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THE EXPERIMENT OF A NEW TYPE OF BUILDING INTEGRATED SOLAR RADIANT HEATING SYSTEM

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Abstract

A heat pipe radiant heating system is discussed, combined with the building and solar energy by heat pipe. The system is composed with solar collector, heat pipe and radiant heating terminal. The heat pipe delivered the heat of solar absorbed by itself from outdoors to indoor and then heating the room by radiant. This paper adopts a combination of experimental and simulation to test and analysis the system. The results showed that the indoor average temperature can reach above 16℃ during the daytime in winter, and the temperature distribution is uniform. The system is an energy-saving and practical building integrated solar radiant heating system.

Keywords: *solar building, radiant heating, gravity heat pipe, zero-energy consumption*

1. Introduction

In the hot summer and cold winter areas without central heating in China, most buildings use small separated heating equipment such as air conditioning, heaters and electric blankets. However, low operating efficiency and high energy consumption can lead to energy waste and environmental pollution when widely-ranging. Thus, it is essential to find an energy-efficient and comfortable way of heating.

Solar energy is clean and efficient and non-polluting, and the solar thermal technology in buildings has been have a certain development in many countries.

Susheela and Sharp (2001) designed and tested a heat pipe system that could be installed on existing homes without demolishing the wall of the building. The absorber portion was mounted on the outside of a south-facing wall, with water contained in tanks as the thermal mass on the inside of the wall. Experiments were performed outdoors, and system efficiencies (defined as the ratio of power delivered to the room over incident insolation) reached as high as 60% during sunny days. Computer simulations were also performed to model the performance of the unit.

Primarily based on design improvements recommended by Susheela and Sharp, Albanese et al. (2012) tested a bench-scale experimental model. Experimental variations included fluid fill levels, addition of insulation on the adiabatic section of the heat pipe, and fins on the outside of the condenser section. Filling the heat pipe to 120% of the volume of the evaporator section and insulating the adiabatic section achieved a system efficiency of 85%. Addition of fins on the condenser of the heat pipe did not significantly enhance overall performance. The heat pipe system provided substantial gains in performance relative to conventional direct and indirect gain passive solar systems and, thus, presents a promising alternative for reducing building energy use.

To better understand system performance in realistic weather conditions, in particular, the relatively cloudy and cool conditions, Robinson et al. (2013) designed, built and installed a full-scale prototype of the heat pipe system in a classroom on the University of Louisville campus in Louisville, KY. During the spring heating season of 2010 (January–April), maximum daily peak thermal efficiency was 83.7% and average daily peak thermal efficiency was 61.4%. The maximum hourly average room gain achieved during the season was 163 W/m^2. On days with good solar insolation, the thermal storage was heated to temperatures

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sufficient to provide significant energy to the classroom – even during the coldest days of the season. During the longest period (4 days) of low insolation during the season, average hourly heat delivery to the room from storage remained positive, and was never less than 16.6 W/m^2.

Operation temperature of solar heating systems makes the use of a radiant floor to transfer heat into the conditioned spaces suitable. Compared with thermal storage wall, temperature radiant floor heating system has more advantages in terms of indoor thermal comfort. In recent years, the application of heat pipe in solar radiant heating becomes more and more.

Manillez et al. (2005) studied and tested the solar floor radiant heating system that 15.36m^2 collector to meet the heating and hot water load of 172m^2 room. The solar fraction recorded this day was of 0.468, that is, solar energy supplied 46.8% of the combined heating and hot water loads, one of the highest solar fractions of the season.

Zhang Yufeng et al. (2006) studied the performance of a carbon-steel/water thermosyphon and applied it to low-temperature under-floor heating system. Experimental investigation has been done to find out the effect of inclination angle (-4°~90°), evaporative length (30~180mm), temperature (40~60 ℃), flow rate (0.1~0.3m^3/h) and flow direction (forward flow, counter flow) of hot water on thermosyphon performance. The evaporator section of the carbon-steel tube is heated by hot water while its condenser section is cooled by air. Experimental results indicate that the thermosyphon performance with counter flow is much better than that with forward flow. The heat transfer rate and surface temperature of condenser section increase with the rise of hot water temperature and flow rate. With increasing inclination angle and evaporative length, heat transfer rate and surface temperature increase at first, and then start to decline after attaining their maxima. This thermosyphon works well in all experimental conditions, and it yields the highest thermal performance with the evaporative length of 120mm, inclination angle of 38°, flow rate of 0.3m^3/h, temperature of 60℃, and counter flow of heating water.

