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Study of a novel solar adsorption cooling system and a solar absorption cooling system with new CPC collectors

Z.S. Lu [a,*], R.Z. Wang [a], Z.Z. Xia [a], X.R. Lu [b], C.B. Yang [b], Y.C. Ma [c], G.B. Ma [c]

[a] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, 200240 Shanghai, China
[b] Himin Solar Energy Group Co., Ltd., Shandong 253700, China
[c] Linuo Group Co., Ltd., Shandong 250103, China

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ABSTRACT

One two-phase thermo-syphon silica gel-water solar adsorption chiller and LiBr-H_2O absorption chiller with new medium CPC (Compound Parabolic Concentrator) solar collectors were investigated. The reliability of adsorption chiller can be improved, because there is only one vacuum valve in this innovative design. Medium temperature evacuated-tube CPC solar collectors were firstly utilized in the LiBr-H_2O air conditioning system. The former system was applied in north of China at Latitude 37.45° (Dezhou city, China), the latter system was applied at Latitude 36.65° (Jinan city, China). Experimental results showed that the adsorption chiller can be powered by 55 °C of hot water. The adsorption chiller can provide 15 °C of chilled water from 9:30 to 17:00, the average solar COP (COPs) of the system is 0.16. In the absorption cooling system, the efficiency of the medium temperature evacuated-tube CPC solar collector can reach 0.5 when the hot water temperature is 125 °C. The absorption chiller can provide 15 °C of chilled water from 11:00 to 15:30, and the average solar COPs of absorption system is 0.19.

1. Introduction

With the economic and social development of the society, more people were paying attention to energy and environmental conservation. The refrigeration and air conditioning systems are one of the major energy consumers. The residential and commercial energy use account for 19% of China's total energy consumption. Moreover, the percentage is expected to rise further in the coming years. In the south of China, the energy consumption for air conditioning systems has recently been estimated at 45% [1], thus electricity supply shortage in summer is often experienced. In addition, the refrigeration and air conditioning systems normally use CFCs as refrigerant that causes ozone depletion and greenhouse effect. The Montreal protocol on substances that deplete the ozone layer requires that CFC and HCFC should be replaced by green refrigerants which have zero or very low ODP (Ozone Depletion potential) and GWP (Global Warming Potential) [2]. Therefore, new air conditioning technologies which can reduce the electric power consumption and CFC usage are desirable.

The use of solar energy to drive sorption cooling cycles has become attractive mainly because: (1) Sorption systems (adsorption system and absorption system) have the benefit of using recovered low-grade heat or solar energy to save energy; (2) They are environmentally benign, they use ammonia, water, methanol, etc. as refrigerants, and can avoid the use ozone-depleting chlorofluorocarbons (CFCs); (3) they are noise & vibration free; (4) the peaks of cooling requirements in summer coincide most of the time with the availability of the high solar radiation.

During recent years, many solar adsorption cooling units and solar absorption cooling system were researched. For example, Meunier [3] and Solmus [4] studied zeolite – water adsorption cooling system. Pons [5] investigated activated carbon-methanol adsorption cooling systems. Rezk studied commercial silica gel – water chillers [6]. That paper presents the key equations necessary for developing a novel empirical lumped analytical simulation model for commercial 450 kW two-bed silica gel/water adsorption chiller incorporating mass and heat recovery schemes. Saha [7], Boelman [8], Chua [9] and Alam [10] discussed the performance of silica gel-water adsorption cooling system. Saha [11] investigated the performance of the advanced three-stage adsorption chiller, driven by 50 °C of low-grade waste heat or solar energy. Eight vacuum valves were used in that system. Vichan [12] added activated carbon in silica gel for use in an adsorption cooling chiller to improve the heat transfer performance. A solar adsorption chiller in an ecological building has been conducted. The COP and the efficiency of the U-type and heat pipe evacuated collectors is 0.28 and

* Corresponding author.
E-mail address: zslu@sjtu.edu.cn (Z.S. Lu).

