Analysis of Air-Conditioning Radiator Based on Thermal Environment Characteristics of Buildings

Chang-chang LIU and Bao-huai ZHANG

School of Energy and Environment, Southeast University, Nanjing, China

*Corresponding author

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Abstract. The heating method based on coal-burning in residential buildings in northern China is seriously polluted and consumes a lot of energy. The "coal-to-electricity" heating using heat pump technology is an energy-saving and emission-reduction measure being implemented by the state. Based on the thermal environment characteristics of the building and the performance characteristics of the heat pump, this paper optimizes the layout of the air conditioner, and numerically simulates the system to analyze the thermal load of the building and the heat pump energy consumption with the outdoor climate. The results show that the wall air-conditioning radiant panels arranged near the outer wall can effectively reduce the heat supply temperature of the heat pump while effectively improving the indoor thermal comfort. The increase of the heat load of the building can reduce the actual heat pump power consumption by the increase of the heat pump COP.

Introduction

Heat pump technology has become the main way to replace scattered coal-fired heating in northern residential areas. In the traditional heating terminal mode, as the ambient temperature decreases, the economics and reliability of the heat pump's operation are significantly constrained. Studying the characteristics and countermeasures of heat pump system design based on the thermal environment characteristics of buildings is of great significance for effectively improving the thermal comfort of the living room and the operating conditions of the heat pump. [1-4]

The existing heating terminal in the living room mainly include fan coil units, floor heating and heat sinks. Conventional air source heat pump forced convection heating mode has obvious blowing feeling, radiant heating mode has no obvious blowing feeling, and has the characteristics of low heat dissipation surface temperature, large heat dissipation area, and uniform heating of indoor air. [5]

The fan coil unit that dissipates heat by air convection has higher temperature requirements for heat supply. The condensing temperature of the heat pump is generally above 50 °C. Under the low temperature condition, the pressure ratio and exhaust temperature will threats to the safe operation of the single-stage compression heat pump system. The floor heating requires less temperature for the heating medium, but the heating capacity is low and the thermal response is slow. Based on the improvement of heating and cooling methods in the north and the development of building energy-saving, this paper explores the proper location of the radiant air-conditioning terminal arrangement under the condition of using heat pump as the heat source, and analyzes the trend of heat pump COP and energy consumption under different working conditions.

Design of Air Conditioning Radiant Panel of Air Source Heat Pump System

This design adopts the heating mode of air-conditioning radiant panel + independent new fan, and uses air source heat pump as heat source to improve air-conditioning comfort, save energy and reduce emissions.
Structural Design of Air-conditioning Radiant Panel Arranged near the Outer Wall

The structural design of the air-conditioning radiant panel arranged near the outer wall is shown in Figure 1. The radiant panel is installed between the inner plastering layer and the brickwork body, and the hot water pipelines are arranged in the radiant panel. The radiant panel will remain within a comfortable temperature range and will maintain a comfortable PMV value in the room compared to conventional air conditioning systems.

![Figure 1. The structure of air conditioning radiant panel.](image)

Air Conditioning Radiant Panel of Air Source Heat Pump System

The schematic diagram of the system is shown in Figure 2. The solid line is the water supply pipes and the dotted line is the return pipes. The air source heat pump is used as the heat source to provide hot water for the air conditioning radiant panel, and the independent new fan sends the fresh air at the same temperature as the indoor air, and bears all the wet load and part of the heat load.

