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Experimental study on closed-cycle solar adsorption cooling system

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Abstract: A closed-cycle solar-powered adsorption cooling system is designed. The system is mainly composed of the evacuated tubular solar collectors with an area of 150 m^2, two adsorption chillers with a rated cooling capacity of 15 kW, a cooling tower, fan coils and circulating pumps. The experiments were carried out to study the operating characteristics and the performance of the system. It is found that the operation of the system presents wave characteristics because of low water capacity. The water temperatures of the inlet and the outlet of the solar collector array cyclically swing since the water entering the solar collector array comes directly from the adsorption chillers. Besides, the inlet water temperature of the adsorption chillers varies distinctly. However, the cooling effect of the system is satisfactory. Compared with an open-cycle system, the closed-cycle system has the advantage of a high electric COP (coefficient of performance) because of the reduced use of circulating pumps.

Key words: solar energy; adsorption cooling; closed-cycle

Solar cooling has been an attractive application for solar energy because of the near coincidence of peak cooling loads with the available solar power. Currently, most of the commonly used solar cooling systems are the hot water driven lithium bromide absorption chillers or the adsorption chillers. Compared with the existing absorption systems, adsorption systems can be built on a small scale and can be operated without moving parts, which means that rectifier or solution pumps are not needed. Also, there exists no corrosion problem in adsorption systems. Tsoutsos et al. [1] reported that the combination of an adsorption chiller with solar collectors offered a technically simple and energy saving solution. Wang[2] suggested that for the minitype solar air-conditioning system, the solar adsorption cooling system is a better choice.

Adsorption cooling utilizes an agent (the adsorbent) to adsorb the moisture from the air (or dry any other gas or liquid) and then uses the evaporative cooling effect to produce cooling. Commercially-available adsorbent-adsorbate pairs include silica gel-water, zeolite-water, activated carbon-methanol, and silica gel-methanol. Silica gel-water has been the preferred pair in adsorption chiller development owing to 1) silica gel's comparatively large uptake capacity for water; 2) the high heat of vaporization of water; 3) the relatively low temperature for desorption; and 4) the harmless nature of the chemicals. Dieng et al. [3] pointed out that a silica gel/water adsorption refrigerator used waste heat at below 100 ℃, which is suitable for a wider range of solar thermal collector types.

Because of the intermittent nature of solar energy, intermittent adsorption refrigeration cycles have long been considered as logical approaches to solar cooling systems. Therefore, up to now, the solar-powered adsorption systems have mostly been intermittent and used only for ice-making applications. For applications such as air conditioning, two or more adsorption beds can be used to continuously produce a cooling effect. Saha et al. [4] examined the performance of an adsorption chiller which is capable of utilizing low temperature solar/waste heat (40 to 75 ℃) as the driving heat source in combination with a coolant at 30 ℃. With a 55 ℃ driving source in combination with a heat sink at 30 ℃, the COP of the two-stage adsorption chiller was reported to be 0.36. Alam et al. [5] presented a thermodynamic optimization of a solar driven adsorption refrigerator. An internally endoreversible model was analyzed numerically to find the optimal conditions of a solar driven adsorption chiller. They concluded that a maximum refrigeration effect can be achieved from an adsorption refrigeration system by optimally distributing the thermal conductance among the adsorber, the condenser, the evaporator and the collector heat exchangers. For a solar-powered air-conditioning system, Li et al. [6] established a lumped parameter model to investigate the performance of a solar-powered adsorption air-conditioning system driven by simple flat plate solar collectors. Zhai et al. [7] reported on the solar adsorption cooling system of the green building of the Shanghai Research Institute of Building Science. The experimental results show that the average cooling capacity is 15.31 kW under the typical weather conditions of Shanghai.

With regard to cycle mode, the existing solar-powered air-conditioning systems are always open-cycle systems. This kind of system includes a heat storage water tank which accumulates heat by solar collecting circulation. The chillers are then driven by hot water from the heat storage water tank. Such systems have been reported by He et al. [8], Li et al. [9], and the like. Few systems have been found to be closed-cycle systems which are characteristic of direct hot water circulation between solar collectors and chillers without a heat storage water tank.

In this paper, a solar-powered adsorption air-conditioning system which can be switched between an open-cycle system and a closed-cycle system is designed. Experimental results under different circulating modes are compared and analyzed. The typical experimental results of the closed-cycle system are summarized.