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Nomenclature

q_h	heating capacity, kW
q_e	cooling capacity, kW
C_w	specific heat of water, kJ kg^{-1} °C^{-1}
m_{ch}	mass flow of chilled water, kg s^{-1}
$T_{ch,i}$	inlet temperature of chilled water, °C
$T_{ch,o}$	outlet temperature of chilled water, °C
A_c	area of solar collectors, m^2
T^*	normalized temperature
T_i	working fluid inlet temperature of solar collector, °C
I	solar radiation intensity, kJ m^{-2} s^{-1}
m_c	mass flow of working fluid in solar collectors, kg s^{-1}
T_o	working fluid outlet temperature of solar collector, °C
T_a	ambient temperature, °C
m_h	mass flow of hot water, kg s^{-1}
$T_{h,i}$	inlet temperature of hot water, °C
$T_{h,o}$	outlet temperature of hot water, °C

Greek symbol

η	efficiency of solar collector
λ	Aperture

Abbreviations

COP	coefficient of performance
COPs	solar coefficient of performance
H_2O	water
LiBr	Lithium bromide
CPC	Compound Parabolic Concentrator
CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbons
ODP	Ozone Depletion Potential
GWP	Global Warming Potential

0.4. The solar adsorption cooling system with glass evacuated-tube collectors were studied [13,14], the daily solar COPs ranged from 0.1 to 0.13. A high efficient adsorption chiller was designed and investigated by Shanghai Jiao Tong University [15–20], whereby methanol was used as heat pipe working fluid.

Ghaddar [21] investigated the performances of a solar absorption system. Florides [22,23] developed several computer models for describing the performance characteristics of absorption chiller, the results showed that the solar absorption cooling system can cover a typical house load for the whole year. A solar powered single stage absorption cooling system, using a water-lithium bromide solution, was simulated by Atmaca [24]. The reference [25] simulated solar air conditioning system with a meteorological year data file containing the weather parameters of Tunis. Kim analyzed solar absorption system performance [26]. The results showed that choice of an absorption cooling machine is primarily dependent on the performance of the solar collector to be used. For solar collectors capable of efficiently working at around 150 °C, double-effect LiBr/H_2O chillers with COPs around 1.2 are available for air conditioning. Agyenim designed and tested an outdoor LiBr/H_2O solar thermal absorption cooling system with a cold store [27]. The results showed that the average thermal COP of the system was 0.58 on a hot sunny day with average peak insolation of 812 W m^{-2} and average ambient temperature of 24 °C. Pongtornkulpanich studied one solar-driven 10-ton LiBr/H_2O single-effect absorption cooling system in Thailand [28]. The test data showed that the solar COPs is about 0.2.

The conventional solar adsorption/absorption cooling systems have low solar COP. The objective of this paper is to (1) to research the innovative technology of one vacuum valve adsorption solar air conditioning; (2) to study the absorption solar air conditioning system using the medium temperature evacuated-tube CPC (Compound Parabolic Concentrator) solar collectors.

2. Working theory of solar adsorption & absorption system

2.1. Few-valve solar adsorption air conditioning system

A compact solar powered silica gel-water adsorption chiller was designed by Shanghai Jiao Tong University. The chiller is composed of evaporators, two adsorption beds, two condensers, mass recovery vacuum valve, condensed water tank, several water valves and a control box. There is only one vacuum valve in this system. Hence, the number of moving parts and the possibility of leakage are reduced and the reliability of the chiller can be improved. The design parameters of the silica gel-water adsorption chiller are shown in Table 1. The working processes are shown in Fig. 1. The detailed description of the processes is shown as the following:

(1) Heating of the right adsorption bed, cooling the left adsorption bed (as shown in Fig. 1a): In this process, the right adsorption bed is heated, and water is desorbed from the right adsorption bed. The desorbed water vapour is then condensed in the right condenser and is stored in the right condensed water tank. Meanwhile, the temperature of the right condensed water tank is higher than that of the evaporating side; Thus, the two-phase thermo-syphon heat transfer cannot be formed by the evaporator and the right condensed water tank. The left adsorption bed is cooled, and water is adsorbed by the left adsorption bed. Much water is evaporated in the left condensed water tank, wherein the temperature declines quickly, and when it is lower than that of the evaporator, the two-phase thermo-syphon heat transfer can be formed by the evaporator and the left condensed water tank. The water evaporates in the evaporator and is condensed in the left heat transfer pipe and then returns back to the evaporator. The cooling capacity can be outputted by the chilled water heat exchanger.