![Figure 2. System schematic.](image)

Numerical Simulation of Air Conditioning Radiant Panel of Air Source Heat Pump System

Room Model Establishment and Parameter Setting

The room model used to set up the numerical simulation has a total area of 40 m$^2$ and a height of 3 m. The east wall of the room is an inner wall with an area of 15 m$^2$, and the north wall is an external wall with an area of 24 m$^2$ and an outer window area of 5 m$^2$. The indoor temperature in winter is 18 °C.
The height of the external wall is 3 m, and the detailed parameters of the wall structure are shown in Table 1. Only consider the wall to dissipate heat both indoors and outdoors. The heat transfer coefficient of the outer window is 2.5 W/(m²*k).

| Floor                        | Thermal Conductivity λ/W/(m²*k) | Heat transfer coefficient h/W/(m²*k) | Thickness d/mm |
|-----------------------------|---------------------------------|-------------------------------------|----------------|
| Inner plaster layer         | 0.75                            | 8.7                                 | 20             |
| Brickwork                   | 0.54                            | -                                   | 240            |
| External plastering layer   | 0.93                            | 23                                  | 20             |

Establishment of the Model of Air-conditioning Radiant Panel System Arranged near the Outer Wall

According to the set conditions, establish the calculation model of the air-conditioning radiant panel system arranged near the outer wall of the room.

**Determination of Fluid Temperature**

It is assumed that the temperature of each point of the heat exchange plate of the system is the same, both are fluid temperatures; the heat transfer between the outer wall of the room and the indoor and outdoor is a two-dimensional heat transfer problem. Then:

\[ Q_n = Q_c \]  \hspace{1cm} (1)

\( Q_n \) — The amount of heat radiated from the radiant panel to the room, kW;
\( Q_c \) — External window heat load, kW.

According to this equation, the average temperature of the fluid in the heat exchanger plate can be calculated. The fluid used in this model is water.

**Determination of Heat Transfer Temperature Difference.** According to the following formula:

\[ Q_f = Q_r + Q_w \]  \hspace{1cm} (2)

\( Q_f \) — The total heat release from the radiant panel, kW;
\( Q_r \) — The thermal load on the radiant panel system, kW;
\( Q_c \) — External window heat load, kW;
\( Q_w \) — The amount of heat radiated from the radiant panel to the outside, kW.

Assume that the heat exchanger plate has an inner diameter of 13 mm and a water flow rate of 0.2 m/s. The heat transfer temperature difference of the heat exchanger plate can be calculated according to the total heat release.

**Determination of the Heat Pump Efficiency.** The heat pump of the model adopts a widely used air source heat pump, and the inlet temperature of the heat exchanger plate is obtained according to the calculated average temperature of the heat exchanger plate and the heat transfer temperature difference. Assume that the temperature difference between the heat pump condenser and the cooling water is 10 °C, and the temperature difference between the evaporator and the air is 10 °C. According to the COP value of the heat pump at different evaporation and condensing temperatures provided by the heat pump manufacturer, the relationship between the COP and the evaporation temperature and the condensing temperature is fitted to estimate the heat pump COP value of the model.

Figure 3 shows the heat pump performance curve fitted to the heat and input power of the air source heat pump according to different evaporation and condensing temperatures provided by the manufacturer.
System Energy Analysis

Effect of Thickness Variation of Insulation Layer on Energy Consumption

The insulation layer used in the analysis and calculation is XPS insulation board, the thermal conductivity is 0.02 W/(m²·K), and the outdoor temperature is -10 °C.

Figure 4 shows the change of the heat pump COP and the water supply temperature with the thickness of the insulation layer. Figure 5 shows the thermal load and the wall temperature of the outer wall as a function of the thickness of the insulation layer. Figure 6 shows the input power of the heat pump as a function of the thickness of the insulation layer. Table 2 shows the contrast of heat pump performance and the heat load when heating by the wall radiant panel to the fan coil, when the thickness of the insulation layer is changed.