The existing experimental studies about heat pipe radiant heating systems with water, the heat transfer loss is inevitable between the water and heat pipe. Besides, the pump needs energy consumption. The building integrated solar radiant heating system can reduce the irreversible loss and improve energy efficiency. The system absorbs solar thermal by heat pipe and heating the room directly by radiant without any power consumption when the solar radiation is enough. This paper will analyse the indoor temperature distribution of the system, and the influence of evaporative length and quantity of working fluid on the performance of heat pipe to further explore the method of improving the syetem efficiency and indoor thermal comfort.

2. Experimental study

2.1. System introduction

The building integrated solar radiant heating system is composed of an outdoor heat collector, an indoor heat release module and heat pipes as Fig. 1 shows. The system uses heat pipes as heat transfer component. The evaporator section is placed in the solar collector. While the temperature rose, the working fluid inside the evaporator section absorbs the heat and evaporates to gas and run into the condenser section. When the gas enters into the condenser of heat pipe, it will sent heat into the indoor air and then turn into liquid, finally it will return back to the evaporator of the heat pipe. Then the new cycle will carry on and solar energy will be transferred into the room. In order to prevent heat transfer from indoor to outside, we use the gravity heat pipe with a thermal diode effect.

Compared with the traditional solar hot water floor radiant heating system, the heat pipe radiant heating system directly transmitted the solar thermal energy for indoor radiant heating without the middle transfer medium, which will reduce the irreversible loss of heat transfer between water and working fluid and improve the utilization rate of solar energy. The system is suitable for office buildings, kindergartens and secondary school classrooms and other daytime office spaces, and it can provide the basis for residential heating temperature, reduce fuel consumption.

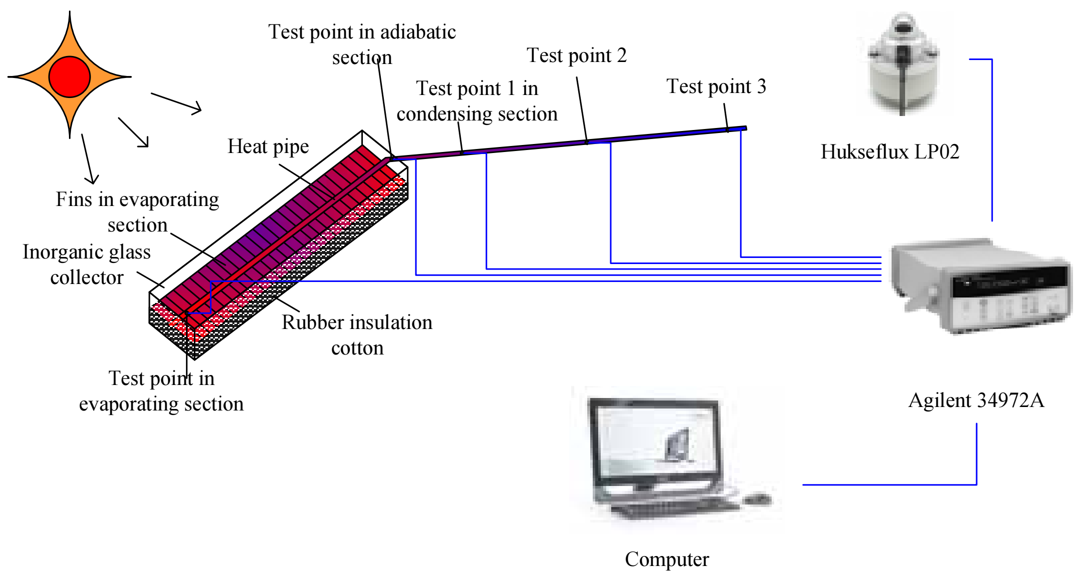
The gravity heat pipe used in the system is 3.12m in total length, and the evaporator section is about 1.8m with 8mm outer diameter, the condenser section is 1.2m with 12mm outer diameter, the insulation section is 120mm with 12mm outer diameter. The working fluid of the gravity heat pipe is R600a and the tube of heat pipe is made of cooper with 1mm thickness of pipe wall. The collector part is basically the same as the ordinary plate type solar collector, that mainly consisted by the collector body, heat insulation material, heat absorbing layer and the transparent glass cover. The heat absorbing layer is the core design of the system, which is borne by the evaporator section of heat pipe with fins. The surface of fins is planted with a blue film, and it wrap up the heat pipe in 360° to absorb the maximum possible radiation and to raise the working fluid temperature. Between the heat pipe and the frame, 60mm thickness insulation cotton is used to keep the heat, and on the top of the collector, the organic transparent glass is used to transfer solar sunshine.