(2) Mass and heat recovery: In this process, the mass recovery valve is opened. The silica gel in the right adsorption bed can desorb more water because of the sharp drop in pressure. And the silica gel in the left adsorption bed can adsorb more water because of the sharp rise in pressure. So the cycle adsorption capacity and coefficient of performance can be improved significantly by mass and heat recovery process.

(3) Heating of the left adsorption bed, cooling the right adsorption bed (as shown in Fig. 1b): this process is similar to process described in (1), the only difference is to turn the three-way water valves to the other direction. In this process, two-phase thermo-syphon heat transfer just can be formed by the right condensed water tank and the evaporator. So the adsorption chiller can automatically change phase without vacuum valves.

Table 1
Design parameters of silica gel-water adsorption chiller.

Item	Hot water		Cooling water		Chilled water		Cooling capacity	COP
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet		
Value	85	80	30	35	20	15	15	0.5
Unit	°C	°C	°C	°C	°C	°C	kW	/

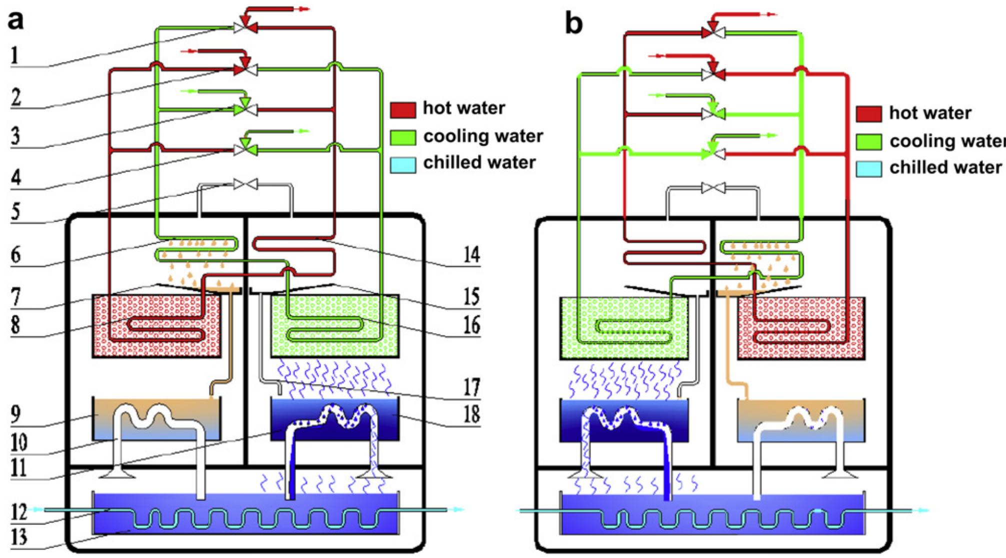

Fig. 1. Schematic diagram of silica gel-water adsorption chiller (1–4: water valves; 5: mass recovery valve; 6: right condenser; 7: right condensed water guide plate; 8: right adsorption bed; 9: right condensed water tank; 10: right heat transfer pipe; 11: left heat transfer pipe; 12: chilled water heat exchanger; 13: evaporator; 14: left condenser; 15: left condenser water guide plate; 16: left adsorption bed; 17: condensed water pipe; 18: left condensed water tank.

The market available adsorption chillers like SorTech [29] have vacuum valves between condenser-adsorption bed and evaporator-adsorption bed. Compared with these chillers, the merit of this adsorption chiller is that few vacuum valves are used. So, the system reliability can be improved significantly. The picture of the silica gel-water adsorption chiller is shown in Fig. 2. The solar adsorption chiller was applied in Dezhou city (Latitude 37.45°) in China. The pictures of the green building and test system are shown in Fig. 3. 79.7 m^2 of medium temperature evacuated-tube CPC (Compound Parabolic Concentrator) solar collectors were used and the instalment angle is 30°.

2.2. Solar absorption air conditioning system

The solar cooling system with lithium bromide-water absorption is shown in Fig. 4, which is manufactured by Jiangsu Huineng New Energy Technology Co., Ltd, China. The solar absorption cooling system is composed of medium temperature evacuated-tube CPC solar collectors, water valves, water pumps, water tanks, expansion tank, cooling tower, lithium bromide-water absorption chiller, water–air heat transfer, etc. The design parameters of the LiBr-H_2O absorption chiller are shown in Table 2.

