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Solar driven air conditioning and refrigeration systems corresponding to various heating source temperatures

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HIGHLIGHTS

- Modular silica gel–water adsorption chiller was designed and tested.
- Single/double effect LiBr–water absorption chiller was operated and tested.
- 1.*n* effect LiBr–water absorption chiller was proposed, designed and tested.
- $CaCl_2$/AC–ammonia adsorption refrigerator was introduced and tested.
- NH_3–H_2O absorption ice maker with better internal heat recovery was introduced.

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ABSTRACT

Solar driven air conditioning systems can cope with solar collectors working in a wide range of temperatures. Sorption systems, including absorption and adsorption refrigeration systems, are among the best choices for solar cooling. Five systems including modular silica gel–water adsorption chiller, single/double effect LiBr–water absorption chiller, 1.*n* effect LiBr–water absorption chiller, $CaCl_2$/AC (activated carbon)–ammonia adsorption refrigerator, and the water–ammonia absorption ice maker with better internal heat recovery were presented. The above five sorption chillers/refrigerators work under various driven temperatures and fulfill different refrigeration demands. The thermodynamic design and system development of the systems were shown. All these systems have improvements in comparison with existing systems and may offer good options for high efficient solar cooling in the near future.

1. Introduction

Energy crisis and environment pollution are two vital problems for the modern society. Researches about sustainable energy utilization and environment friendly technologies are essential. Solar driven sorption air conditioning and refrigeration systems combine the solar utilization and thermally driven refrigeration technologies which can be good solutions for the above mentioned problems [1–3]. These systems mainly include the LiBr–water absorption refrigeration systems, the water–ammonia absorption refrigeration systems and the adsorption refrigeration systems. They have different driving temperatures and correspond with different solar heat sources. However, these systems all have their own weaknesses which need to be further improved.

LiBr–water absorption chillers are very popular in solar cooling systems for commercialized availability. For solar driven LiBr–water absorption cooling, the coupling between chiller and solar collector is the key point. Single effect absorption chiller (heating source 80 °C or high, COP = 0.6–0.7) can work with low temperature solar collectors like evacuated tube collector [4,5] and flat-plate collector [6]. It can also work with medium temperature solar collectors (150–200 °C) like parabolic trough collector [7] or even LFR. As the medium temperature solar collectors could yield heat source of higher temperature, single effect absorption chiller cannot match such a high temperature heat source (140 °C or higher) and have to be replaced with a double effect absorption chiller with a COP higher than 1.2. Good examples of solar powered double effect LiBr–water absorption chiller include LFR driven system [8] and linear parabolic trough solar collector driven system [9]. Besides, auxiliary heat source (natural gas for example) is sometimes needed to ensure the continuous operation of the system. When auxiliary heating was used, the solar system with single effect absorption chiller is not highly efficient. In real operation of a solar cooling system, the heat source temperature could be varied greatly. Problems including intermittency and instability

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Nomenclature

COP	coefficient of performance	ch	chilled water
SCP	specific cooling power (W kg^{-1})	d	desorption
T	temperature (°C)	m	mass recovery
Q	heat transfer amount (kW)	h	heat recovery
t	time (s)	gen	generator
		1	inlet
Subscripts		2	outlet
hot	hot water		
c	cooling water		

exist in the coupling between solar energy and chiller. In order to solve this problem, novel absorption cycles and solar thermal storage have been researched a lot. Novel absorption cycles include the SE/DL cycle [10,11], 1.5 effect cycle [12], EAX cycle [13], 1.*n* effect cycle [14,15] and so on. They provide better coupling or better adaptation with the solar heat source. Solar thermal storage researches include the sensible heat storage, latent heat storage and chemical heat storage [16].