2.2. Test method

The experimental testing system is composed of two parts:

(1) Tests of heat transfer performance of single heat pipe

The experimental test system is shown as Fig.1. a HuksefluxLP02 short wave radiation sensor is used to measure insolation values with and the sensitivity of 12.13μV/(w•m^{-2}). Fluke hot wire anemometer is used to measure the wind speed with the sensitivity of 0.01m/s, twenty J-type thermocouples were placed in the evaporator and condenser respectively, to assess temperature difference between of them at the same time. Another one J-type thermocouples was placed outside to measure ambient air temperature. All data was collected using Agilent 34972 a.



(2) Tests of building integrated solar radiant heating system

The installation of gravity heat pipe of the system is shown as Fig.2. The GHPRHS prototype was fabricated, which used a plate solar collector as evaporator. The collector was consisted of nine copper tubes (10mm diameter) wrapped with fins soldered on the rubber insulation cotton (40mm thick). The dimension of the fins was 138mm×180mm×1mm. The total length of the each heat pipe was 3 m. and the diameter of the condenser was 12mm. The total surface area of the collector was 2.2 m^2. The fin surface was a selective black coating surface. The 2m×1.4m glazing consisted of 3.18 mm thick glass with an anti-reflective coating. At the indoor section, the copper pipe was fixed on the groove of the insulating material with the distance of 200mm between of them, which was covered with aluminum sheet with high thermal conductivity. In addition, 40mm thick insulation layer was put on the floor to avoid the heat loss from the floor. Above these heat pipes, laminate flooring was put on in order to simulate the real floor. The whole indoor surface area was 2.4m^2. All the condenser of the heat pipes were mounted at 5° from the horizontal.

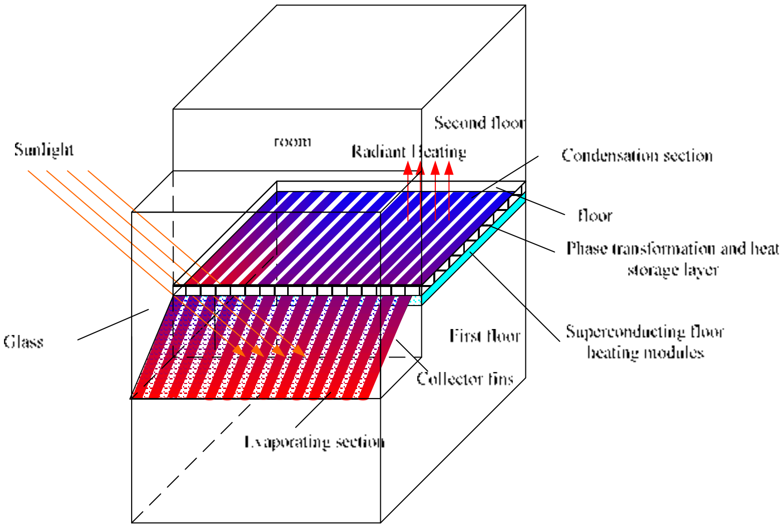


Fig. 2: The installation of the building integrated solar radiant heating system

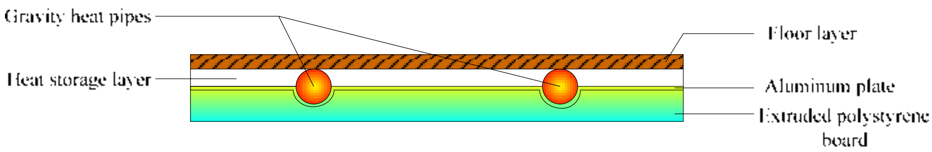


Fig. 3: The structure of indoor radiant heating model

3. Results and discussion

3.1. Theoretical model

Traditional evaluation method of heat pipe heat transfer performance is to compare the equivalent heat conduction coefficient, its mathematical expression is:

$$\lambda_{eff} = \frac{4L^2}{{d_0}^2} \cdot \left[\frac{1}{\left(\frac{\ln(d_0/d_i)}{2e}\right) + \frac{\lambda}{\alpha_e d_f e} + \frac{\lambda}{\alpha_c d_f c} + \frac{\ln(d_0/d_i)}{2c}}\right] \cdot \lambda \qquad \text{(eq. 1)}$$

