, where has higher solar radiation and higher solar radiation intensity in winter. Ye Hai et al. [7] proposed to use a heating and air-

conditioning system to drive phase change material to store heat. Lin Kunping [8] proposed a floor electric heating system with phase change material energy storage and simulated the changes of indoor air temperature and ground temperature.

Even though there are many previous researches on phase change energy storage technologies, very few theoretical and experimental studies on the combination of phase change energy storage technology in walls with radiant heating and cooling systems are conducted. In this article, the phase change cooling and heating wall radiant (PC-CHWR) air conditioning system was build up in a laboratory in Wuhan, where in the hot summer and cold winter zone in China. Both numerical simulation and field experiment were conducted to evaluate the performance of the PC-CHWR air conditioning system, which aiming to provide theoretical and experimental guidance for the application of the PC-CHWR air conditioning system.

2 Numerical simulation of indoor thermal environment in the experimental platform

Information of the laboratory

The building model was built based on a building located at Wuhan, and the laboratory is at the first floor of the building, it is a north-facing room and size of the room is 6.0m × 4.0m × 2.8m with a total area of 24m². The size of the south window is 2.40m × 1.5m, the window sill is 0.8m from the ground. The size of the north door is 1.0m × 2.0m and the size of the north

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window is $1.0\text{m} \times 1.5\text{m}$. The plan view of the laboratory is shown in Fig. 1. Radiant air conditioning systems are usually combined with fresh air systems, thus, in this paper, the fresh air system is also considered in the simulation model, which makes the simulation more similar to real operating conditions. The components in the room model are shown in Fig. 2. The red part is the phase change hot and cold wall and thermal parameters of envelope are shown in Table 1. The temperature and velocity field model are simplified as follows:

1) After the phase change process completed, the wall temperature is assumed to be stable at a certain value.

Fig.1. Floor plan of the laboratory

2) Heat dissipation of the envelope structure and the heat dissipation due to cold air penetration will be considered, but heat transfer between the laboratory with upper and lower floors and the left and right rooms will not be considered.

3) The air will be regarded as an incompressible fluid since the velocity of the air from outlet is relatively low. In terms of the buoyancy, the Boussinesq density assumption is utilised in the model. In addition, condensation on the wall is solved by displacement ventilation.

Fig.2. 3D model of the laboratory

Table 1. Thermal parameters of the envelope.

Parameters	Setting value
Heat transfer coefficient of wall	$0.35\text{W/m}^2\cdot\text{K}$
Heat transfer coefficient of roof	$0.25\text{W/m}^2\cdot\text{K}$
Temperature of Door, wall, and roof interior surface	$28/12^\circ\text{C}$
Temperature of Radiation surface of phase change cooling and heating wall	$21/28^\circ\text{C}$
Temperature of inner surface of window	$33/5^\circ\text{C}$
Indoor initial temperature	$32/13^\circ\text{C}$
Iteration number	1500

Table 2. Boundary conditions setting in the simulation model.

Number	Items	Boundary condition type	Required value	Set value
1	Inlet	Velocity-inlet	Velocity, Temperature	0.2m/s , 26°C
2	Outle	Outflow		
3	Computer	Constant heat flux	Heat flux	50W
4	Table lamp	Constant heat flux	Heat flux	40W
	Human body	Constant heat flux	Heat flux	50W
5	Walls	Constant temperature	Temperature, Heat transfer coefficient	28°C , $0.35\text{W/m}^2\cdot\text{K}$
6	Roof	Constant temperature	Temperature, Heat transfer coefficient	28°C , $0.25\text{W/m}^2\cdot\text{K}$
7	Windows	Constant temperature	Temperature, Heat transfer coefficient	33°C , $2\text{W/m}^2\cdot\text{K}$

Note: There is no Inlet or Outlet in winter

2.1 Boundary conditions

- 1) Boundary conditions of the wall surface are given in Table 1
- 2) Boundary conditions of the components in the room as shown in Table 2.

2.2 Simulation results and analysis

2.3.1 Summer condition

For a more comprehensive understanding of the indoor environment, the simulation result of the indoor air temperature are present with three directions, thus, X direction(south-north), Y direction(east-west) and Z direction(vertical).

- 1) Contour of temperature distribution in Y direction

Fig.3. Temperature distribution at Y=1m (left)

Fig.4. Temperature distribution at Y=3m (right)

Fig.5. Temperature distribution at X=3.3m (left)

Fig.6. Temperature distribution at X=5.5m (right)

- 2) Contour of temperature distribution in X direction

Fig.5 and Fig.6 revealed that the low-temperature fresh air enters the room through the air outlet and mixes with the high-temperature air in the room. The temperature field changes rapidly and the isotherms are relatively dense. The vertical temperature field is significantly stratified, and the temperature from the bottom to the top shows gradually rises tendency. The temperature is the lowest at a height of 0.1m, which is about 24°C, the temperature in the working area (1.1m) is about 25°C, and the approximate temperature at a height of 1.7m (in a standing position) is 25.6 °C. The overall temperature field is relatively uniform, and no obvious thermal stratification is formed, which meets the requirements of ASHRAE Thermal Comfort Standard [9].

