Journal of Southeast University (English Edition) Vol. 28, No. 1, pp. 52 - 57 Mar. 2012 ISSN 1003—7985

Thermal comfort assessment and energy consumption analysis of ground-source heat pump system combined with radiant heating/cooling

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Abstract: A new ground source heat pump system combined with radiant heating/cooling is proposed, and the principles and the advantages of the system are analyzed. A demonstration of the system is applied to a rebuilt building: Xijindu exhibition hall, which is located in Zhenjiang city in China. Numerical studies on the thermal comfort and energy consumption of the system are carried out by using TRNSYS software. The results indicate that the system with the radiant floor method or the radiant ceiling method shows good thermal comfort without mechanical ventilation in winter. However, the system with either of the methods should add mechanical ventilation to ensure good comfort in summer. At the same level of thermal comfort, it can also be found that the annual energy consumption of the radiant ceiling system is less than that of the radiant floor system.

Key words: ground-source heat pump; radiant heating/cooling; thermal comfort; energy consumption

doi: 10.3969/j.issn.1003 - 7985.2012.01.010

With the growth of the national economy and the continuous improvement of people's living standards, the air-conditioning system has been indispensable. Developing new energy and renewable energy has become one of the main objects in the development of the national economy. To achieve the coordination of economic development and energy consumption, the urgent need is to give serious consideration to the energy-saving air-conditioning problems and promote energy-efficient and environment-friendly air-conditioning products [1].

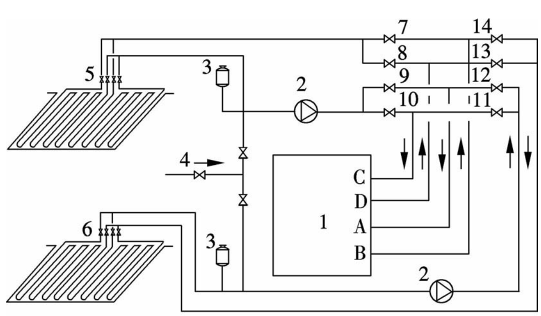
The ground-source heat pump is one of the more important technologies which can use low level renewable energy. It is a new method that uses low-temperature heat sources to heat or cool[2]. It has many advantages, such as saving energy and using renewable energy. When used for heating purposes, it is not only energy-efficient, but also avoids the pollution of the heating boiler. It has significant environmental benefits [3].

In the radiant air-conditioning system, energy is transferred through the radiant floor or ceiling. For example, in the radiant floor heating system, the air is heated through convection heat transfer. At the same time, the furniture and the building envelope are also heated through the radiant heat transfer. As the indoor mean radiant temperature rises and the thermal radiation dissipation from the human body is reduced, the human thermal comfort can be improved. Using radiant heating, the indoor design temperature can be 2 to 3 ℃ lower than that using the traditional air-conditioning systems. Similarly, when using radiant cooling, it can be 2 to 3 ℃ higher than that using the traditional air-conditioning systems to obtain the same thermal comfort [4].

In this paper, a ground-source heat pump system combined with radiant heating/cooling is presented and it is applied to Xijindu exhibition hall in Zhenjiang, China. The thermal comfort of the air conditioning system is assessed and its energy consumption is analyzed by TRNSYS software.

1 Principle of Air-Conditioning Systems of Ground-Source Heat Pump Combined with Radiant Heating/Cooling

As shown in Fig. 1, the ground-source heat pump radiation air-conditioning system is composed of the geothermal exchange system, the water source heat pump unit and the



1—Ground source heat pump unit; 2—Pump
3—Constant pressure tank; 4—Filling water
5—Radiant terminal; 6—Outdoor buried pipes
7 to 14 —Valve

Fig. 1 Diagram of ground-source heat pump radiant heating/cooling system

Received 2011-03-15.

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Foundation items: The National Natural Science Foundation of China (No. 51036001), the Natural Science Foundation of Jiangsu Province (No. BK2010043).