The equivalent heat conduction coefficient is directly evaluated, and the parameters are easy to be measured. However, it still has shortcomings. By the formula, the longer the heat pipe is and the smaller the diameter is, the equivalent heat conduction coefficient will be high even if the heat transfer coefficient of the evaporating and condensating section are not high, especially for heat pipe with long length. This is exactly the deficiency of the equivalent heat conduction coefficient. The equivalent convection heat transfer coefficient is introduced to the model by Yu Tao(2008) and establish the formula as follow:

$$\alpha_{eff} = \frac{2\lambda Q(L_c+L_e)}{2\pi\lambda d_i(T_e-T_c)L_cL_e - Qd_i(L_c+L_e)\ln(d_0/d_i)} \qquad \text{(eq. 2)}$$

Here, α_{eff} is a weighted average of the boiling heat transfer coefficient and the condensation heat transfer coefficient, which is a comprehensive reflection of boiling and condensation heat transfer processes in the heat pipe. Besides, the right parameters of eq.2 can be obtained by measurement. Therefore, it is objective to evaluate the heat transfer performance, especially the gravity heat pipe by the equivalent convection heat transfer coefficient.

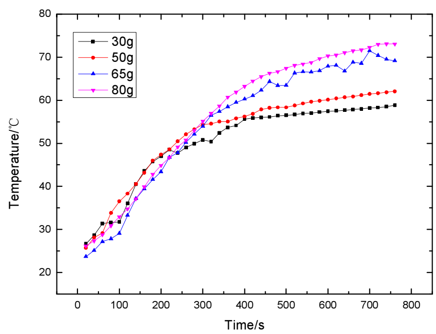
3.2. Heat transfer analysis of heat pipe with different charging ratio

Fluid charging rate is an important parameter to study the heat transfer performance of gravity heat pipe. When charging rate is too low, heat pipe will appear dry phenomenon; and when it is too high, heat pipe will appear boiling limit. The existing researches showed that the appropriate charging rate for heat pipe is between 30%~ 80%. Therefore, this experimental study on the filling rate in this range to observe the variation of heat transfer performance with the charging rate of two phase flow heat pipe, and provide a theoretical and experimental basis for the heat pipe radiant heating system.

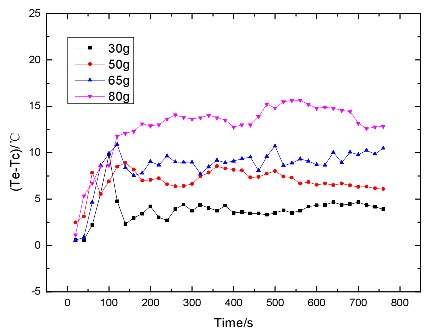
A series of daily outdoor tests have been performed, the amount of working fluid was varied in the range of 30g-80g corresponding to a ratio of fill charge volume to inner volume of the evaporator zone range of 30%-80%. The variation are given in Fig.5 including temperature in the condensing section, temperature difference of evaporating and condensing section and the equivalent convection heat transfer coefficient, the variation of temperature difference of evaporating and condensing section, the variation of the equivalent convection heat transfer coefficient with time in the same solar irradiance. It can be seen in Fig. (a) that the higher the charging ratio, the higher the temperature of condensing section after the start-up process. It's because the condensate film is the main factor to affect the heat resistance in condensing section in the same solar irradiance. The steam quantity follows the same trend as the charging ratio increasing, more steam generated in the evaporating section, the more steam be condensed in the condensing section, which will increase the thickness of condensate film and heat transfer thermal resistance. In addition, higher charging ratio made the steam flow faster and the friction between the steam and liquid film increasing, which will also increase the thickness of condensate film and is unfavourable to the heat transfer in the condensing section. While the condensation heat transfer coefficient decreases, the amount of steam generated by the evaporation section increases, leading to the rise of tube wall temperature of condensing section.

Fig.(b) shows that the temperature difference between the evaporating and condensing section are all increased first and then decreased and tend to be stable with different charging ratio. This is because the heat pipe needs time to start-up, and the evaporating temperature rise sharply in start-up time while the condensing temperature rise gradually after the steam reached a certain value in evaporating section. Higher charging ratio needs more time to start-up. Therefore, the time of temperature difference tends to be stable is shortest when the fluid amount is 30g in Fig.(b). It also can be seen from Fig.(b) that the temperature difference between the evaporating and condensing section is bigger with more charging ratio. This is because high charging ratio will lead more steam generated in the evaporating section and the condensing liquid in the condensing section increased, and the temperature of condensing liquid is always lower than that of the boiling liquid in evaporating liquid pool, which will reduce the temperature of tube wall of condensing section.