There are two working modes in this system, one is cooling mode in summer and the other is heating mode in winter. In summer, the water is heated by solar collectors. The heated water is used to heat the generator of the absorption chiller. Meanwhile, the condenser and the absorber are cooled by cooling water. The chilled water from the evaporator goes into the water–air heat transfer, wherein, the cold air is provided. In winter, the water is heated by solar collectors. The heated water goes to the water–air heat transfer, thus the hot air can be provided. In all seasons, hot water can be provided by solar collectors. If the solar energy is inadequate in cloudy or rainy day, the waste vapour from industry can be used as supplementary heating source.

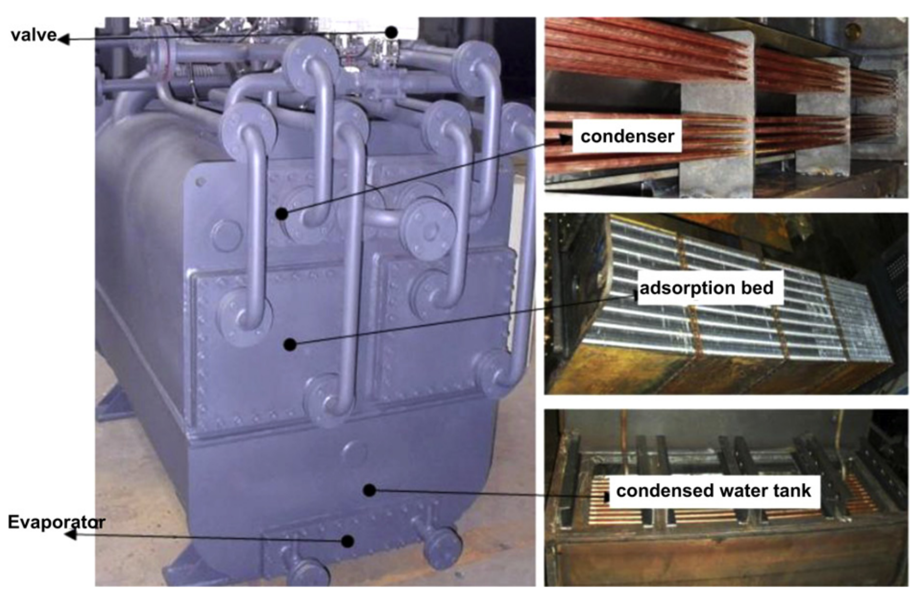

Fig. 2. Silica gel-water adsorption chiller.

Fig. 3. Solar adsorption air conditioning system in China.

Compared with other absorption air conditioning system, new compound parabolic concentrating solar collectors are used and tested in this system. The CPC solar collector produced by Linuo-Ritter Co. Ltd. is medium temperature collector with high collecting efficiency through improving the efficiency of selective absorption coating and utilizing the non-imaging edge-ray concentrator. The CPC solar collector is a stationary collector without the tracking system and can receive the direct radiation and a part of diffuse radiation. Here, the copper U-tube with the aluminium fin is used as the heat transfer configuration inner the all-glass evacuated-tube. The specification of the CPC collector is shown in Table 3. The solar collectors have high efficiency at high temperature (higher than 130 °C). 105 m^2 of this kind of collectors were installed on the roof of the green building in Jinan city (Latitude 36.65°) in China, the installation angle was 20°, as shown as Fig. 5.

3. Experimental investigation

The cooling capacity, heating capacity, coefficient of performance, solar coefficient of performance, normalized temperature and efficiency of solar collector were determined from Equations (1)–(6).

