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Experimental investigation on a ceiling capillary radiant heating system

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Abstract

In this paper, a radiant heating system is introduced, which was developed based on the model of capillary radiant terminal (CRT) combined with solar thermal energy usage and phase change thermal storage (PCTS) technology. The aim of this work is to investigate the feasibility and the stability of the system that could be applied into residential buildings in the actual construction. The indoor thermal environment based on the tested system is analyzed in this paper. According to the weather condition of Xi'an, the winter average solar insolation and the ambient temperature were 9.14 MJ/m^2 and 8.9°C, respectively. The experimental results show that the average heating capacity of the designed system was about 1.08 kW for a typical sunny day in the winter. It was higher than the simulated heating load. As a result, the indoor air temperature reached 18°C, which sufficiently met the requirement of indoor thermal condition. It is also found that the indoor air temperature distributes uniformly and the maximum difference of the vertical temperatures was less than 3.2°C. This indicates that the indoor thermal comfort of the test room can be classified in the comfort level of A.

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Keywords: solar energy; radiant heating; capillary network; PMV and PPD

1. Introduction

With increasingly short energy source and aggravating environment problems, the efficient usage of energy and environment protection have become of the most important issues. The energy consumption in building is one of the biggest portion of the total energy demand in China, even in the world. The main reason is high HVAC (Heating Ventilation Air Conditioning) systems energy consumption, especially the cooling and heating applications. It made urgent the search of alternative supply and technical solutions

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are trying to lower the energy consumption and use energy in more efficient ways. Many studies have involved the aforementioned problems in this filed [1-6]. Renewable energy has been paid more attention, being solar thermal energy a very interesting future option [7].

In this paper, an integrated system of solar energy, air source heat pump, PCTS tank and capillary radiant heating system was designed and tested. Nevertheless, the incorporation leads to a more complex system and several problems may occur, which need to be avoided [8]. The aim of this work is to investigate the feasibility and the stability of the designed system that could be applied into residential buildings in the actual construction. The performance of the ceiling radiant heating system is also examined by the indoor thermal comfort level.

Nomenclature

G	global solar radiation, W/m^2	ASHP	air source heat pump
Q_l	heating load, kW	CRT	capillary radiant terminal
Q_s	supply heating capacity, kW	PCTS	phase change thermal storage
T_a	ambient temperature, ^oC	PMV	predicted mean vote
$T_{c,o}$	outlet temperature of solar collector, ^oC	PPD	predicted percentage dissatisfied

2. The experimental setup

2.1 System introduction

The integrated system was composed of thermal collection, storage and release processes. The flow diagram of the whole system is shown in Fig. 1. Water was heated by the solar collectors and heat carried by water was stored in the PCTS tank units. After heat exchange process in the PCTS, water in the radiant system was circulated into the CRT to heat up the space. Air source heat pump (ASHP) served as an auxiliary heating source when heat storage was insufficient in nighttime, cloudy or rainy day.

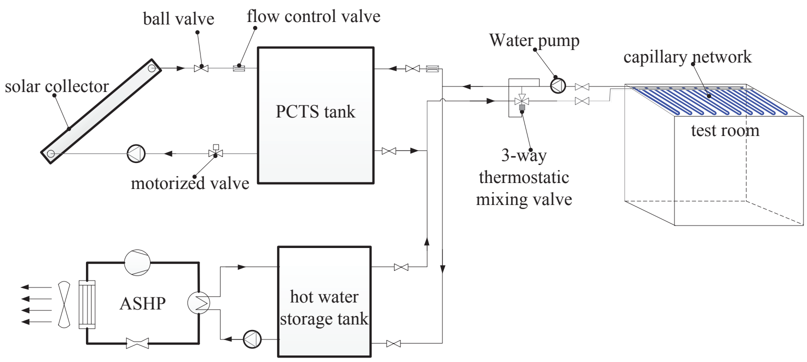


Fig. 1 The flow diagram of the integrated system

2.2 Experimental facility

All glass evacuated tube solar collectors were installed on the building roof in order to capture more solar radiation. The area of collectors is of 16 m^2. An ASHP extracting the heat from the outside air was employed in order to provide continuous and stable heat energy. Thermal energy storage contains the PCTS tank and the water tank. The PCTS tank was connected to the solar collectors to accumulate unstable solar insolation. Hot water storage tank was designed to match the performance of the ASHP.