Citation: Lu Shikui, Zhang Xiaosong. Thermal comfort assessment and energy consumption analysis of ground-source heat pump system combined with radiant heating/cooling[J]. Journal of Southeast University (English Edition), 2012, 28(1): 52 - 57. [doi: 10.3969/j.issn.1003 - 7985.2012.01.010]

air conditioning terminal system. The geothermal exchange system includes buried horizontal pipes, circulating pump, and pipelines. The air-conditioning terminal system includes radiation coils, circulating pump, and pipelines.

When the room temperature is high in summer, the system starts the cooling cycle, and valves 7, 9, 11, 13 are on. Chilled return water in radiant coils enters inlet A of the water chilling unit via valve 9, and chiller refrigerant in the evaporator absorbs the heat emitted by them. Chilled water which is cooled passes chilled water exit B, then reaches flow pipes and the radiant coils in the room via valve 7. Water in buried pipes enters cooling water inlet C via valve 11, then reaches buried pipes through cooling water outlet D via valve 13 after absorbing heat, and heat will release to the ground.

When the room temperature is low in winter, the system starts the heating cycle, and vavles 8, 10, 12, 14 are on. Cooling return water in radiant coils enters cooling-water inlet C of the water chilling unit via valve 10. Water absorbs the heat emitted by the refrigerant in the condenser. Cooling water which is heated passes cooling water exit D then reaches the flow pipes and the radiant coils in the room via valve 8. The refrigerant which has released heat in the condenser will arrive at the evaporator through a throttle, and then exchanges the heat with water which flows from buried pipes through chilled water entrance A via valve 12 to the evaporator. Then the water returns to the buried pipes through chilled water exit B via valve 14, then absorbs heat from soil [5].

2 Design of Ground-Source Heat Pump Radiant Air-Condition System

2.1 Project overview

The detailed construction schematic diagram of the hall is shown in Fig. 2, which is 36 m in length, 16 m in width,

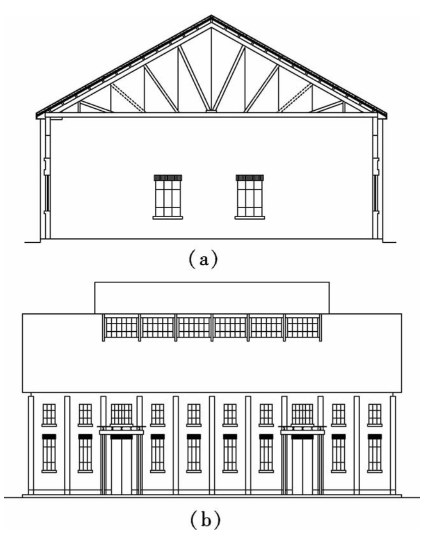

Fig. 2 Schematic diagram of Xijindu exhibition hall. (a) Elevation of the East; (b) Elevation of the North

and 9.4 m in height. The height of the tilted roof is 4 m. The construction area is 576 m^2. The outer wall is composed of a 40-mm thick polystyrene foam board plus a 20-mm thick cement mortar. The roof is composed of a 12-mm thick corrugated aluminum roof board plus a 50-mm thick polystyrene foam board. The cooling load in summer is 47.5 kW, and the heat load in winter is 40 kW.

2.2 Design of ground-source heat pump system combined with radiant heating/cooling

1) Extraventricular geothermal exchange system

The area of available ground surface is about 1 200 m^2. Because the shallow rock soil temperature and the thermal properties are less influenced by climate, rainfall and planted depth, we can use horizontal buried pipes due to the smaller initial investment required. There are three layers of horizontal buried pipes. The depths of the first, the second and the third layers are 2.5, 4.0 and 5.5 m, respectively, and the pipe spacing is 0.7 m. The total pipe length is about 2 400 m in serial and monolayer. The pipe layout is shown in Fig. 3.