As shown in Figures 3 and 4, the indoor air temperature is in the range of 22.4°C to 25,6°C and 24.4 °C to 27.2 °C at Y=1m and Y=3m respectively, and most of the air temperature are around 25.6°C under both cases. It can also be found that there is a thin layered boundary layer near the window. The temperature of the boundary layer is relatively higher, and the gradient is relatively large. The reason is that the outer window is in direct contact with the outdoor environment and the heat flux is relatively large. Fig. 4 also indicate that near the radiant hot and cold wall, the temperature gradient is large and there is a tendency for the cold air to sink. According to the isotherm, it can be inferred that at the same height, the closer to the radiant cooling wall surface, the lower the air temperature is. This mainly because that the heating and cooling effect is more intense where is closer to the wall surface.

Fig.7. Temperature distribution at Z=1.1m (left)

Fig.8. Temperature distribution at Z=1.7m (right)

- 3) Contour of temperature distribution in Z direction

There are also thin layered boundary layers near the outer windows on both sides of the room as shown in Fig.7 and Fig.8. There is a dense isotherm in the upper part of the personnel, and the ambient temperature is relatively high. The overall temperature distribution is uniform and suitable. The temperature is about 25.6°C ~ 26.4 °C at the height where people often stay (Z = 1.1m), which can meet the requirements of human thermal comfort.

In summary, based on the simulation results of the indoor temperature, it can be concluded that the phase change cooling and heating wall radiant (PC-CHWR) air conditioning system is able to meet the requirement of acceptable thermal environment recommended by ASHRAE Thermal Comfort Standard. What should be point out is that the simulation result of the indoor air temperature under summer condition might be higher than real situation, this mainly because the cooling and heating walls and the external walls and windows both are set to be adiabatic, which is inconsistent with reality to simplify the building model. Another reason is that radiating cooling and heating walls is equivalent to a uniform radiant panel with a constant wall temperature, which will cause the cooling capacity to be greater than in real situation.

2.3.2 Winter condition

Similarly, the indoor air temperature distribution under winter condition also present in three directions.

- 1) Contour of temperature distribution in Y direction

As shown in Figures 9 and 10, indoor air temperature is in the range of 16.6 °C to 21.4 °C and 16.6 °C to 22.6 °C at Y=1m and Y=3m respectively, and most of the air temperature are around 20.6 °C under both cases. Like the summer conditions, there is also a thin layered boundary layer near the window under winter condition. As shown in Fig.10, the temperature gradient is larger, and the temperature disorder appears near the radiant cooling and heating wall. It can also be found that the closer to the wall, the stronger the radiation effect will be, and finally result in higher of the air temperature.

Fig.9. Temperature distribution at Y=1m (left)

Fig.10. Temperature distribution at Y=3m (right)

2) Contour of temperature distribution in X direction
In Fig.11 and Fig.12, vertical air temperature is also stratified significantly like in summer condition. There are obvious low-temperature thin layers at the bottom distribution is uniform and suitable. The temperature is about 20.6 ~ 21.4 °C at the place where people often stay (Z = 1.1m), which meets the requirements of human thermal comfort. Moreover, the overall temperature of the temperature field in Fig. 14 is higher than that in Fig. 13 because the hot air rises with the rise of the indoor air temperature, and the temperature of the upper layer is generally higher than that of the lower layer.

Fig.13. Temperature distribution at Z=1.1m (left)

Fig.14. Temperature distribution at Z=1.7m (right)

In summary, the indoor temperature provided by the phase change cooling and heating wall radiant (PC-CHWR) air conditioning system is relatively higher than air temperature recommended by ASHRAE Thermal Comfort Standard in winter condition. The underlying reason maybe that entry of cold air from the outside was ignored when the model was established and radiant cooling and heating walls are equivalent to a uniform radiant panel with a constant wall temperature, which makes the heat supply is greater than the real situation.

3 Field experiment and measurement

In the laboratory's energy-saving retrofitting project, polyurethane foam insulation material (XPS board) was

and upper part, and the middle part gradually rises in temperature from bottom to top. The temperature is the lowest at the height of 0.1m, which is about 19 °C; the temperature in the working area (1.1m) is about 20 °C, and the temperature at the height of 1.7m (the standing position) is about 20.5 °C, and the overall temperature field is relatively uniform. The obvious thermal stratification phenomenon meets the requirements of ASHRAE Thermal Comfort Standard.