The experimental CRT, presented in Fig. 2, was equipped with capillary mats using polypropylene as material and was fixed on the ceiling of the test room. The CRT requires much lower inlet temperature to heat up the desired space than that of the traditional heating system, due to its extremely large heating surface. Consequently, the ceiling capillary radiant system would make the best use of low-grade energy (solar energy). In this study, the test room (Fig. 2) was built in a common residential building in order to reproduce as better as possible the characteristics of a real residence with a radiant ceiling system by CRT.

2.3 Measuring system and experimental procedure

The indoor air temperature of the test room was measured using T-type thermocouples and the thermocouple distribution is shown in Fig. 3. The thermocouple holders were not placed near the door

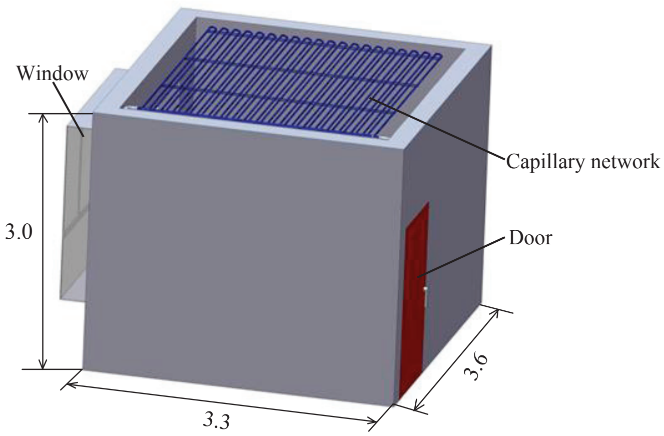
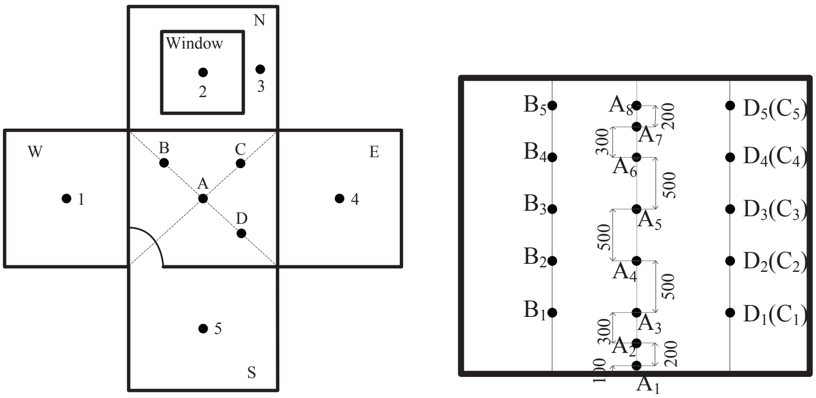


Fig. 2. The model of test room and capillary network (dimensions: m)



(a) Expanded view (b) Elevation view

Fig. 3. Thermocouple distribution in the test room (dimensions: mm)

Table 1. Accuracy of main measurement sensors

Type	Parameter	Unit	Accuracy
TR-72U	Ambient temperature	ºC	±0.3ºC (-20 to 80ºC)
	Outdoor air relative humidity	%RH	±5%RH (at 25ºC, 50% RH)
Swema 05	Black globe temperature	ºC	±0.1ºC (0 to 50ºC)
Swema 03+	Indoor air velocity	m/s	±0.04m/s (at 15 to 30°C)
Hygroclip 2-S	Indoor air humidity	%RH	±0.8%RH (at 23°C)
TBQ-2	Solar radiant intensity	W/m^2	<5%

because of considering the influence of opening the door. Four T-type thermocouple probes were distributed on the middle point of the walls, in order to measure the temperature of each unheated surfaces. All thermocouples were calibrated by using thermostatic bath. The temperature data were recorded at an interval of 40 seconds and stored in computer.