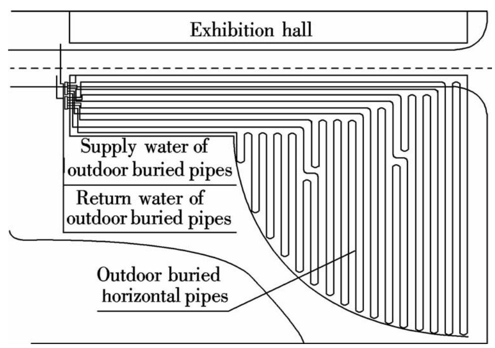

Fig. 3 Disposal of buried horizontal pipes

2) Ground-source heat pump

This project chooses one small ground source heat pump unit. Technical parameters are given as follows: in summer, the cooling capacity is 55 kW, and the refrigeration input power is 11 kW; in winter, the thermal capacity is 57.4 kW, and the heat input power is 13.8 kW. When used for radiant cooling, the designed outlet cooled water temperature is 13 ℃ and the inlet water temperature is 17 ℃ in summer. When used for radiant heating, the outlet heating water temperature is 45 ℃ and the inlet water temperature is 35 ℃ in winter.

3) Radiant heating/cooling system

The building covers an available area of 576 m^2. According to design technology rules, the hall is divided into 27 intervals and each interval is about 20 m^2. Choose a 20-mm diameter PE-X pipe as the radiation pipe, which is laid according to the Chinese word "回". The tube spacing is 200 mm and the spacing of the pipe tube against the wall is 150 mm (see Fig. 4).

4) Control strategy

The air-conditioning system installed with a temperature

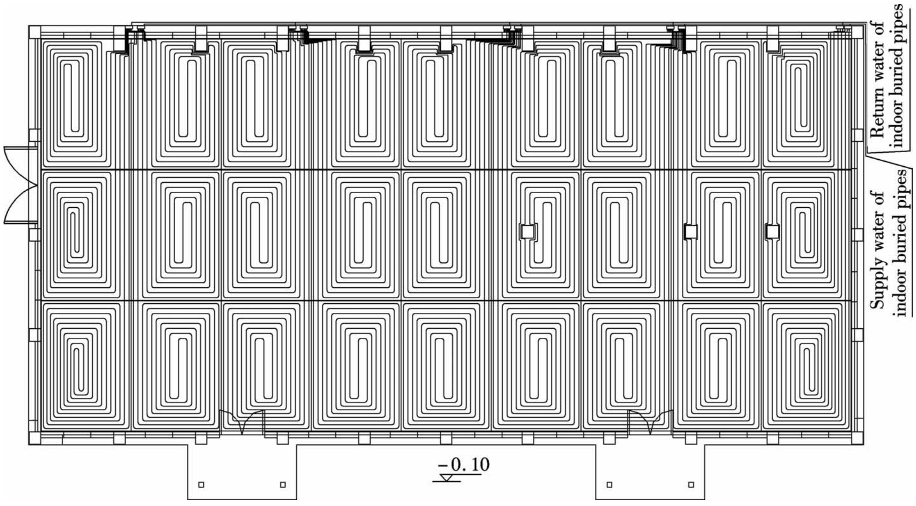

Fig. 4 Disposal of floor radiant pipes

controller will start when the room temperature is below 16 ℃ or over 26 ℃. In summer, we can use the ventilation system to avoid feeling hot and condensation caused by excessive air humidity. In addition, the fresh air into the room after dehumidification can bear a certain amount of sensible heat load[6].

3 Analysis of Ground-Source Heat Pump System with Radiat Heating/Cooling

3.1 TRNSYS software

TRNSYS software is a modular dynamic simulation software, the so-called modular, that is, all the systems is composed of a number of components (labeled Type), and each component has a particular function. They are produced by FORTRAN language and assigned in the data base. Each component has an independent type serial number to make FORTRAN subroutines be associated with it. This component structure has a great deal of flexibility, and it is easy to increase new components in the standard TRNSYS data base. In addition, it is very suitable for analyzing a system which depends on the time process. Each component has a range of parameters, which produce the output based on the time relying on the input of the time. The output of a component can be used as its own or the input of other components since the system components can link to each other. As a result, as long as doing the system simulation analysis, we just choose these special function components and give inputs, and then we can carry out simulation analysis of the system[7].