Fig.11. Temperature distribution at X=3m (left)

Fig.12. Temperature distribution at X=5.5m (right)

3) Contour of temperature distribution in Z direction
Like Y direction, Fig.13 and Fig.14 shows that the temperature near the window is significantly lower than other parts of the room. There is a circle of isotherms in the upper part of the personnel, and the surrounding temperature is relatively high. The overall temperature used to insulate the entire laboratory (except the ground). The XPS board's thermal conductivity of 0.022W / m · K and thickness is 40mm. Regular window glass were replaced with high transmission hollow Low-e glass with a thermal conductivity of 2.0W / m · K and a shading coefficient of 0.56, and the window is strictly sealed with a rubber sealing strip. The envelope of the laboratory before retrofitting were show in Fig 15 and the thermal parameters of the laboratory after retrofitting are shown in Table 3.

Fig 15. The envelope of the laboratory

The phase change cooling and heating wall radiant (PC-CHWR) air conditioning system is made up with water medium coil terminal unit, water pump, heat source device, hot water tank, etc. The schematic diagram of the measuring system is shown as Fig 16, and the 4.5m (length) × 2.5m (height) phase change cold and hot wall radiation air-conditioning system is deployed inside the east side wall of the laboratory, as shown in Fig 17. Solar energy is utilised as the cooling and heating source, the solar water heater to provide hot water (45 °C / 35 °C). Limited by the experiment condition, the field experiment and measurement were only conducted in winter operation condition.

Table 3. Thermal parameters of laboratory after retrofitting.

Items	Construction	Heat transfer coefficient ($\text{W/m}^2 \cdot \text{K}$)
Walls	Walls	Walls
Ordinary brick + XPS board	Ordinary brick + XPS board	Ordinary brick + XPS board
0.35	0.35	0.35
Ground	Ground	Ground
C20 fine stone concrete	C20 fine stone concrete	C20 fine stone concrete

Fig. 16. Schematic diagram of the test system

Fig. 17. Layout of the PC-CHWR air conditioning system(left)

Fig. 18. PC-CHWR air conditioning system (right)

Composite shaped phase change material was selected as the phase change material in this study. Composite shaped phase change material was made in the following process: phase change material (paraffin) and support material (high density polyethylene) are blended and melted at a temperature of 140°C , and then cooled below the melting point of high-density polyethylene and the liquid paraffin is formed by being bound into it. The PC-CHWR air conditioning system is installed directly on the wall surface, as shown in Fig 18. Fig 19 gives the picture of measurement instruments and solar water heater, TSI Special Race TSI8345 wind

speed and air volume temperature measuring instrument, Raytek ST20 infrared thermometer are applied in this study.

Five measuring points are arranged in the laboratory, the position of the measuring points is displayed as Fig 20. The height of the measuring points is 1.1m above the floor. Field measurement on are conducted wall temperature, indoor and outdoor temperature, etc sunny weather (November 20-November 25, 2018). The data was recorded every half an hour in the early stage of the test, and after the phase change completed after 3 hours, it was recorded once every hour.

Fig. 19. Measuring instruments: Water heater control panel, Infrared thermometer, Wind speed meter, air volume meter, Solar water heater and temperature meter. (From left to right)

Fig. 20. Position of measuring points

4 Analysis of experimental results

The outdoor air temperature was in the range of 3°C ~ 7°C , and the indoor air temperature fluctuates from 8 to 12°C during the experiment period. The following graphs are drawn based on the average value of the cooling and heating wall temperature of the six-day testing data.

As shown in Fig. 21, the temperature of cooling and heating wall fluctuates from 18 to 27°C , and the temperature changes of the measuring points at different cooling and heating wall positions are quite similar. The temperature of points 4 and 5 are slightly higher than other measuring points since they are below the wall. During the heat storage process, the temperature first increases rapidly and then slowly rises as the heat are continuing produced.

For indoor air temperature, before the test, the indoor starting temperature was 13.2°C . As the radiant hot and cold walls continuously transmitted heat to the room in the form of convection and radiation, the temperature rose rapidly and then slowly, as shown in Fig 22. The temperature at points 1 and 2 is slightly higher than the others since they are more near to the wall surface. The air temperature was basically stable between 17°C and

18.5°C after 6 hours of the experiment and it was stabilized around to 19°C , and finally stable at 16.8°C after the heat storage process completed.

Fig. 21. Temperature of the wall during the experiment (left)

Fig. 22. Curve of indoor air temperature (right)

According to the recommended value in the Chinese HVAC code, the indoor air temperature in winter should be in the range of 16°C - 18°C , based on the testing result, it can be found that the indoor air temperature can meet the requirement in the code. Since the tested indoor air temperature is about 16.8°C , it can be considered to extend the heat storage time to increasing the wall surface temperature by $1 \sim 2^{\circ}\text{C}$.