Other measurement sensors and measuring accuracies are shown in Table 1. The ambient temperature and relative humidity were measured by the temperature/humidity recorder (T&D TR-72U). Six PT1000 sensors were used to measure the supply and return temperature of water, including solar collectors, ASHP and capillary radiant system. The black globe temperature, air velocity and humidity were measured by thermal comfort measurement equipment which contained black global radiation thermometer, omni-directional anemometer and air humidity sensor and was located at the level of 1.1 m above the floor. Solar radiation pyranometer, TBQ-2, was used to measure the solar radiant intensity and flow meters (Zenner MTHI) were used to regulate the flow rate of water. The different operating modes system were switched by a temperature controller operated automatically. The different operating modes are as follows: domestic hot water mode, phase change thermal storage heating mode, ASHP heating mode and coupling heating mode. If the outlet temperature of domestic water tank was lower than the required inlet temperature of capillary network, the hot water from PCTS system would mix with the domestic tank water to increase the inlet temperature. The ASHP heating mode was ran only when solar heat storage was not sufficient.

3. Results and discussion

The steady conditions were obtained after two days because the influence of the prior working condition had been hardly eliminated in the measuring procedure. The test procedure was operated continuously. According to the tested results in December 2013, the performance of the experiment and the indoor thermal environment is analyzed in this discussion section.

3.1 Heat collection

Figure 4 shows the variation of ambient temperature, solar radiation and the collector outlet water temperature over a typical-full-day. From this figure it can be noted that the whole day's mean ambient temperature and the collector outlet water temperature were about 8.9ºC and 38.5ºC, respectively. The maximum solar radiation intensity was 528 W/m^2 and average solar insolation was 9.14 MJ/m^2. The variation tendencies of the collector outlet water temperature and solar radiation are in similar shape in the figure, but there is a time gap between the two sets of data. Solar radiant intensity was measured by the solar radiation pyranometer, TBQ-2 which was calibrated before test and paralleled installation with the plate of solar collector. The peak of solar radiation appeared at a quarter past 1 pm, while the maximum of the collector outlet water temperature showed up at about 3 pm. This phase lag trend is observed in the similar tests, which is due to the thermal capacity of water and the time required of heating the water.

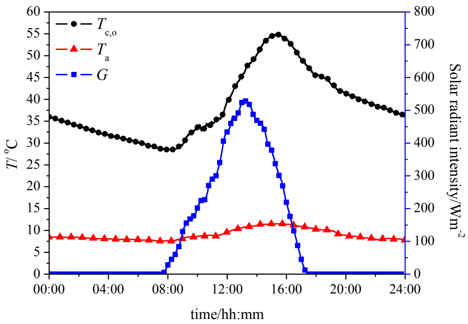


Fig. 4. Variation of temperature and solar radiation intensity

3.2 Capillary radiation heating performance

Figure 5 shows variations of the hourly thermal load Q_l and the heating capacity Q_s. The whole day's thermal load of the test room was simulated by the commercial software DeST. The results of simulation indicate that the average thermal load is about 0.73 kW. When the supply and water temperature was 40°C or 36°C, the average of heating capacity was around 1.08 kW. From the figure we can see that the thermal load was almost constant, while the heating capacity varied relatively significantly with an average value higher than that of the heating load. This implies that the heating capacity from the ceiling radiant system may satisfy the thermal load of the room.

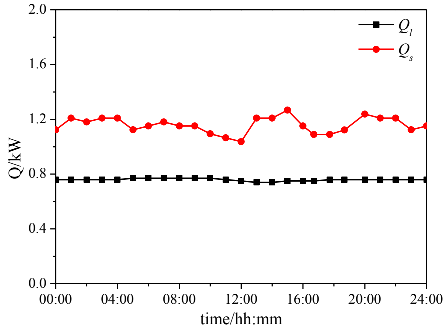


Fig. 5. Variation of the hourly thermal load and the heating capacity

3.3 Test room environment performance

Vertical temperature gradient of the test room is shown in Fig. 6. The temperature difference of the thermocouples along holder A was 2.8°C above the floor from 0.1 to 2.6 m, and was 1.5°C above the floor from 0.1 to 1.1 m. The maximum temperature difference was around 3.2°C. It may sufficiently meet the requirement of indoor thermal comfort.