1 Experimental Set-up

A solar-powered air-conditioning system is designed and

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set up. The system is mainly composed of 150 m^2 evacuated tubular solar collectors, two adsorption chillers (chiller 1 and chiller 2), one cooling tower, and three circulating pumps for solar collectors (pump 1), hot water (pump 2) and cooling water (pump 3), respectively. Besides, for the open-cycle system, a heat storage water tank of 2.5 m^3 in volume is employed to collect solar heat, thereby providing hot water for the air-conditioning system. Fig. 1 shows the flow diagram of the solar-powered adsorption cooling system. By switching valves, the solar-powered cooling system can be operated in different cycle modes. When turning on the valves of V_2, V_3, V_4, V_5 and V_8, and, meanwhile, turning off the valves of V_1, V_6 and V_7, the system operates as an open-cycle system; otherwise, the system operates as a closed-cycle system. In the open-cycle system, the heat storage water tank acts as the link between solar collecting circulation and hot water circulation for adsorption chillers. The hot water from the solar collector array flows into the top of the water tank. In the meantime, the back water from adsorption chillers is gathered at the bottom. The hot water for adsorption chillers comes from the top of the water tank. However, the heat storage water tank is insolated in the closed-cycle system; the hot water pump (pump 2) is not in use. The back water from the adsorption chillers is directly pumped to the solar collector array where it is heated by solar energy, and then flows into adsorption chillers again. In addition, an expansion tank of 0.1 m^3 in volume is installed above the pipe network in order to set the pressure for the pipe network.

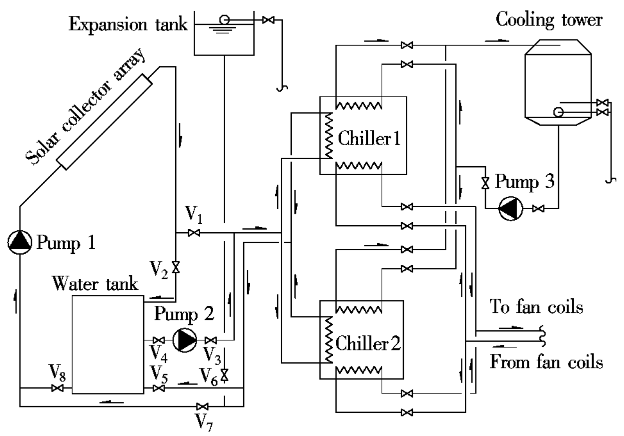

Fig. 1 Flow diagram of solar-powered adsorption cooling system

The adsorption chiller with the working pair of silica-gel/water is invented by Shanghai Jiao Tong University. The cycle process of the adsorption chiller is as follows: the heating/cooling time is 900 s; the mass recovery time is 180 s and the heat recovery time is 60 s. The nominal refrigeration capacity is 8.5 kW when the hot water temperature is 85 ℃.

2 Experimental Results and Analysis

The experimental results of 2 d with similar ambient conditions (the daily solar insolation and the daily average ambient temperature are about 18 MJ/m^2 and 34 ℃, respectively) are chosen to compare the system operating characteristics in different cycle modes. The solar cooling system continuously operates from 9:00 to 17:00.

Fig. 2 shows the variations of inlet and outlet water temperatures of the solar collector array. For the open-cycle system, it is seen that the inlet water temperature of the solar collector array initially goes up with the increase in solar radiant intensity, and approaches peak values at about 14:00 or so, and then decreases with the decrease in solar radiant intensity. A similar trend can be seen for the outlet water temperature. Also, what can be seen is that the inlet water temperature profile is relatively smooth since the water entering the solar collector array comes from the bottom of the heat storage water tank. The average inlet water temperature during system operation is estimated to be 62.38 ℃.

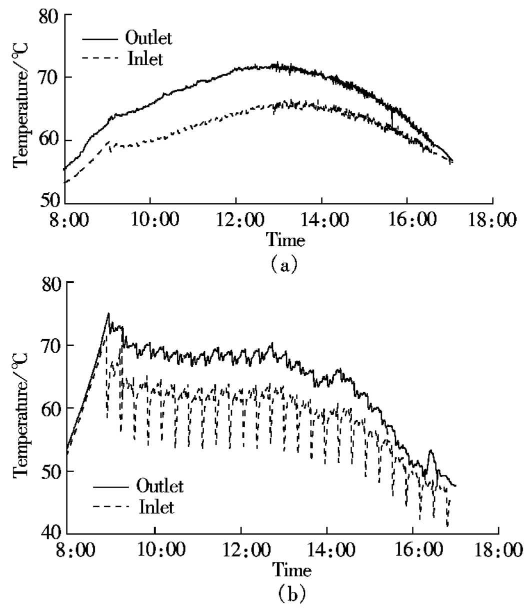

Fig. 2 Variations of inlet and outlet water temperatures of solar collector array. (a) Open-cycle system; (b) Closed-cycle system