| Insulation thickness d_e/mm | 65 | 60 | 55 | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 |
|----------------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Heat pump COP increase percentage φ_1/% | 39.0 | 38.9 | 39.1 | 39.1 | 39.2 | 39.2 | 39.4 | 39.6 | 39.9 | 40.1 | 40.5 |
| Heat pump input power reduction percentage φ_a/% | 17.9 | 16.8 | 18.1 | 19.6 | 19.8 | 20.4 | 21.7 | 23.9 | 25.3 | 27.9 | 30.5 | 35.3 |
| Heat load increase percentage φ_α/% | 17.9 | 18.9 | 17.8 | 16.3 | 16.2 | 15.6 | 14.4 | 12.6 | 11.4 | 9.3 | 7.3 | 3.9 |

It can be seen from Figure 4, Figure 5 and Figure 6 that with the decrease of the thickness of the insulation layer, the COP of the wall radiant panel and the heat pump using the fan coil unit is reduced, and the COP is reduced when the wall radiant panel is used; The input power decreases as the thickness of the insulation increases.

It can be seen from Table 2 that the heat pump COP increased by an average of 39%, and the heat pump input power decreased by an average of 25%.
Effect of Thermal Conductivity Change of Insulation Layer on Energy Consumption

The thickness of the insulation layer used in the analysis and calculation is 40 mm, and the outdoor temperature is \(-10\) °C.

Figure 7 shows the change of the heat pump COP and the water supply temperature with the thermal conductivity of the insulation layer. Figure 8 shows the thermal load and the wall temperature of the outer wall with the thermal conductivity of the insulation layer. Figure 9 shows the change of the heat pump input power with the thermal conductivity of the insulation layer. Table 3 is the contrast of heat pump performance and the heat load when heating by the wall radiant panel to the fan coil unit, when thermal conductivity of insulation layer is changed. Figure 7 shows the change of the heat pump COP and the water supply temperature with the thermal conductivity of the insulation layer. Figure 8 shows the thermal load and the wall temperature of the outer wall with the
thermal conductivity of the insulation layer. Figure 9 shows the change of the heat pump input power with the thermal conductivity of the insulation layer. It is the heat pump performance and heat load when heating the wall radiant panel when the thermal conductivity of the thermal insulation layer is changed, and the comparison when using the fan coil heating. It can be seen from Figure 7, Figure 8 and Figure 9 that with the decrease of the thermal conductivity of the thermal insulation layer, the heat pump COP has a small increase when heating with two air conditioner end forms, and the COP increases greatly when the wall radiation plate is used. The heat pump input power both has a large reduction.

It can be seen from Table 3 that the heat pump COP increased by an average of 39%, and the heat pump input average power decreased by 23%.

Table 3. The contrast of heat pump performance and the heat load when heating by the wall radiant panel to the fan coil unit, when thermal conductivity of insulation layer is changed.

| Thermal Conductivity $\lambda$/W/(m²·K) | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.08 | 0.1  | 0.12 |
|----------------------------------------|------|------|------|------|------|------|------|------|
| Heat pump COP increase percentage $\varphi$/% | 38.8 | 39.1 | 39.2 | 39.4 | 40.1 | 39.9 | 40.1 | 40.3 |
| Heat pump input power reduction percentage $\varphi$/% | 14.8 | 19.2 | 20.4 | 23.3 | 25.2 | 27.9 | 30.2 | 32.4 |
| Heat load increase percentage $\varphi$/% | 20.0 | 16.1 | 14.8 | 12.3 | 5.6  | 8.1  | 6.4  | 4.9  |

Figure 7. The COP and water supply temperature variation of heat pump with thermal conductivity of insulation layer.

Figure 8. The variation of heat load and the inner surface of exterior wall temperature with thermal conductivity of insulation layer.
The Effect of Outdoor Temperature Changes on Energy Consumption

When calculating the influence of outdoor temperature change on energy consumption, the insulation layer used is a 40 mm thick XPS insulation board with a thermal conductivity of 0.04 W/(m²·K).

Figure 10 shows the change of the heat pump COP and the water supply temperature with the outdoor temperature. Figure 11 shows the heat load and the wall temperature of the outer wall as a function of the outdoor temperature. Figure 12 shows the change of the heat pump input power with the outdoor temperature. Table 4 shows the contrast of heat pump performance and the heat load when heating by the wall radiant panels to the fan coil unit, when outdoor temperature is changed.

