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Concept design and formation of a lithium bromide–water cooling system powered by supercritical CO_2 solar collector

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ABSTRACT

In this study, concept design and tests for the combination of a supercritical CO_2 solar collector powered LiBr–H_2O refrigeration system has been investigated. The system is basically consisted of one supercritical CO_2 solar collector system and one double effect lithium bromide–water absorption refrigeration cycle. The assessment of the overall performance is based on the theoretical analysis of the refrigeration cycle and experiments on a supercritical solar collector system in Shaoxing City, Zhejiang Province of China. Energy balance and seasonal efficiency analysis are developed in this study. The maximum daily averaged *COP* (Coefficient of Performance) of the proposed system is estimated up to 1.08, while the averaged *COP* ranges from 0.53 to 0.91 for different months. The obtained results indicate considerable improvement to conventional solar-assisted cooling systems. In addition, it is also found that this system performs better than traditional systems even when the solar radiation is not at high level, which is due to the stability and high efficiency of supercritical circulation collector cycle proposed. The system feasibility and possible future directions of the proposed system are also discussed in detail in this study. It is hoped that the current results can be of help to related system designs.

1. Introduction

Effective cooling and heating has become one of the major concerns both in domestic sectors and industrial fields in recent years. However, energy sources should be guaranteed first when discussing the efficiency of various technologies involved. Many believe that fossil fuels, which have been used as energy source for long time, will gradually be replaced by new ones in the near future [1,2]. Meanwhile, the utilization of fossil fuels also brings about heavy emission of green-house gases, which is generally proved responsible for global warming and climate changes. To alleviate these problems, the utilization of renewable energies has been put forward [3–5]. Solar energy, as a renewable energy source, is abundant, clear and free. Therefore in recent decades solar energy has been one popular source for energy systems [5–7]. For both heating and cooling/refrigeration systems, solar energy can provide one convenient and cheap source. It has won expanded market in recent years, especially in developing countries of Asia, Africa and South America [3]. In some tropical and subtropical cities, air-conditioning may consume more than 50% of the total electric energy during summer days [2]. Major reviews in the developments can be found in Refs. [3–7].

For solar heating and cooling systems, usually the system will be consisted of two parts: the solar collector circulation loop side and the heating/cooling cycle side. For solar collector loop side, there are large numbers of publications in literature, and the representative ones can be found in review articles in Refs. [4,5]. The latest developments focused on the topics such as effective solar radiation receiver, high efficiency heat transfer, and circulation flow dynamics. Specifically on the working fluids, most traditional systems used water. However, due to the relative high specific heat and high viscosity, hot water temperature is limited (usually below 90 °C) and large system pressure loss can be seen [2,6–9]. In recent years, supercritical CO_2 fluid based solar collector has been proposed, which utilizes the preferable fluid thermal and transport properties [10].

As shown in Fig. 1, supercritical CO_2 is very sensitive with good thermal properties in the supercritical region. It has also been proved to have high energy transport potential when used in basic flow geometries [11–13], heat transfer loops [14–17] as well as thermal cycles [8,9,18–20] (especially supercritical solar Rankine cycle has become one hot topic in recent years [9,20]). Different from traditional solar collector systems, heat transfer of

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Nomenclature

A	collector area (m^2)
COP	coefficient of performance
h	specific enthalpy (J/kg)
Q	heat load (kW)
H	enthalpy (kJ)
q	heat quantity (kJ)
t	celsius temperature (°C)
W	work (kW)
ε	effectiveness of heat exchanger
η	collector efficiency
m	mass flow (kg/s)