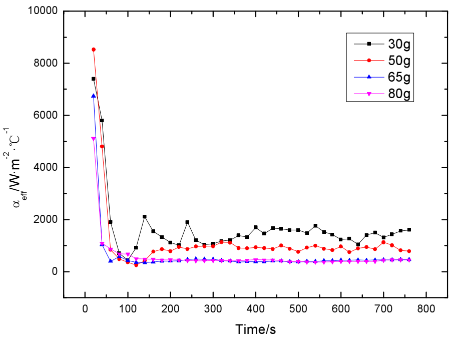
Fig.(c) shows that the equivalent heat transfer coefficient decreased with the increase of charging ratio. This is because when the charging ratio is low, the liquid level of liquid pool in the evaporating section is low and the heat transfer resistance is small which is beneficial to the liquid boiling in the liquid pool and the heat transfer coefficient of evaporating section is relatively large. However, when the charging ratio is higher, the liquid level of liquid pool increased and the heat transfer thermal resistance is larger, which decrease the velocity of bubble movement in the evaporating section and reduce the boiling heat transfer in the liquid pool, so that the heat transfer coefficient of evaporating section is reduced. Besides, the condensation heat transfer coefficient is also decreased with the increase of liquid charging ratio, and the equivalent convective heat transfer coefficient is the comprehensive reflection of the evaporating and condensing section, so the equivalent convection heat transfer coefficient decreased with the increase of liquid charging ratio.



(a)Variation of temperature in the condensing section



(b) Variation of temperature difference of evaporating and condensing section



(c) Variation of the equivalent convection heat transfer coefficient with time

Fig.5 The curve of heat transfer performance of heat pipe with different charging ratio

Table 1 is the calculated data of heat pipe heat transfer performance in different charging ratio. According to the data, the higher the charging ratio is, the smaller the heat transfer coefficient of condensing section, which is consistent with the analysis in Figure 5. However, the higher the working quality of the evaporation section, the more quantity of condensing heat release and the higher the solar thermal utilization rate of the heat pipe. This is because the temperature of tube wall of condensing section increases with the increase of working fluid, which lead to the temperature difference between the tube wall and the steam inside larger. Compared with the heat transfer coefficient, the temperature difference has a greater impact on the condensing heat release. Therefore, the higher charging ratio can lead to more quantity of condensing heat release, as a result, the solar thermal utilization rate of heat pipe can be higher with the high charging ratio.

Although the higher charging ratio brings the more heat energy from the condensing section, and will probably lead to the overheating of the condensing section. It can be seen from Fig.2 that the temperature of tube wall of condensing section can be up to 70℃ when the charging ratio is 60% and 80%. However, the tube wall temperature of indoor heating pipe should not be higher than 60℃ according to relevant regulations (2008). Indoor heating temperature is too high to get human thermal comfort with the local overheating. Comprehensively considering the heat pipe condensing temperature and heat release, the best liquid charging ratio is about 45%~50% in the system, with highest pipe wall temperature about 60℃ and the heat quantity about 70W highest pipe wall temperature is about 60℃ and the heat quantity is about 70W.

Tab. 1: Table of heat transfer performance in different charging ratio

Quantity of working fluid	Filling radio	t_v/℃	t_w/℃	h_c/W·(m^{-2}K^{-1})	Q′	η
30g	30%	59.5	57.2	565.53	58.8	0.341
50g	45%	63.1	59.7	426.78	66.8	0.402
65g	60%	72.3	66.1	325.24	98.7	0.473
80g	75%	78.1	69.2	259.08	178.1	0.823

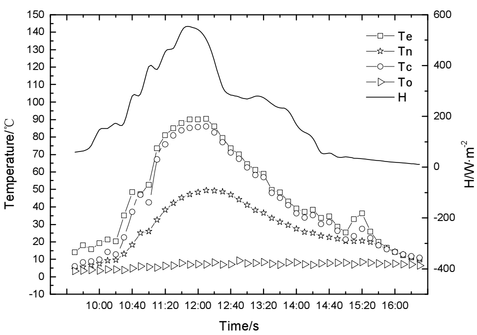
3.3. Heat transfer and indoor thermal environment analysis of the radiant heating system

The experimental data were collected continuously under the condition of sunny days in winter in Nanjing.