3.2 Building simulation platform

Using TRNSYS simulation software, a simulation platform of the ground-source heat pump system combined with radiant cooling is built (see Fig. 5).

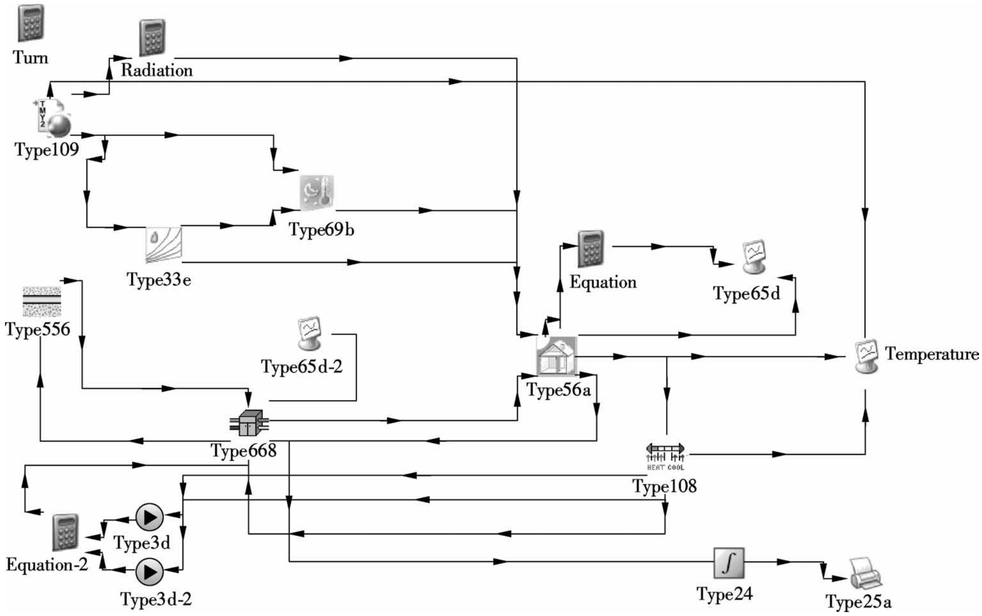

Fig. 5 Simulation diagram of ground-source heat pump system with radiant heating/cooling

In order to run the simulation system, it is necessary to assign the meteorological parameters. Type109, Type69b, Type33e are used to realize the input of meteorological parameters in Type56a. Type109, the meteorological data file, is based on its use in Nanjing, China, which is the meteorological data with a one-year time span and per hour steps. Type69b is used to provide a fictive sky temperature to Type56a. Type33e provides the thermodynamic property parameters of moist air such as dry-bulb temperature, dew point temperature, wet bulb temperature, and the relative humidity to Type56a.

Type108 is a room temperature controller. When the room temperature is lower than 16 ℃, it brings the heating signal to the heat pump to start the heating cycle; when room temperature is higher than 26 ℃, it brings the cooling signal to the heat pump to start the refrigeration cycle. The room temperature controller generates a refrigeration or a heating signal.

Type668, Type556, Type3d are the main components to achieve heat collection. Type668 is a water-water heat pump. When the temperature controller instructs it to open, it supplies cold water in the summer and hot water in the winter. Type556 is a ground pipe heat exchanger. Type3d is a circulation pump.

3.3 Evaluation of thermal comfort

3.3.1 Evaluation of radiant heating in winter[8]

In winter, simulation analysis focuses on 0 to 730 h in January for radiant heating without the mechanical ventilation. In the control strategy, the times of infiltration ventilation is 0.2/h. The comfort status of the room using the radiant floor system and the radiant ceiling system are simulated in Fig. 6 and Fig. 7, respectively.

From Figs. 6 and 7, it can be seen that the room temperature can be maintained at around 18 ℃ in both the radiant floor system and the radiant ceiling system. It can also be found that the PMV is about 0.3, and the PPD is about 8% for the radiant ceiling system and 10% for the radiant floor system. These all meet the ISO 7730 of the PMV-PPD values (The PMV value is between −0.5 to 0.5 and the PPD is less than 10%). It can achieve good comfort in winter without mechanical ventilation.