$$q_e = m_{ch} C_w (T_{ch,i} - T_{ch,o}) \tag{1}$$

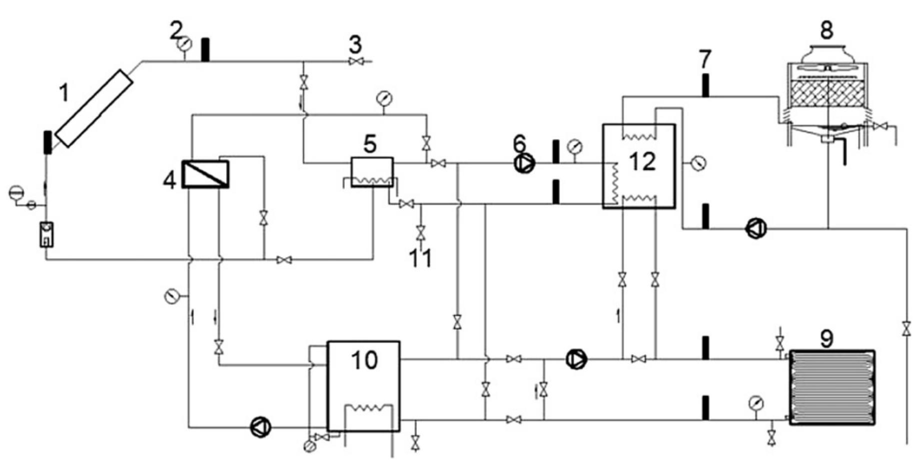

Fig. 4. The schematic diagram of LiBr-H_2O absorption solar air conditioning system (1-solar collector, 2-water flow-metre, 3-water valve, 4-heat exchanger, 5-pressure hot water tank, 6-water pump, 7-temperature sensor, 8-cooling water tower, 9-water–air heat transfer, 10-normal hot water tank, 11-waste vapour of supplementary heating source, 12-absorption chiller).

Table 2
Design parameters of LiBr-H_2O absorption chiller.

Item	Hot water		Cooling water		Chilled water		Cooling capacity	COP
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet		
Value	90	85	30	35	15	10	10	0.6
Unit	°C	°C	°C	°C	°C	°C	kW	/

Table 3
The specification of the CPC collector.

Items	Unit	Value
No. of evacuated tubes		18
λ (Aperture)	%	64.2
Grid dimensions (length × height × depth)	m	2.08 × 1.64 × 0.1
Gross surface area	m^2	3.41
Aperture area	m^2	3.0
Collector contents	l	2.4
Weight	kg	54
Max. working overpressure	bar	10
Max. stagnation temperature	°C	272
Connection diameter, clamping ring	mm	15
Sensor sleeve	mm	6
Glass tube material		Borosilicate glass 3.3
Selective absorber coating material		Aluminium nitride
Glass tube (outside diameter/ inside diameter /wall thickness/ tube length)	mm	47/37/1.6/1500
ColourColour (aluminium frame profile, anodised)		Aluminium grey
Colour (plastic parts)		Black

where q_e is cooling capacity, kW; m_{ch} is mass flow of chilled water kg s^{-1}, C_w is specific heat of water, kJ kg^{-1} $°C^{-1}$; $T_{ch,i}$ is inlet temperature of chilled water, °C; $T_{ch,o}$ is outlet temperature of chilled water, °C.

$$q_h = m_h C_w (T_{h,i} - T_{h,o}) \tag{2}$$

where q_h is heating capacity, kW; m_h is mass flow of hot water, kg s^{-1}, C_w is specific heat of water, kJ kg^{-1} $°C^{-1}$; $T_{h,i}$ is inlet temperature of hot water, °C; $T_{h,o}$ is outlet temperature of hot water, °C.

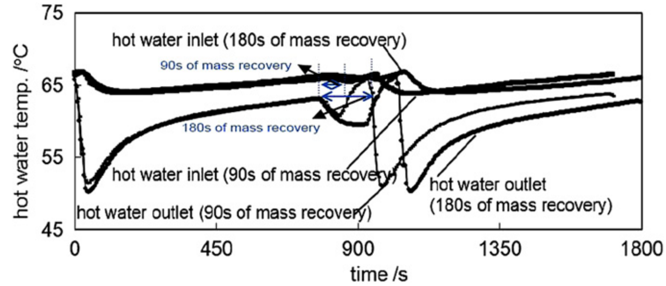

Fig. 6. Adsorption chiller hot water temperature variation with the cycle time.

$$\mathrm{COP} = \frac{m_{ch} \cdot C_w \cdot (T_{ch,i} - T_{ch,o})}{m_h \cdot C_w \cdot (T_{h,i} - T_{h,o})} \tag{3}$$

where COP is coefficient of performance.

$$\mathrm{COP}_s = \frac{q_e}{A_c I} \tag{4}$$

where COP_s is solar coefficient of performance; q_e is cooling capacity, kW; A_c is area of solar collectors, m^2; I is solar radiation intensity, kJ m^{-2} s^{-1}.