Subscripts

a	absorber
atm	atmosphere
c	condenser
CO_2	carbon dioxide
col	collector
ce	chilling effect
e	evaporator
ext	external
$hx1$	high-temperature heat recovery system in solar collection cycle
$hx2$	low-temperature heat recovery system in solar collection cycle
hpg	high-pressure generator
$hphx$	high-pressure heat exchanger in chiller cycle
lpg	low-pressure generator
$lphx$	low-pressure heat exchanger in chiller cycle
int	internal
sol	solution
$solar$	solar

supercritical CO_2 in some conditions is found to be greatly enhanced, which also lead to high temperature and good collector efficiency [8,21–23]. According to recent theoretical and experimental studies [21–23], the pressure loss of supercritical state CO_2 circulation flow is very small, which is due to the relative low viscosity compared with traditional water or normal state fluid flow. Thus high circulation rate can be achieved. The overall solar to thermal heat transfer rate is also improved in such systems. Indeed, the overall solar thermal conversion efficiency has been found above 60% even only natural circulation is used [21–23]. Due to the above reasons, the supercritical CO_2 based solar collector systems have attracted a lot of studies for energy conversion and coupled heating/cooling systems.

In this study, different from previous solar heating discussions of solar energy conversion and solar water heaters [18–23], supercritical fluid based solar cooling is focused. Among various solar-assisted cooling/refrigeration systems, lithium bromine–water absorption cooling system is one of the most popular kinds for generating solar cooling capacity [25–30]. Bromine–water absorption cooling cycle can operate with low-grade energy sources and have good system performance [6,7]. Recent developments of solar-assisted lithium bromine–water absorption cooling systems can be found in Refs. [6,7]. For representative studies, Mazloumi et al. [23] reported one lithium bromide–water absorption cooling system and suggested that it has better performance than traditional ones.

Also, there are several groups that have studied the solar based LiBr–water refrigeration cycles. The representative models and their operation ranges, basic *COP* (Coefficient of Performance) data and other related model information are summarized in Table 1. In those studies [25–30], LiBr–water is the basic refrigeration cycle fluid. The specific system design and operation spot are different from one by one, however the *COP* falls around 0.5–0.85. Experimental ones show basic feasibility of the solar assisted refrigeration cycles in those studies. However, most of which are designed and tested form small office use and laboratory scale tests, and there still exists a lot of problems during the operation. The performance of those systems is still less optimized. New systems and optimal designs, including the refrigerant, cycle design, seasonal operation strategy, etc., are still wanted for next step development.

Indeed, most existing solar cooling designs use single effect LiBr–H_2O absorption systems as chillers [6,7]. Double effect LiBr–H_2O absorption system can reduce heat transfer irreversibility; therefore it can achieve relative higher *COP* (around 1.2) than that of single effect system. However, double effect system requires higher temperature in its high-pressure generator (about 140 °C), which is beyond the limit of conventional solar water heaters. Liu and Wang [31] proposed a solar/gas based double effect LiBr–H_2O absorption system. In that study, only the low-pressure generator can utilize solar energy because of the limit of hot water temperature. The high-pressure generator of the system is still powered by gas combustion, which accounts for 60–70% of total energy consumption. Though the *COP* of that system is relatively high, it is still strongly dependent on traditional fossil fuels. From the above discussion, it can be seen that the solar to thermal conversion and stable operation are major key points for solar powered LiBr–H_2O absorption systems. If the double-effect LiBr–H_2O absorption systems can be stably operated with high efficient solar conversion component as discussed formerly, possible energy-saving kind of refrigeration capacity can be achieved.

In the present study, a new solar cooling system is proposed using supercritical CO_2 at the collector side and by using double effect LiBr–H_2O absorption at the refrigeration side. By combining the advantages of both systems, experimental set ups of the supercritical fluid side are tested. For the LiBr–H_2O side, theoretical analysis and system performances are discussed. The system formation of the connected cycles and its basic features and feasibility are also included in the discussion. This study is one first trial on such combined cycles, so as to achieve a continuous effort of increasing collecting thermal temperature and enhancing solar cooling efficiency. It is hoped that this study can contribute to related application system designs and optimizations.

2. System design and experimental set-ups

2.1. Basic system design

Improved solar collector can provide relatively higher thermal recovery efficiency and improve the performance of combined solar-assisted LiBr–water double effect absorption cooling cycle. Zhang et al. [8,22,23] reported that an evacuated tube solar collector using supercritical carbon dioxide as heat transfer fluid can obtain a higher collector efficiency (over 65%) and operate under a higher temperature (185 °C at noon). Later, based on recent experimental and theoretical works [16,17,32], Zhang et al.