3.3.2 Evaluation of radiant cooling in summer

Fig. 8 shows the simulation results in summer without mechanical ventilation, which covers 4 380 to 5 110 h in July.

From Fig. 8, it can be seen that the room temperature can be maintained at around 25 ℃. The PMV is about 1.5 and the PPD is approximately 45%. The results cannot meet the ISO 7730 for the PMV-PPD recommended indicators. The reason is that there is no use of the ventilation system, and the indoor air flow rate is low and the indoor air humidity is high. As shown in Fig. 8, most of the relative humidity reaches 100%. Excessive humidity leads to an increase in skin moisture, and the skin feels "stickiness" resulting in thermal discomfort.

Considering ventilation, the time of infiltration ventilation

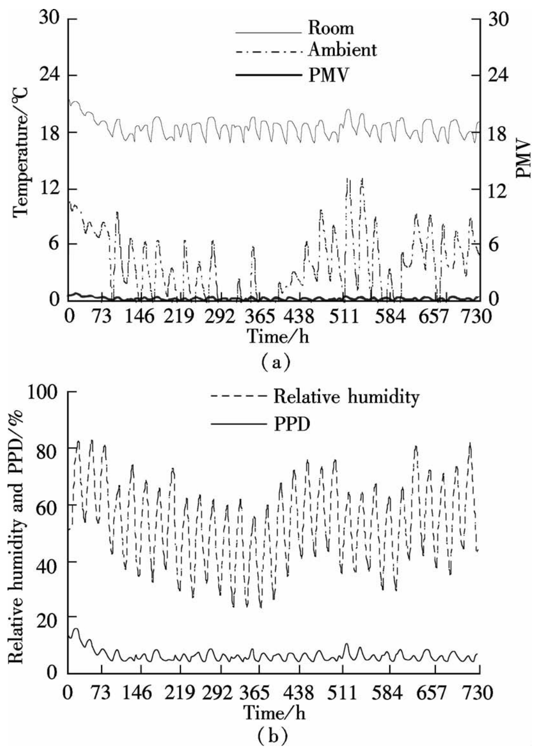

Fig. 6 Simulation results of ground source heat pump with radiant floor system in winter. (a) Temperature and PMV; (b) Relative humidity and PPD

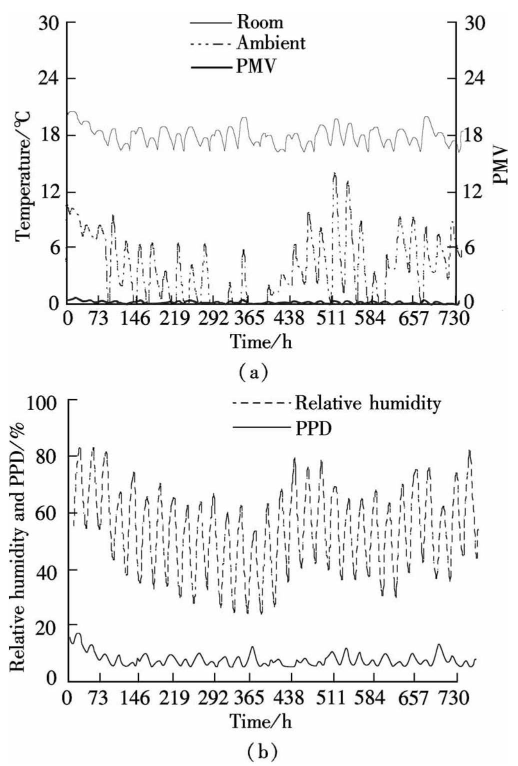

Fig. 7 Simulation results of ground source heat pump with radiant ceiling system in winter. (a) Temperature and PMV; (b) Relative humidity and PPD

is 0.2/h and the time of mechanical ventilation is 7/h from six o'clock in the morning to 18 o'clock[8]. The results are shown in Fig. 9.