From the Fig. 6, we also can observe that the temperature above the floor 0.1 m was greater than that above the floor 0.3 m. The radiant heat exchange occurs between the specific surface (heated surface) and all the other surfaces (unheated surfaces) in the room. The convection heat transfer enhances the heat exchange between the specific surface and the air boundary layer [9]. The difference could be attributed to the characteristics of the radiation heating that the heated surface makes a temperature increment to the unheated surface (floor), and then diffuses to the surrounding air. All the temperatures measured on the A-D thermocouple holders exhibited a similar variation trend, as shown in Fig. 6, and the temperatures of the corresponding positions were relatively close. It indicates that the temperature distribution in the test room was rather uniform. Besides, the temperatures measured for the level 0.6 m above the floor on the holder C were near 18ºC because of the influence of the outdoor environment via the external wall. The other indoor air temperatures were higher than 18ºC.

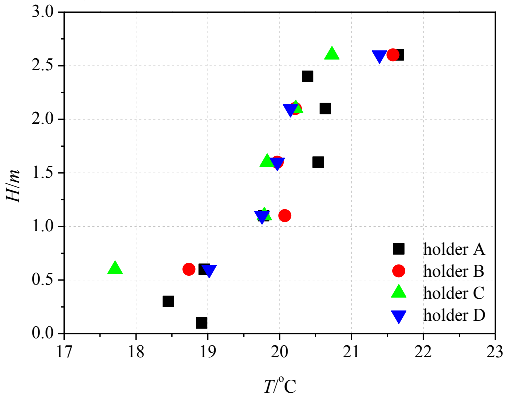


Fig. 6. Vertical temperature gradient distribution of test room

3.4 Indoor thermal comfort

The indexes of PMV and PPD are used to evaluate the general thermal sensation and degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. The PMV is an index that predicts the mean value of the votes of a large group of persons on the range of -3 to +3 corresponding to cold and hot thermal sensation, based on the heat balance of the human body. The PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm.

The calculated values of PMV and PPD are plotted in Fig. 7. During the system operating time, it was assumed that the thermal insulation of clothing was 1.0 clo (1.0 clo = 0.155 $m^2 \cdot {}^oC/W$), while the metabolic rate was 1.2 met (1.2 met = 69.78 W/m^2), which are applied mainly to the sitting activities such as the commercial office and residence in winter. It is observed from the figure that the variation of PMV and PPD remained approximately stable, and the averaged values of PMV and PPD are -0.014 and 5.26%, respectively. According to the three classes of acceptable indoor thermal environment for general comfort, the test results could be classified to class A (- 0.2 < PMV < + 0.2; PPD < 6%) [10].

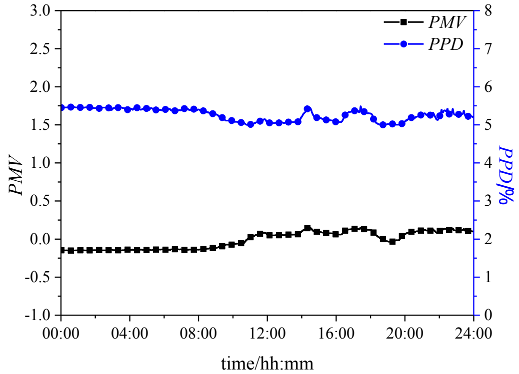


Fig. 7. PMV and PPD of the test room

Conclusion

An experimental study of a ceiling radiant heat system was carried out using solar heat stored from solar collectors. During the system operating time, the supply and return water temperatures were about 40^{o}C and 36^{o}C, respectively, and the ambient temperature was at 8.9^{o}C. The indoor air temperature was greater than 18^{o}C and maintained uniform and stable. The heating capacity of the designed was about 1.08 kW which was greater than the simulated thermal load. It met the demand of heating. The maximum difference of the vertical temperature was lower 3.2^{o}C, while the PMV and PPD was calculated to be -0.014 and 5.26%, respectively, which imply that the thermal comfort of the test room is within class A.

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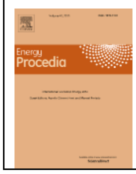

Biography

Prof Liu Xing is currently working at the Department of Building Environment and Energy Engineering of Xi'an Jiaotong University, China. His research efforts focus on the building energy saving technologies and two-phase heat transfer problems.