$$T^* = \frac{\frac{(T_0 + T_i)}{2} - T_a}{1000 \times I} \tag{5}$$

where T^* is normalized temperature; T_o is working fluid outlet temperature of solar collector, °C; T_i is working fluid inlet temperature of solar collector, °C; T_a is ambient temperature, °C.

$$\eta = \frac{C_w \cdot m_c \cdot (T_o - T_i)}{A \cdot I} \tag{6}$$

where η is efficiency of solar collector; m_c is mass flow of working fluid in solar collectors, kg s^{-1}; A_c is area of solar collectors, m^2.

Fig. 5. Solar absorption air conditioning system in China.

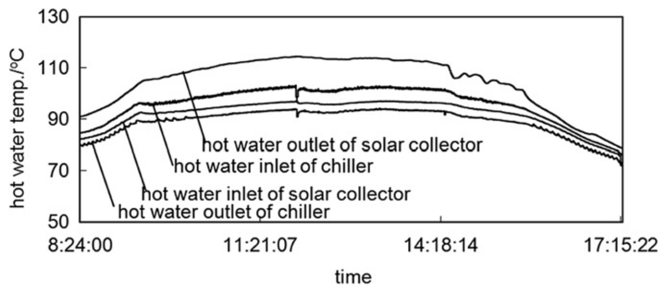

Fig. 7. Absorption chiller hot water temperature variation with the cycle time.

3.1. Performance variation and comparison of two solar air conditioning system influenced by hot water

The silica gel-water adsorption chiller and the LiBr-H_2O absorption chiller can be driven by hot water. The dynamical characteristics of hot water of the adsorption chiller and the absorption chiller are shown in Figs. 6 and 7, respectively. Fig. 6 shows that: (1) The hot water outlet temperature drops sharply when the cold adsorption bed begin to be heated. Then the hot water outlet temperature rises slowly, and drops again during the process of mass-heat recovery. (2) The mass recovery duration has influence on the cycle characteristics. The hot adsorption bed can re-desorb more water vapour because of the sharp drop of pressure during the process of mass recovery. More heat is needed for re-desorption, so the hot water outlet temperature will decrease. Mass recovery time has important impact on system performance. After the 90s of mass recovery, if the hot water outlet temperature still decline, it means that 90s is short for re-desorption. After the 180s of mass recovery, the hot water outlet temperature becomes constant, it means that the re-desorption is processed completely. (3) The silica gel-water adsorption chiller can be powered by very low temperature hot water. Fig. 7 shows that: (1) The hot water inlet and outlet temperature of the absorption cooling system is more stable than that of adsorption chiller system; (2) The absorption chiller can be powered by relatively higher temperature hot water. Usually, the hot water temperature should be higher than 80 °C.

3.2. Performance variation and comparison of two solar air conditioning system influenced by cooling water

The dynamical characteristics of cooling water of the adsorption chiller and the absorption chiller are shown in Figs. 8 and 9, respectively. Fig. 8 shows that: (1) The cooling water outlet temperature rises sharply at the beginning of the cooling process, then it declines slowly, and rises again during the process of mass-heat recovery.

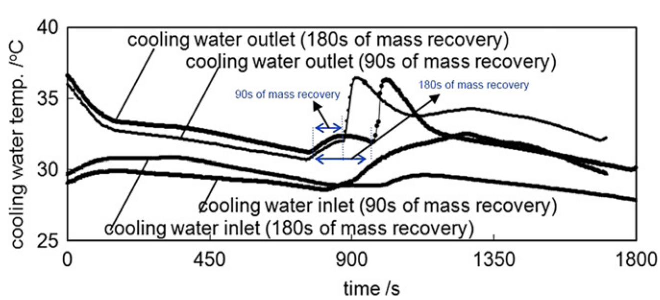

Fig. 8. The adsorption chiller cooling water temperature variation with the cycle time.