From Fig. 9, it can be seen that the room temperature in summer can be maintained at around 24 ℃ with the PMV around 0.5 and the PPD about 10%. It can meet the PMV-PPD values of the ISO 7730. Furthermore, using the radiant ceiling method, we also have a similar thermal comfort.

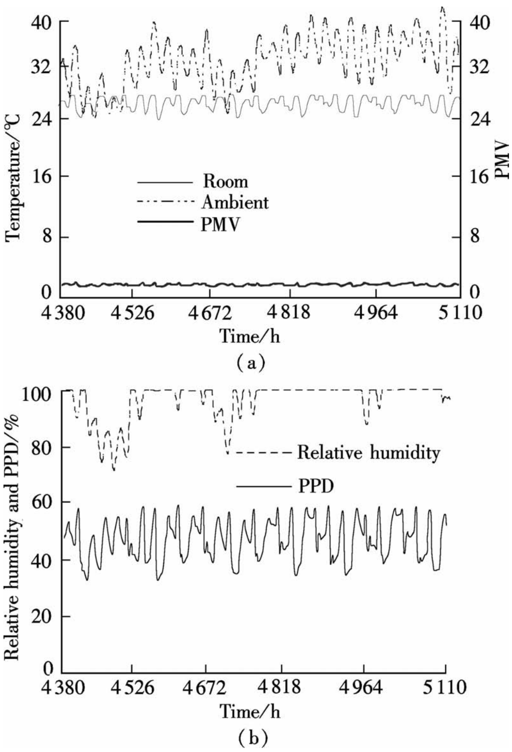

Fig. 8 Simulation results of ground source heat pump with radiant floor system in summer without mechanical ventilation. (a) Temperature and PMV; (b) Relative humidity and PPD

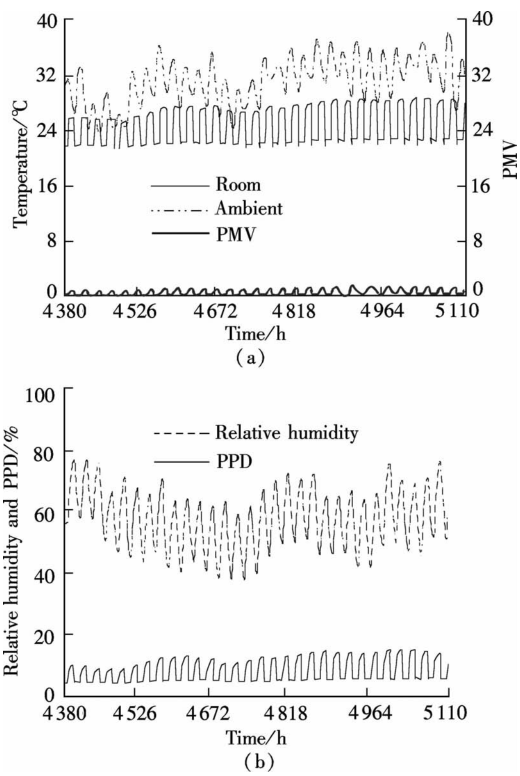

Fig. 9 Simulation results of ground-source heat pump with radiant floor system in summer using mechanical ventilation. (a) Temperature and PMV; (b) Relative humidity and PPD

3.4 Evaluation of energy consumption

Fig. 10 shows the comparison of the energy consumption of the radiant floor system with the radiant ceiling system at the same thermal comfort level in the room. The heat pump power is cumulated per month[9].