Comparatively, the inlet and outlet water temperatures of the closed-cycle system rapidly rise in phases until 9:00, and then go down suddenly due to the start-up of the two adsorption chillers. Generally speaking, the variations in inlet and outlet water temperatures are small from 10:00 to 15:00, indicating the balance between solar collecting heat and heat consumption by the adsorption chillers. Afterwards, the inlet and outlet water temperatures descend with the decrease in solar radiant intensity. It is interesting to find that the inlet and outlet water temperatures cyclically swing since the inlet water comes directly from the adsorption chillers. It is concluded that the average inlet water temperature is 57.92 ℃, which is 4.46 ℃ lower than that of the open-cycle system. Accordingly, under otherwise identical conditions, the solar collecting efficiency of the closed-cycle system is higher than that of the open-cycle system. Experimental results show that the daily average solar collecting efficiency for the closed-cycle system is 39.16%, which is higher than that of the open-cycle system by 5.14%.

Fig. 3 shows variations of the inlet and outlet water temperatures of the adsorption chillers. With regard to the open-cycle system, the inlet water temperature is 60.70 ℃ when the adsorption chillers are turned on at 9:00, then gradually rises, and approaches a peak value of 69.29 ℃ at 13:00 with a rate in a temperature rise of 0.04 ℃/min. During this temperature rise period, the mean temperature of the inlet water is 64.90 ℃. From then on, the inlet water temperature decreases with a rate of a temperature drop of 0.06 ℃/min, and reaches 55.86 ℃ at 17:00 when the adsorption chillers are shut down. During the period of temperature drop, the mean temperature of the inlet water is 64.44 ℃. Because of this, the temperature of the inlet water varies smoothly during the 8 h operation of the cooling system with a mean value of 64.67 ℃. Taking temperature variations into account, the thermal source driving the adsorption chillers is considered to be relatively stable.

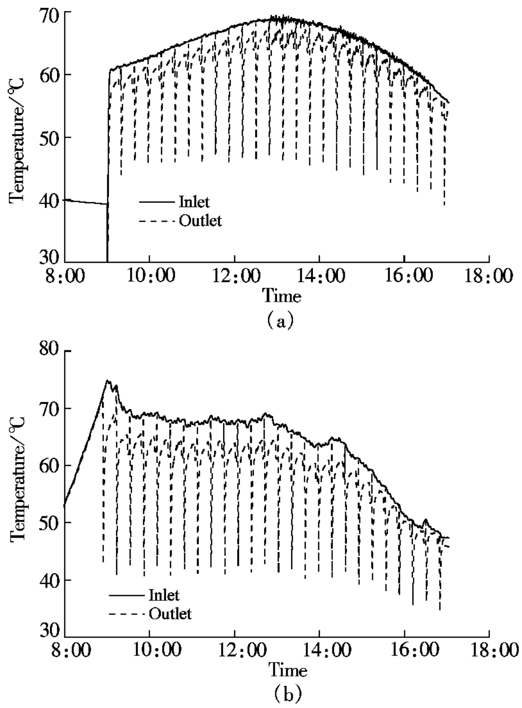

Fig. 3 Variations of inlet and outlet water temperature of adsorption chillers. (a) Open-cycle system; (b) Closed-cycle system

However, the temperature of inlet water varies dramatically in the closed-cycle system. From the starting of the solar cooling system at 9:00, the inlet water temperature decreases from 74.90 ℃ to 67.50 ℃ with a rate of a temperature drop of 0.12 ℃/min because the two adsorption chillers consume a large amount of heat stored in the pipe network. The mean temperature of inlet water is 70.47 ℃ from 9:00 to 10:00. From 10:00, with the increase in solar radiant intensity, besides meeting the heat consumption of two adsorption chillers, solar collecting heat is partly stored in the pipe network, which leads to the increment in inlet water temperature. At about 13:00, the inlet water temperature reaches 69.18 ℃. The mean temperature of inlet water is 67.92 ℃ during this period with a rate of a temperature rise of 0.01 ℃/min. Hereafter, the inlet water temperature tends to slowly decrease. It is found that the inlet water temperature descends quickly after 15:00, indicating that heat consumption by the adsorption chillers overwhelms solar collecting heat. During the last 2 h of operation, the rate of the temperature fall is 0.11 ℃/min, and the average value of the inlet water temperature is 52.82 ℃. The average inlet water temperature during the 8 h operation of the closed system is concluded to be 63.87 ℃. According to the variations of inlet water temperature, the thermal source driving the adsorption chillers is relatively stable from 10:00 to 15:00 since the temperature varies in the order of 0.01 ℃/min. However, in the other two time intervals (9:00 to 10:00 and 15:00 to 17:00), the supply water temperature varies dramatically in the order of 0.1 ℃/min, comparatively; the chillers can be considered to be driven by a variable thermal source.