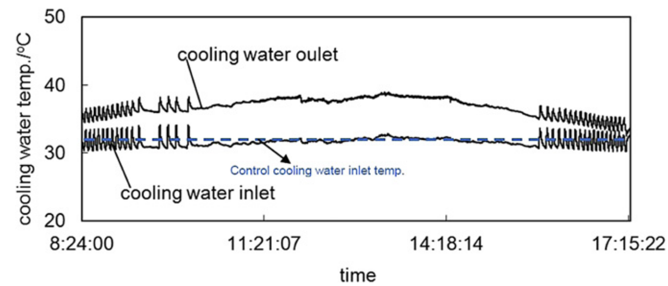

Fig. 9. The absorption chiller cooling water temperature variation with the cycle time.

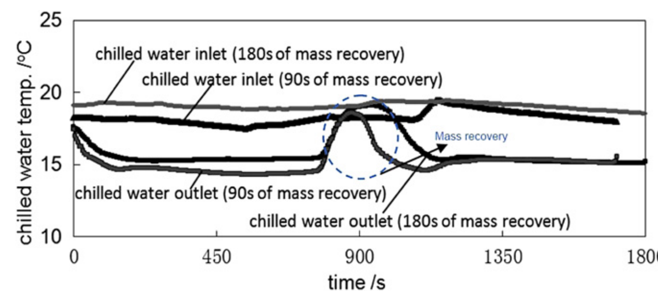

Fig. 10. The adsorption chiller chilled water temperature variation with the cycle time.

(2) The cold adsorption bed can re-adsorb more water vapour because of the sharp rise of pressure during the process of mass recovery. More heat will be rejected, and the cooling water outlet temperature will rise. Fig. 9 shows that the cooling water inlet and outlet temperature of the absorption cooling system is more stable than that of adsorption chiller system. The cooling water inlet temperature of absorption cooling system can be controlled by the starting/stopping of the fan.

3.3. Performance variation and comparison of two solar air conditioning system influenced by chilled water

The dynamical characteristics of chilled water for the adsorption chiller and the absorption chiller are shown in Figs.10 and 11, respectively. Fig. 10 shows that: (1) the chilled water outlet temperature declines sharply at the beginning of the cycle, then it becomes constant, and it rises again during the process of mass and heat recovery. (2) The adsorption cooling performance with different mass recovery time is shown in Table 4. If the mass-heat recovery time is too short, the re-adsorption and re-desorption cannot be completed. Otherwise, if the time of mass-heat recovery is too long, the cooling capacity will be influenced by the long cycle time. Fig. 11 shows that: (1) The chilled water inlet and outlet temperature of the absorption cooling system is more

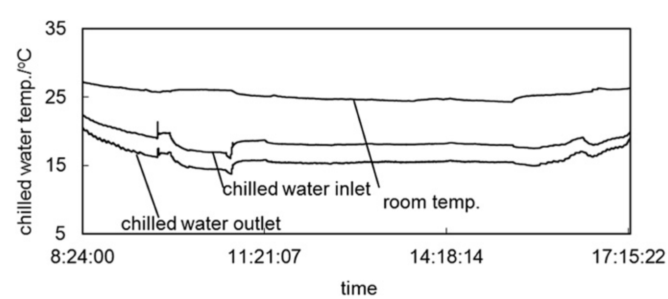

Fig. 11. The absorption chiller chilled water temperature variation with the cycle time.

Table 4
The adsorption cooling performance with different mass recovery time.

Mass recovery time (s)	Hot water inlet (°C)	Hot water outlet (°C)	Cooling water inlet (°C)	Cooling water outlet (°C)	Chilled water inlet (°C)	Chilled water outlet (°C)	Cooling capacity (kW)	COP
180	64.7	59.6	29.6	32.0	18.5	15.2	7.5	0.36
90	65.2	60.6	30.2	33.0	18.2	15.4	6.5	0.32

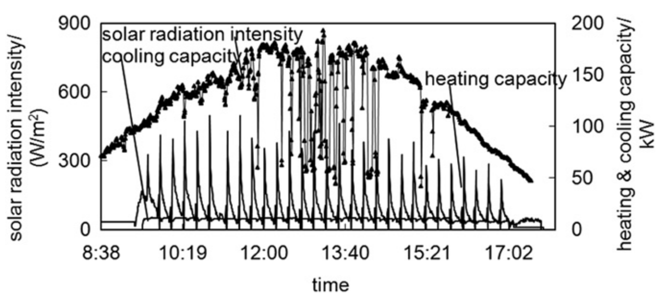

Fig. 12. The heating and cooling capacity variation with solar radiation for the adsorption cooling system.

stable than that of adsorption chiller system. (2) The solar absorption system can provide chilled water at 15 °C from 11:00 to 15:30. The working time of solar absorption cooling system is shorter than that of solar adsorption cooling system.