The dry-bulb temperature of the air is generally used in code and standards to recommend the acceptable indoor air temperature, and mainly consider the convective heat transfer between airs, however, for radiant cooling or heating system, it would be more

sensible to use the average radiant temperature and the operative temperature to evaluate the indoor comfort temperature. In practical engineering applications, it is generally thought that the average radiation protection temperature is equal to the average temperature of the inner surface of the envelope structure [11]. Studies have shown that when the indoor air velocity is less than 0.2 m/s , the difference between the average radiant temperature and the indoor temperature of the air will be less than 4 K , and the operative temperature can be considered to be equal to the average of the average radiant temperature and the indoor air temperature.

Table 4 shows the average temperature and action temperature during a heat storage period.

Table 4. Average radiation temperature and operative temperature ($^{\circ}\text{C}$).

System run time	Hot and cold wall average temp.	South wall average temp.	North wall average temp.	Interior wall average temp.	Ceiling average temp.	Ground average temp.	Average radiation temp.	Indoor temp.	Operative temp.
0	14.8	15.0	14.6	16.6	15.2	15.0	15.3	13.6	14.4
0.5h	18.5	15.8	15.0	17.4	15.9	16.2	16.7	15.4	16.1
1h	20.1	16.4	15.5	17.6	16.1	16.4	17.2	15.7	16.5
2h	22.7	16.8	15.9	17.9	16.5	16.7	17.7	15.9	16.8
3h	24.8	17.3	16.4	18.2	16.9	17.0	18.4	16.3	17.4
4h	25.2	17.8	16.9	18.5	17.2	17.1	18.4	16.4	17.4
5h	25.9	18.1	17.2	18.7	17.3	17.2	18.5	16.8	17.7
16h	19.1	18.0	17.0	18.3	17.0	16.9	18.3	17.6	18.2

As shown in the table, during the experiment, the initial indoor air temperature was about 13.6°C , and it reached to 15.7°C after the system run about 1 hour, actually the indoor air temperature had reached to 15.4 in half an hour, which can be conclude that the heating effect under experimental conditions is quite significant, this partly due to that the outdoor air temperature is not very low in Wuhan unlike other cold areas in China. For cold area, it is recommended to use better heat storage materials extend the heat storage time to ensure that there is enough heat to supply the room's heat dissipation during the heat release period.

During the experiment, it is found that the flow velocity also has an obvious impact on the heating effect of the system. In the experiment, the rated flow of the water pump is set at 25 L/min , and the corresponding flow rate is 2 m/s . Fig. 23 shows the average temperature change in a room for 2 h at different flow rates by adjusting the opening of the water supply pipe valve to measure the average indoor air temperature when the flow in the pipe is 0.4 m/s , 0.5 m/s , and 1 m/s , respectively.

As shown in the figure, when the flow rate is 1 m/s , the room air temperature rises by about 2°C within 1h, which means the heating effect is significant; when the flow rate is reduced to 0.5 m/s , the temperature is raised by 1.8°C in 1h; when the flow rate reaches 0.4 m/s , the temperature rose by 1.7°C in 1 h. It can be concluded that when the flow velocity in the pipe is large, the indoor temperature rise rate is fast; but the increase of

the flow velocity will make the water circulation to be too fast, result in the water temperature to dropping rapidly, the heat consumption to be too fast and finally leads to heat waste. Once the flow is high, excessive heat will be lost due to rapid cycling, so a suitable flow rate is very important. Comparing the air temperature rise at 0.5 m/s and 0.4 m/s , the flow velocity at 0.5 m/s is only 0.1°C higher than 0.4 m/s . At the same time, research shows that excessive flow velocity is not conducive to the storage of phase change materials. So, when the flow velocity in the pipe is 0.5 m/s , the phase change hot and cold wall radiation system has the best effect, which can not only ensure good comfort, but also avoid heat wastage caused by excessive flow velocity.

Fig. 23. Indoor air temperature under different flow rate at 2 hour of operation time

By comparing the result of simulation and experiment, the measured indoor air temperature in

winter are generally lower than the simulation results, this mainly because that the cooling and heating walls are set to be insulated from the outside in the simulation, and the heat emitted from the outside and the heat from the outside are ignored.

5 Conclusion

Based on a real "zero energy consumption" energy-saving retrofitting project, both numerical simulation and field experiment are carried to study on the phase change cooling and heating wall radiant (PC-CHWR) air conditioning system in hot summer and cold winter area in China, both the simulation and experiment result support that the PC-CHWR air conditioning system can meet the heating and cooling requirement and is able to provide a comfortable thermal environment.

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