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Experimental investigation on a solar-powered absorption radiant cooling system

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Abstract

Solar cooling has been proved to be technically feasible. It is particularly an attractive application for solar energy, because of the near coincidence of peak cooling loads with the available solar power. Currently, most of the solar cooling systems commonly used are the hot water driven lithium bromide absorption chillers. Solar absorption cooling systems are available from various reports, in large capacities up to several hundred kilowatts. In this paper, a minitype solar absorption cooling system was designed and installed in Shanghai Jiao tong University. The system mainly contains 96 m2 solar collector arrays, one absorption chiller with the rated cooling capacity of 8 kW, and a heat storage water storage tank of 3 m3 in volume. The chilled water can be delivered either into fan coils or into radiant cooling panels which are installed to satisfy the indoor thermal environment of the test room. As for the fan coil cooling mode, it was found that the average cooling output reached 3.62 kW during 8 h operation under typical weather condition of Shanghai. With regard to radiant cooling mode, an individual fresh air unit was installed for the purpose of preventing the cooling panels from condensation. Compared with the experimental results of the fan coil cooling mode, the average cooling output of the radiant cooling mode reached 4.47 kW, which increased by 23.5%. Furthermore, the PMV inside the test room was between -0.5 and 0.5, which showed great advantage in meeting the indoor thermal comfort.

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Nomenclature

COP	coefficient of performance
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
T1	temperature at low position (^oC)
T2	temperature at middle position (^oC)
T3	temperature at high position (^oC)
Tb	black ball temperature (^oC)
Tchilled-in	inlet temperature of chilled water (^oC)
Tchilled-out	outlet temperature of chilled water (^oC)
Tcooling-in	inlet temperature of cooling water (^oC)
Tcooling-out	outlet temperature of cooling water (^oC)
Thot-in	inlet temperature of hot water (^oC)
Thot-out	outlet temperature of hot water (^oC)

1. Introduction

Energy crisis and environmental pollution are the two serious problems that human is facing. About 30% of the total energy consumption was caused by buildings and this value will be higher in the future with the development of the global economy and people's living standard. Consequently, it is important to exploit renewable energy to save energy; it will meet the sustainable development demand of architectures, energy and the environment.

Solar cooling systems have the advantage of using absolutely harmless working fluids such as water, or solutions of certain salts. They are energy efficient and environmentally safe. They can be used, either as stand-alone systems or with conventional air-conditioning systems, to improve the indoor air quality of all types of buildings [1]. The current technologies in the market for cold water production, using thermal solar energy (SE) are: Absorption machines, solid and liquid desiccant and solid adsorption. The most commercially developed are the absorption systems [2].

As for the experimental researches, S. Rosiek et al. [3] reported the solar-powered single-effect absorption cooling system installed in the Solar Energy Research Center of Spain. For covering the cooling demand, a single-effect absorption chiller with the cooling capacity of 70 kW was chosen. During one year of operation it could be seen that the solar collectors were able to provide sufficient energy to supply the absorption chiller during the summer mode and sufficient to cover the whole heating demand. The average values of COP and the cooling capacity were calculated for summer months, obtaining values of the order of 0.6 and 40 kW respectively. A. Syed et al. [4] investigated a solar cooling system consisting of a 35 kW LiBr/H_2O absorption machine energized by 49.9 m^2 of flat-plate collectors. Thermal energy was stored in a 2 m^3 stratified hot water storage tank during hours of bright sunshine. The generator design of the machine allowed the use of hot water in the temperature range of 65-90 ^oC. The measured maximum instantaneous, daily average and period average COP were 0.60 (at maximum capacity), 0.42 and 0.34, respectively. The daily average collector efficiency (without considering pipe and plate heat exchanger losses) was 0.50. Through the analysis of energy flows in the system, it was demonstrated that the technology worked best in dry and hot climatic conditions where large daily variations in relative humidity and dry bulb temperature prevailed. A. Pongtornkulpanich et al. [5] designed a solar-driven 10-ton LiBr/H_2O single-effect absorption cooling system. It was shown that the 72 m^2 evacuated tube solar collector delivered a yearly average 81% of the thermal energy required by the chiller, with the remaining 19% generated by a LPG-fired backup heating unit. O. Marc et al. [6] presented an experimental study of a solar cooling absorption system implemented in Reunion Island, located in the southern hemisphere near the Capricorn Tropic. The solar cooling system was used to cool the 4 classrooms without any backup system during the occupancy period. It was reported that thermal comfort had been reached since the difference between internal and external temperatures was about 6 ^oC.