In the closed-cycle system, the variation in the inlet water temperature of the adsorption chillers is nearly in phase with the variations in solar radiant intensity. Solar energy has the characteristics of a variable thermal source. As a result, the operation of the closed-cycle system presents wave characteristics. However, the open-type system is capable of stable operation, owing to the regulating effect of the heat storage water tank.

According to the experimental results, the cooling effects of the closed-cycle solar adsorption cooling system are satisfactory. The cooling effects of the system under two different cycle modes are similar. The daily average cooling capacities of the open-cycle system and the closed-cycle system are 13.09 and 11.91 kW, respectively. However, as an energy-saving technology, it is significant to reduce power consumption; consequently, electric COP is another important index in evaluating the performance of the system. Electric COP is indicated as the refrigerating output divided by the power consumption of the solar-powered cooling system.

As for power consumption, in the open-cycle system, taking solar collecting pump (pump 1), hot water pump (pump 2) and cooling water pump (pump 3) into account, the whole power consumption is 1.87 kW, and then the electric COP averages at about 7 during the 8 h of the operation. Whereas, the whole power consumption in the closed-cycle system reduces to 1.32 kW because of the non-use of the hot water pump (pump 2). The average electric COP is 9.02 during the 8 h of the operation period, which is 28.86% higher than that of the open-type system. Tab. 1 shows the typical experimental results of the closed-cycle system. It is observed that the daily average electric COP increases with the increase in the daily solar insolation. Moreover, it always exceeds 6. Compared with the widely used air-source heat pump cooling systems with an electric COP of 2.8 in Shanghai, the closed-cycle solar-powered cooling system shows a great potential for energy conservation during the summer months.

Tab. 1 Typical experimental results of the closed-cycle solar cooling system

Daily average ambient temperature/℃	Daily solar insolation/($MJ \cdot m^{-2}$)	Daily average solar collecting efficiency/%	Daily average inlet water temperature of chillers/℃	Daily average cooling capacity/kW	Daily average electric COP
32.78	15.65	38.61	60.43	9.10	6.89
29.89	16.04	39.93	60.21	8.98	6.80
23.42	17.30	43.53	59.46	9.73	7.37
35.72	18.37	39.16	63.87	11.91	9.02

3 Conclusion

A solar-powered adsorption cooling system which can be switched between an open-cycle system and a closed-cycle system is designed. Experiments are carried out to compare the operating characteristics of the system under the two cycle modes. As a brief summary, it is wished to emphasize the significant points of this work in the future.

The temperature profiles of the solar collector array and the adsorption chillers show that the open-cycle system operates stably because of the regulating effects of the heat storage water tank. However, the cooling effects of the closed-cycle solar adsorption cooling system is satisfactory although it has obvious wave characteristics.

Compared with an open-cycle system, a closed-cycle system has the advantages of higher solar collection efficiency and higher electric COP. Consequently, the energy-saving effect of a closed-cycle system is more notable.

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闭式循环太阳能吸附式制冷系统实验研究

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摘要:设计了一套闭式循环太阳能吸附式制冷系统,该系统主要包括150 m^2 的真空管太阳能集热器、2 台额定容量为 15 kW 的吸附式制冷机组、1 台冷却塔、风机盘管以及循环水泵. 实验表明:由于水容量较小,系统的运行过程呈现出波动特性;由于进入太阳能集热器阵列的水直接来自吸附式制冷机组,太阳能集热器阵列的进出口水温周期性地振荡;此外,吸附式制冷机组的进口水温波动明显. 然而,系统的制冷性能达到令人满意的效果. 与开式循环系统相比,闭式循环系统由于减少了循环水泵的数量具有高电力 COP 的优势.

关键词:太阳能;吸附式制冷;闭式循环

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