Figure 6 shows the variation of indoor and outdoor parameters with time. It can be seen from the figure that the variation trends of the evaporating and condensing temperature are consistent, which increase and decrease with the solar irradiance. When the solar irradiance is about 100W/m^2, the heat pipes began to start-up and the evaporating and condensing temperature gradually increased, and it reached a maximum at 12:00 and then decrease. After about 16:00, the condensing and the indoor temperature tend to be equal and the heating collect is ineffective. In winter, the effective heating time is about 6 hours from 10:00 to 16:00. During 11:30 to 12:30, the solar irradiation has high intensity, and the temperature of condensing section is so high that leading the indoor temperature above 35℃. This is due to the non-thermal storage wall and without heat storage material in the experimental room, and the heat storage material will be added to reduce the indoor temperature and maintain the human comfortable temperature.

Comparing the indoor air temperature and outdoor air temperature variation curves in figure 6, the outdoor air temperature is in range of 3.5~9.2℃ with the average temperature 6.9℃, while the indoor average temperature is 22.5℃, the average temperature difference can reach about 15℃. The results show that the indoor air temperature is greatly improved under the building integrated solar radiant heating system.

Figure 7 shows the curve of indoor temperature during the effective heating time, the two curves are respectively gained by the average value at the height of 1.0m and 1.7m in the room. The results show that the temperature difference is relatively small, which is very small with the variation range from 0.01℃ to 0.77℃. Therefore, the air temperature distribution in the room is relatively uniform and no obvious temperature stratification appears. Compared with the system proposed by Ji Jie(2011), the floor radiant heating system has a more uniform temperature field distribution and the indoor thermal comfort is higher.



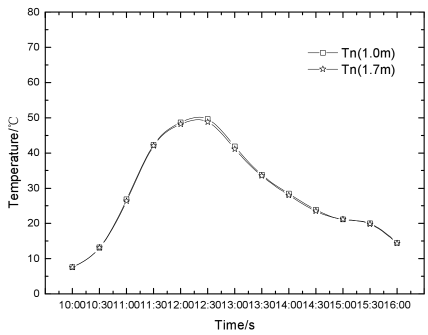


Fig.6 Variation of parameters versus time of indoor and outdoor

Fig.7 Variation of temperatures of air in the room versus time

From the analysis above, it shows that the system can run normally in sunny days and is an economic, environmentally friendly, and effective passive solar heating system. The indoor temperature can reach up to 20℃ in 30 minutes under the irradiance of 400W/m^2, while the outside temperature is around 5~6℃. Therefore, in the regions with abundant light supply, even if the outdoor temperature is very low, the system is still able to meet the needs of winter indoor heating with good heat-preservation wall.

Nomenclature

α_{eff}	equivalent convection heat transfer coefficient	d_0	outer diameter of heat pipe
λ	heat transfer coefficient of pipe shell	d_i	internal diameter of heat pipe
Q	heat flux of heat pipe	t_v	steam temperature in heat pipe
L_c	length of condensing section	t_w	tube wall temperature of heat pipe
L_e	length of evaporating section	h_c	heat transfer coefficient
T_e	temperature of evaporating section	Q'	heat release of condensing section
T_c	temperature of condensing section	η	solar thermal utilization

4. Conclusion

This work focuses on the testing of the performance of gravity assisted heat pipe and the radiant heating system, and gets the following conclusions:

(1) Charging ratio has a great impact on the performance of gravity heat pipe. The equivalent heat transfer coefficient decreased with the increase of charging ratio, while the quantity of heat release rose with charging ratio. Comprehensively considering the heat pipe condensing temperature and heat release, the best liquid charging ratio is about 45%~50% in the system, with highest pipe wall temperature about 60℃ and the

heat quantity about 70W highest pipe wall temperature is about 60℃ and the heat quantity is about 70W.

(2) The system is currently only used for indoor heating in winter, and in order to prevent the overheating in summer, installing globe valve on every heat pipe. Latter, the separated heat pipe will be taken to paralleling connect with hot water system in the heating system, which can produce hot water in summer when the heating system stop by the switch of the control valve. In non-heating period, the valve between the heat pipe radiant heating system and the collector will be closed, and the valve between hot water system and the collector will be open. It can also realize the energy saving in summer, using solar collector to heat the water and provide the hot water for life.

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