With regard to theoretical analysis, Ibrahim Atmaca et al. [7] simulated a solar cooling system based on a 10.5 kW constant cooling load. It was found that high reference temperature, which was the minimum allowable hot water inlet temperature, increased the system COP and decreased the surface area of system components. However, lower reference temperature gave better results for the solar fraction than high reference temperatures did. For the studied case, an 80 ^{o}C reference temperature was the best choice. It was also found that the storage tank mass should be kept at a minimum on the condition that it shouldn't cause the storage tank temperature to decrease excessively at the end of the working hours. Darine Zambrano et al. [8] described the dynamic model of a solar cooling plant that had been built for demonstration purposes using market-available technology and had been successfully operational since 2001. The plant used hot water coming from a field of solar flat collectors which fed a single-effect absorption chiller of 35 kW nominal cooling capacity. The simulation model was done in a modular way, and could be adapted to other solar cooling-plants since the main modules (solar field, absorption machine, accumulators and auxiliary heater) could be easily replaced. This simulator was a powerful tool for solar cooling systems both during the design phase, when it could be used for component selection, and also for the development and testing of control strategies. M. Balghouthi et al. [9] presented a research project aiming at assessing the feasibility of solar-powered absorption cooling technology under Tunisian conditions. The system was modelled using the TRNSYS and EES programs with a meteorological year data file containing the weather parameters of Tunis, the capital of Tunisia. The optimized system for a typical building of 150m^2 was composed of a water lithium bromide absorption chiller of a capacity of 11 kW, a 30 m^2 flat plate solar collector area tilted 35^o from the horizontal and a 0.8 m^3 hot water storage tank. G.A. Florides et al. [10] designed a LiBr-H_2O absorption unit with the cooling capacity of 11 kW, which could cover the cooling load of a typical model house in Cyprus. The optimum system as obtained from the complete system simulations, consisted of 15 m^2 compound parabolic collector tilted at 30^o from horizontal and 600 l hot water storage tank.

Theoretical and experimental studies on solar cooling systems were also carried out by N. Nakahara et al. [11], M.R. Yeung et al. [12] and T. Bong et al. [13]. The existing researches were mainly based on the performances of the solar cooling systems. In addition, nearly all the air-conditioning terminals were fan coils. In this paper, a minitype solar absorption cooling system using both fan coils and the radiant ceiling as terminals was designed and installed. The system performance as well as the indoor thermal environment was analyzed.

2. System description

The solar-powered absorption cooling system mainly consists of evacuate collectors (with CPC) with area of 96 m^2, a hot water storage tank with the capacity of 3 m^3, an 8 kW LiBr/H_2O absorption chiller, a cooling tower, the terminals of the air-conditioning system. In summer, the system was used to supply cooling to meet the cooling requirement of a test room with the area of 50 m^2. Two different terminals of the air-conditioning system including the fan-coils and the radiant cooling ceiling were fixed in the test-room. Besides, a fresh air handling unit was installed to supply fresh air and remove latent heat away from test room.

2.1. Solar collector array

The solar collectors were installed on the building roof and designed to be tilted 30^o with horizontal for better performance, as shown in Fig. 1. The solar collector array was divided into four rows. Each row was composed of four solar collector units, which were connected in series for the purpose of achieving hot water with a relatively high temperature.