It can be seen from the figure that with the increase of outdoor air temperature, the heat pump COP has a significant increase when the two air conditioners are used for heating, and the heat pump input power is greatly reduced.

As can be seen from Table 4, when the outdoor temperature changes, the heat pump COP increases by an average of 40%, and the heat pump input power decreases by an average of 19%.

Table 4. The contrast of heat pump performance and the heat load when heating by the wall radiant panels to the fan coil unit, when outdoor temperature is changed.

| Outdoor temperature $t_o$/°C | -20.0 | -18.0 | -16.0 | -14.0 | -12.0 | -10.0 | -8.0 | -6.0 | -4.0 | -2.0 | 0.0 | 2.0 | 4.0 |
|------------------------------|-------|-------|-------|-------|-------|-------|------|------|------|------|-----|-----|-----|
| Heat pump COP increase percentage $\phi_3$/% | 32.1  | 33.6  | 35.2  | 36.5  | 37.8  | 38.9  | 40.2 | 41.3 | 42.3 | 43.3 | 44.3 | 44.9 | 45.4 |
| Heat pump input power reduction percentage $\phi_c$/% | 14.3  | 15.1  | 17.2  | 17.9  | 18.4  | 18.8  | 19.2 | 19.6 | 19.7 | 19.8 | 21.5 | 21.2 | 20.8 |
| Heat load increase percentage $\phi_\gamma$/% | 14.5  | 16.3  | 15.4  | 15.8  | 16.2  | 16.7  | 17.1 | 17.6 | 18.2 | 18.8 | 17.7 | 18.3 | 19.0 |
Conclusion

According to the simulation calculation, under winter heating conditions:

(a) The outer insulation layer is XPS insulation board, the thermal conductivity is 0.04 W/(m²·k), the inner insulation layer is XPS insulation board, the thermal conductivity is 0.04 W/(m²·k), the thickness is 20mm. And when the outdoor temperature is -10 °C, the energy consumption of using the wall radiant panel is lower than that of using the fan coil unit heating, the heat pump COP is increased by 39% on average, and the heat pump input power is reduced by 25% on average.

(b) The thickness of the outer insulation layer is 40 cm, the inner insulation layer is XPS insulation board, the thermal conductivity is 0.04 W/(m²·k), the thickness is 20 mm, and when the outdoor temperature is -10 °C, heat pump input power which using the wall radiant panel heating is lower than using the fan coil unit heating. The heat pump COP is increased by an average of 39%, and the heat pump input average power is reduced by 23%.

(c) The outer insulation layer is a 40 mm thick XPS insulation board with a thermal conductivity of 0.04 W/(m²·k), and the inner insulation layer is an XPS insulation board with a thermal conductivity of 0.04 W/(m²·k) and a thickness of 20 mm. When the temperature changes, the input power of using the wall radiant panel is on average 19% lower than that of using the fan coil unit heating.
It can be seen that the heat pump air conditioning system with the radiant panel arranged at the outer wall is energy-saving and environmentally friendly under the specific winter conditions than the conventional heating mode using the fan coil unit, and the exhaust temperature of the heat pump system is operated suitable under the low temperature condition. This mode providing a new way of thinking for heating in the north.

The air-conditioning radiant panel arranged near the outer wall adopts the concept of heat shielding, and the radiant panel is arranged at the position of the outer wall. In the traditional air conditioning mode, the air conditioner needs to deal with the cold load or heat load supplied from the outer wall to the room. This heat shielding method directly offsets the cold load and heat load on the outer wall, eliminating the intermediate steps and achieving the purpose of increasing efficiency and reducing power consumption. Moreover the wall surface temperature in the winter room is increased to maintain the PMV value within a comfortable range.

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