3.4. Analysis of two solar air conditioning system operation characteristics

The operation characteristics of heating and cooling capacity variation with solar radiation intensity for the adsorption chiller and the absorption chiller are shown in Figs. 12 and 13. Figs. 12 and 13 show that: (1) The heating capacity is influenced directly by solar radiation intensity. Usually, the solar radiation is strongest in the day between 11:00 to 13:00, so, the average cooling capacity is largest during this time. The cooling capacity of the adsorption cooling system and the absorption cooling system are 9.4 kW and 9.2 kW, while their COPs are 0.16 and 0.19, respectively. (2) The heating and cooling capacity of the adsorption cooling system changes sharply at the switching time, while the fluctuation of the absorption cooling system is much smoother.

Medium temperature evacuated-tube CPC (Compound Parabolic Concentrator) solar collectors were used in the absorption cooling system. These solar collectors have higher efficiency compared to that of traditional solar collectors. The solar collector efficiency of the two systems is shown in Fig. 14, which shows that the solar

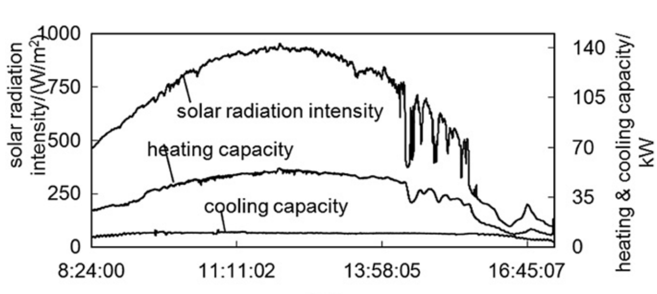

Fig. 13. The heating and cooling capacity variation with solar radiation for the absorption cooling system.

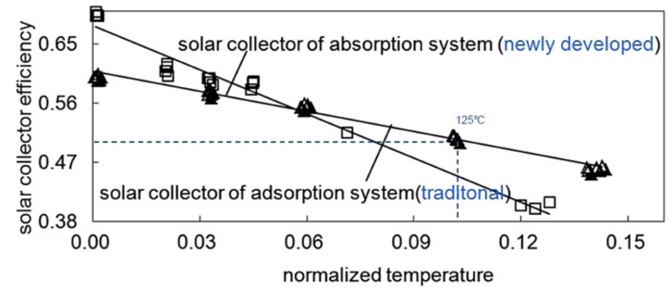

Fig. 14. Comparison of the solar collector efficiency for adsorption and absorption cooling systems.

collector efficiency of the newly developed collector can reach 0.5 when the hot water temperature is about 125 °C.

4. Conclusions

Performance comparison of solar powered silica gel-water adsorption chiller and LiBr-H_2O absorption chiller was experimentally investigated and applied in north of China. The thermal kinetics characteristics and system performance comparision of these two kinds solar chiller were studied. The following conclusions were obtained:

(1) The duration of mass recovery in the adsorption cooling chiller has influence on the system performance, when the hot water inlet temperature, cooling water inlet temperature, chilled water outlet temperature and mass recovery time is about 65 °C, 30 °C, 15 °C and 180 s, respectively; the cooling capacity and the COP are 7.5 kW and 0.36.
(2) Two-phase thermo-syphon adsorption chiller is designed, which has few valves and the system reliability can be improved. The output of cooling capacity can be controlled to different bed automatically by the design of two-phase thermo-syphon. The adsorption chiller can be powered by low temperature hot water of 55 °C, and it can provide 15 °C of chilled water from 9:30 to 17:00, the average solar COPs is 0.16.
(3) New medium temperature evacuated-tube CPC (Compound Parabolic Concentrator) solar collectors were used in the absorption cooling system, which solar collector efficiency can reach 0.5 when the hot water temperature is 125 °C. The absorption chiller should be powered by hot water with a temperature of at least 80 °C, and it can provide 15 °C of chilled water from 11:00 to 15:30, and the average solar COPs is 0.19.

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