Fig. 1. Photo of solar collector array

2.2. Heat storage

The hot water storage system has been proved significant for the whole system. Different styles of hot water tanks result in different performance of the chiller. The system employed a hot water storage tank with the capacity of 3 m^3 that supplied hot water for the chiller generator. The water tank is capable of keeping the temperature of hot water steady, which guarantees the stable operation of the absorption chiller. The water tank and the solar collector array are connected through a plate heat exchanger with the heat exchange capacity of 30 kW.

2.3. Absorption chiller

The LiBr/H_2O single-effect absorption chiller was shown in Fig. 2. Under the nominal operating mode, the inlet hot water temperature is 70-95 ^oC with the flow rate of 4 t/h. The chilled water at about 9 ^oC with the flow rate of 1.5 t/h is produced. The chiller COP of 0.7 can be achieved under the nominal condition. The absorption chiller is the key position in the solar cooling system. It is driven by the hot water to generate cooling effect. Meanwhile, it releases heat to the environment through the cooling tower. A solution circulation pump is fixed inside the chiller to driven strong solution to flow from the absorber to the generator.

Fig. 2. LiBr/H_2O single-effect absorption chiller

2.4. Test room and terminals

The area of the test room is 50 m^2. The north wall is an outer envelope with 6 m^2 glass windows. The other three walls can be treated as inner envelopes. The cooling ceiling with the area of 30 m^2 and two fan coils were fixed in the test room. Besides, an independent fresh air system was installed in the neighbor room to supply fresh air and meat the latent load of the room. The fresh air can be cooled by both solar cooling and electric cooling. So when solar insolation is not enough, the electric cooling device can be operated to meet the entire indoor cooling load.

2.5. System control and data acquisition

The entire system was automatically controlled. Fig. 3 shows the schematic diagram of the experimental set up. By means of the PT1000 sensors, the circulation pumps can be switched on or off, which in turn dominates the solar collector cycle, hot water tank cycle, cooling tower cycle and chilled water cycle. Besides, the solar insolation and the temperatures were all recorded by a data logger. In the morning, when the hot water temperature achieves 75 ^oC, the system is turned on. The system is turned off when the hot water temperature is below 65 ^oC or when the time is after 18:00. In order to calculate the indoor comfortable level, 20 PT1000 sensors, three black ball thermometers, a hygrometer and an anemobiagraph have been arranged in the test room.

Several kinds of sensors have been employed in the pipeline of the whole system including thermometers, flow meters, irradiation sensors, hygrometers and pressure gauges. The platinum resistance sensors were fixed on the important locations such as the inlet and outlet of the water tank, chiller and cooling tower. The water flow rate meters collect the data of flow rate and transmit them to a computer. There is a data acquisition logger of Keithley 2700, which connects to the computer and records the data every 15 s. The measuring accuracy of the irradiation sensor is 1 W/m^2; correspondingly, 0.01 ^{o}C and 0.1 t/h for the platinum resistance sensors and the water flow rate meters, respectively.

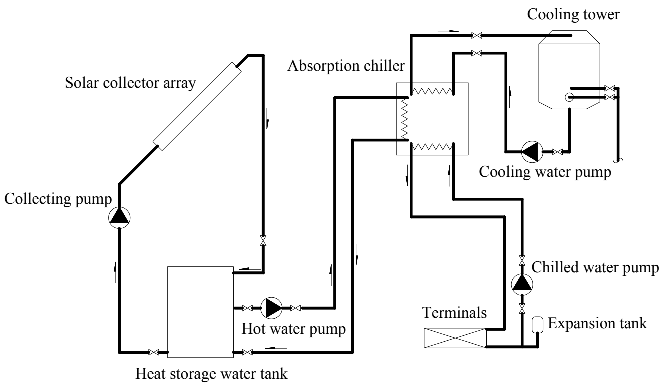

Fig. 3. Schematic diagram of the experimental set up

3. Experimental investigation

3.1. Solar collector array

Fig. 4 shows the variations of the solar collecting efficiency of the solar collector array and the solar radiation intensity in a typical summer day. It was obvious that the solar radiation intensity had a maximum value of at 11:20. Meanwhile, the collector efficiency gently rose from the morning and then kept nearly constant from 8:30 to 12:30. And then the collector efficiency reduced with the decrease of solar radiation intensity. From 12:30 to 15:30, the collector efficiency decreased slowly although the solar radiation intensity remained a high level with above 400 W/m^2. When the solar insolation was less than 300 W/m^2, the collector efficiency had a dramatic reduction because the heat loss to the surrounding was more than heat collected by the solar collector array. The heat storage water tank received heat from solar collector array by means of a flat plate heat exchanger. The daily average solar collecting efficiency of the collector array was concluded to be 0.46.