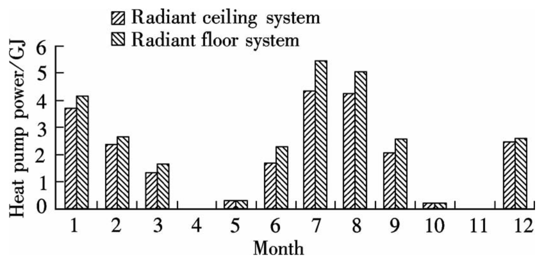

Fig. 10 Comparison of energy consumption

From Fig. 10, it can be seen that the energy consumption per month of the radiant floor system is greater than the radiant ceiling system at the same thermal comfort level in the room. The annual total energy consumption of the radiant floor system is 26.9 GJ, but that of the radiant ceiling system is 22.3 GJ, namely, the energy consumption of the radiant floor system is about 16% more than that of the radiant ceiling system system. However, the form and construction of the radiant floor system is simpler than that of the radiant ceiling and the cost of the radiant floor system is also much lower. When choosing the radiation plate, the techno-economic conditions should be considered.

4 Conclusions

This paper introduces the application of the ground-source heat pump air-conditioning system in a practical project. Through the analyses, the following conclusions can be drawn:

1) The engineering application of the ground-source heat pump air-conditioning system combined with radiant heating/cooling is feasible and successful. It uses renewable energy and has the advantages such as high efficiency, significant environmental benefits, and notable energy-saving effect, etc.

2) The system with the radiant floor method or the radiant ceiling method can provide good thermal comfort without mechanical ventilation in winter. However, the system with either of the methods must use mechanical ventilation in summer, and then thermal comfort can be achieved.

3) At the same level of thermal comfort, the annual energy consumption of the radiant ceiling method is less than that of the radiant floor method.

References

[1] Wang Zijie. *Low-temperature radiant heating and radiation cooling* [M]. Beijing: Mechanical Industry Press, 2004: 201 − 220. (in Chinese)

[2] Conroy C L, Mumma S A. Ceiling radiant cooling panels as a viable distributed parallel sensible cooling technology integrated with dedicated outdoor air systems [J]. *ASHRAE Transactions*, 2001, **107**(1): 578 − 585.

[3] Mumma S A. Chilled ceiling in parallel with dedicated outdoor air systems: addressing the concerns of condensation[J]. *ASHRAE Transactions*, 2002, **108**(2): 220 − 231.

[4] Lu Shikui, Zhang Xiaosong. Independent humidity control air conditioning systems combined liquid desiccant with radiant cooling[J]. *Journal of Chemical Industry and Engineering*, 2006, **57**(Sup): 101 − 105. (in Chinese)

[5] Zogou O, Stamatelos A. Optimization of thermal performance of a building with ground source heat pump system[J]. *Energy Conversation and Management*, 2007, **48**(11): 2853 − 2863.

[6] Memon R A, Chirarattananon S, Vangtook P. Thermal comfort assessment and application of radiant cooling: A case study [J]. *Building and Environment*, 2008, **43**(7): 1185 − 1196.

[7] Strand R K, Baumgartner K T. Modeling radiant heating and cooling systems: integration with a whole-building simulation program strand [J]. *Energy and Buildings*, 2005, **37**(4): 389 − 397.

[8] Song D, Kim T, Song S, et al. Performance evaluation of a radiant floor cooling system integrated with dehumidified ventilation[J]. *Applied Thermal Engineering*, 2008, **28**(12): 1299 − 1311.

[9] Strand R K. Investigation of a condenser-linked radiant cooling system using a heat balance based energy simulation program[J]. *ASHRAE Transactions*, 2003, **109**(2): 647 − 655.

地源热泵-辐射供冷/暖复合空调系统的热舒适度评价和能耗分析

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摘要:提出了一种新型的地源热泵-辐射供冷/暖复合空调系统,分析了该系统的原理和特点. 该系统被应用于镇江西津渡展览馆中,并利用 TRNSYS 软件对其热舒适度和能耗进行了模拟分析. 结果表明,地源热泵-辐射供冷暖复合空调系统在冬季采暖运行时,地板辐射和顶板辐射方式均具有良好的热舒适度,且无须采用机械通风;在夏季空调运行时,地板辐射和顶板辐射必须配合合理的机械通风,才能具有良好的热舒适度;在同样的热舒适度条件下,顶板辐射供冷/暖的全年能耗比地板辐射低.

关键词:地源热泵;辐射供冷/暖;热舒适度;能耗

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