Water–ammonia absorption refrigeration system can also be driven by solar energy. The ammonia–water GAX absorption cycle is able to utilize heat source of variable temperature which is suitable for solar cooling [17]. Recently, the researches on ammonia water absorption system are mostly focus on three interests including absorption enhancement [18–21], new cycles [22–24] and combined systems [25–28]. Moreover, there are some advantages compared to a LiBr–water absorption system such as no crystallization, easier maintenance and applications below 0 °C. However, the key point for solar driven water–ammonia absorption refrigeration system is not the coupling between solar collector and chiller, but the drawbacks of the chiller such as low COP, large bulk and high initial investment. A rectification process is also commonly necessary because the generated vapor contains a certain amount of water which deteriorates the system performance if it flows into the evaporator [29]. It is more important in low temperature applications because the water content is considerable. The purifier increases not only the initial investment but also the heat consumption. It is important to improve the system COP to extend the applications of water–ammonia absorption systems. There are various demonstration projects using water–ammonia absorption refrigeration (both for chiller or ice maker) system, in which a medium temperature solar collector (around 150 °C) is usually required. High performance water–ammonia absorption refrigeration is the most concerned issue if it is driven by a medium temperature solar collector.

Another promising thermally driven refrigeration technology is adsorption refrigeration. This is becoming more and more popular in solar driven air conditioning and refrigeration systems since it can work under wide heat source temperature range. Adsorption chiller using silica gel–water working pair can be driven by 50–90 °C hot water directly and supply 5–15 °C chilled water, which is quite suitable for solar air conditioning. Due to its low driven temperature, silica gel–water adsorption chiller can couple well with the solar power for the whole daytime [30]. The commercialized products of silica gel–water adsorption chiller were developed by the Nishiyodo Kuchouki, Co. Ltd. as early as 1986 [1]. This product is still sold by the HIJC USA Inc. [31], Mycom [32], SorTech [2] and SJTU have also developed their own silica gel–water adsorption chiller products in recent years [33–35]. Except for this, ammonia or methanol is always used as refrigerant for adsorption ice maker. However, activated carbon–methanol adsorption refrigerator has low SCP (specific cooling power) which leads to large system size [36]. So, chemical adsorbent–ammonia adsorption refrigerator seems more advantageous for solar freezing application. But agglomeration and expansion problems of single chemical adsorbent limit its performance. In this case, composite adsorbent, consisting of chemical adsorbent and porous medium, was proposed and widely applied [37,38]. Integrated and compact adsorption chillers and refrigerators with a series cooling capacity and high COP are usually requested in the market.

In this paper, experimental works about five different options of solar cooling systems are introduced. LiBr–water absorption systems, water–ammonia absorption systems and adsorption refrigeration systems (silica gel–water, and composite compound–ammonia) are all included, in which 3 of the systems are designed for air conditioning and the other 2 systems are designed for refrigeration. These systems all have improvements in comparison with existing systems and may offer good options for highly efficient solar cooling. For the utilization of solar heating power, whether it can be utilized is more important than how it is utilized. So, driven temperature is chosen as the classification criteria instead of refrigeration principle or working pair.

2. Modular silica gel–water adsorption chiller (heat source temperature: 55–90 °C)

The silica gel–water has been commercialized. However, silica gel–water adsorption chiller has not been widely used due to its shortcomings, like large size, low efficiency and high cost. A 50 kW silica gel–water adsorption chiller was recently developed by SJTU. Modular design concept is adopted to increase the efficiency and reduce system size and cost. The heat source temperature of the chiller is between 55 °C and 90 °C.

2.1. Description of the chiller

The 50 kW silica gel–water adsorption chiller with rated COP over 0.4 is shown in Fig. 1. It has 2.88 m length, 1.92 m width and 2.52 m height. This chiller includes two adsorbers, two condensers, two evaporators, one chilled water pump, one chilled water tank and eight valves. The two adsorbers can alternate between adsorption and desorption phases to realize continuous cooling via switching the hot/cooling water valves (V1–V4). After desorption phase, adsorber is still very hot and heat can be recovered to reduce energy input. A partly heat recovery process can be fulfilled after adsorption/desorption switch via valves V1–V4. Besides, evaporator temperature shows periodical change due to adsorption/desorption switch, which will cause dissipation of cooling capacity. To reduce the dissipation, a mass recovery-like process [35] is adopted via chilled water valves, while no vacuum valve is used. The system reliability is enhanced without vacuum valve. Considering the remarkable feature of adsorption refrigeration system, the cooling capacity will change periodically. For better cooling effect, a chilled water pump is installed to guarantee a stable outlet temperature of chilled water. In addition, chilled