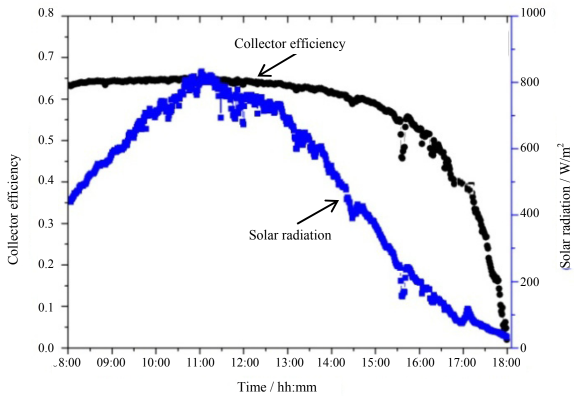

Fig. 4. Solar radiation and the collector efficiency

3.2. Operation of the solar absorption chiller

Fig. 5 shows the main operation parameters of the solar absorption chiller, which includes the inlet and outlet temperatures of hot water, cooling water and chilled water, respectively. The inlet temperature of hot water varied from 74.8 to 89.1 ^{o}C with an average value of 84.9 ^{o}C. The average outlet temperature of chilled water was 12.8 ^{o}C. It can be seen from Figure 5 that the variations of inlet and outlet temperatures of the three cycles were smooth with few vibrate during the operation of the absorption chiller. The chilled water temperature could remain below 15 ^{o}C until 17:00 which was enough to guarantee a comfortable thermal condition in the test room.

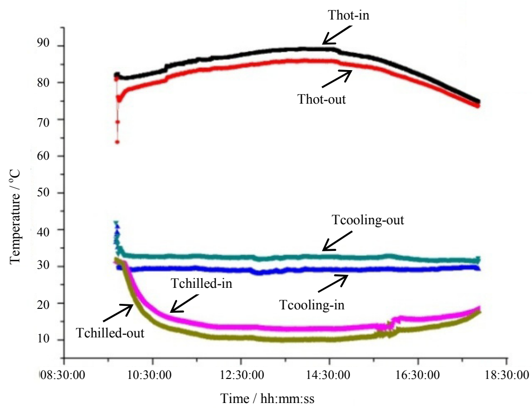

Fig. 5. Variations of temperatures of hot water, cooling water and chilled water

Fig. 6 shows the variations of heating consumption, cooling output and COP of the chiller. The cooling output was estimated through the flow rate of the chilled water and the temperature difference of the chilled water between the inlet and outlet of the absorption chiller. It is seen that 4.5 kW cooling output can be obtained from 10:00 to 18:00. The chiller COP varied from 0.25 to 0.38 with an average value of 0.32. After 16:00, the hot water temperature began to decrease, which resulted in the decrease of heat consumption. The COP went up from 16:00 because the decrease of heat consumption overwhelmed the decrease of cooling output. In this experiment, because the chiller worked at partial load, a low efficiency from solar to cooling was obtained. Therefore, it is important to select the adequate size of the absorption machine, to make it work at nominal operating conditions, so that the system COP reaches the nominal value and solar fraction, consequently, is higher.

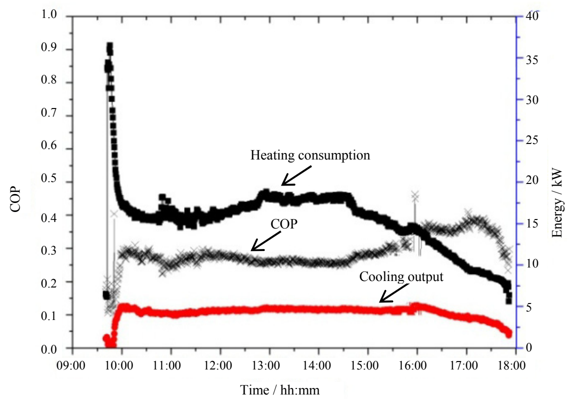

Fig. 6. Variations of heating consumption, cooling output and COP

3.3. Indoor thermal environment

Fig. 7 shows the variations of air temperatures at different altitude and the black-ball temperature. Owing to the cooling output generated by the chiller, the temperatures inside the room decreased quickly. This process continued for about 2 hours until the room temperatures decreased to be 25 ^{o}C. From then on, the temperatures inside the room declined gently and remained at 23-24 ^{o}C. The black ball temperature was lower than all the three air temperatures which were collected from different heights inside the test room.

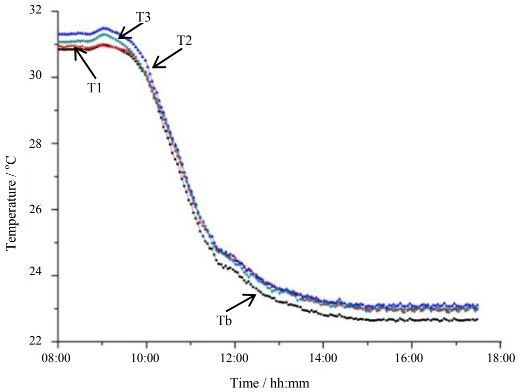

Fig. 7. Variations of the room air temperatures and black-ball temperature

According to the experimental results, it was calculated that the average PMV value during the system operation was 0.22. Besides, the average PPD value was 5.89. Here, the indices of PMV and PPD were calculated according to the ASHRAE Handbook. Taking the average values of PMV and PPD into consideration, the solar absorption air conditioning system could meet the indoor thermal comfort.

3.4. Comparison of different terminals

The fan coils and the cooling ceiling have been employed as terminals in this system, respectively. The performance of the solar driven absorption chiller combined with fan coils was compared with that combined with radiant cooling panel, as shown in Fig. 8. The average cooling output of the former was 3.62 kW, correspondingly, 4.47 kW for the latter based upon the experimental results under similar weather conditions. By means of the radiant ceiling, the cooling output of the absorption chiller increased by 23.5%. That is due to the higher evaporating temperature of the chiller when the cooling radiant process was applied.

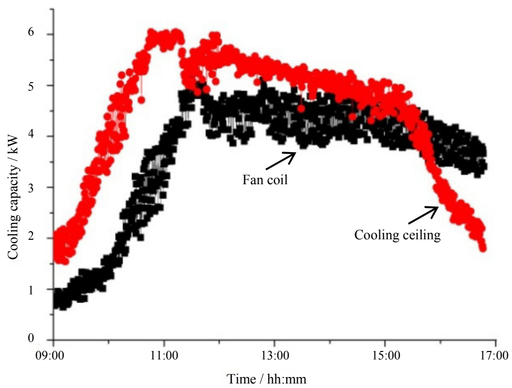

Fig. 8. Comparison of cooling capacity by fan coils and that by radiant ceiling

4. Conclusions

A solar powered absorption cooling system was designed and installed. Based on the experiment results, the performance of the whole system has been presented and analyzed. The main conclusions can be summarized as follows:

1) The daily average solar collecting efficiency of the collector array was 0.46.
2) The cooling capacity of 4.5 kW can be obtained during the continuous operation of 8 hours. The chiller COP was 0.32.
3) The average PMV and PPD was 0.22 and 5.89, respectively, which showed that the solar absorption air conditioning system could meet the indoor thermal comfort.
4) Under similar weather conditions, the cooling output by means of radiant cooling panels increased by 23.5% compared with the operation mode of fan coils.

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