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Performance advancement of solar air-conditioning through integrated system design for building

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ABSTRACT

This study is to advance the energy performance of solar air-conditioning system through appropriate component integration from the absorption refrigeration cycle and proper high-temperature cooling. In the previous studies, the solar absorption air-conditioning using the working pair of water – lithium bromide (H_2O–LiBr) is found to have prominent primary energy saving than the conventional compression air-conditioning for buildings in the hot-humid climate. In this study, three integration strategies have been generated for solar cooling, namely integrated absorption air-conditioning; integrated absorption-desiccant air-conditioning; and integrated absorption-desiccant air-conditioning for radiant cooling. To realize these ideas, the working pair of ammonia – water (NH_3–H_2O) was used in the absorption cycle, rather than H_2O–LiBr. As such, the evaporator and the condenser can be separate from the absorption refrigeration cycle for the new configuration of various integrated design alternatives. Through dynamic simulation, the year-round primary energy saving of the proposed integration strategies for solar NH_3–H_2O absorption air-conditioning systems could be up to 50.6% and 25.5%, as compared to the conventional compression air-conditioning and the basic solar H_2O–LiBr absorption air-conditioning respectively. Consequently, carbon reduction of building air-conditioning can be achieved more effectively through the integrated system design in the hot and humid cities.

1. Introduction

Air-conditioning becomes indispensable due to the effect of climate change and global warming. If the conventional electrical air-conditioning is still adopted but the electricity is generated from fossil fuels, the carbon emission problem would certainly aggravate the climate change, in turn the demand of air-conditioning would soar. With proper use of solar energy for air-conditioning, such dead loop can be ceased. For continuous population and economic growth, wider use of solar air-conditioning would even secure the increasing energy demand and maintain sustainable development. Henning [1] and Eicker [2] have provided design calculations and discussions on various basic solar refrigeration and air-conditioning systems, including solar absorption air-conditioning, solar adsorption air-conditioning and solar desiccant cooling. It is popular to adopt the absorption chiller with the refrigerant-absorbent working pair of water-lithium bromide (H_2O–LiBr) [3]. A number of general studies of solar H_2O–LiBr absorption air-conditioning have been carried out [4–6]. In the building applications of solar air-conditioning systems, besides commercial buildings [7–9], solar H_2O–LiBr absorption air-conditioning has been provided in a variety of premises, like the hospital [10], classroom [11], medical centre [12], residential villa [13] and research institute [14].

Continual development of solar absorption air-conditioning system has been carried out. Sumathy et al. [15] presented the feasibility of solar absorption air-conditioning using a 2-stage H_2O–LiBr absorption chiller. Although 75 °C hot water was effective to operate this 2-stage absorption cycle and provide 9 °C chilled water, but the COP (coefficient of performance) was relatively low, only around 0.4. Li and Sumathy [16] increased 19% of COP for a solar H_2O–LiBr absorption refrigeration system by using a 4-segment partitioned hot water tank rather than a stratified one. Gonzalez-Gil et al. [17] used air-cooled heat dissipation for the condenser and the absorber of H_2O–LiBr single-effect absorption chiller and found that the COP was around 0.6 when the chilled water supply temperatures were between 14 °C and 16 °C. Bujedo et al. [18] applied appropriate control strategy to enhance the part-load performance of solar absorption air-conditioning system. Due to the intermittent nature and night time unavailability of solar energy, performance enhancement studies of solar absorption air-

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Nomenclature

COP	Coefficient of performance
COP_{AB}	Coefficient of performance of absorption chiller
COP_{AAU}	Coefficient of performance of absorption air conditioner
COP_{ADAU}	Coefficient of performance of integrated desiccant air conditioner
$H_{fa,i}$	Enthalpy of fresh air intake (kW)
$H_{ma,saci}$	Enthalpy of mixed air at supply air coil inlet (kW)
$H_{ra,saci}$	Enthalpy of return air at supply air coil inlet (kW)
H_{sa}	Enthalpy of supply air (kW)
Q_{ab}	Regenerative heating for absorption chiller (kW)
Q_c	Cooling capacity (kW)
Q_{hrc}	Regenerative heating of heat recovery coil (kW)
Q_{pcb}	Total capacity of the passive chilled beams (kW)
Q_{rc}	Regenerative heating of regenerator coil (kW)
Q_{solar}	Solar thermal gain (kW)
RH_{zone}	Zone relative humidity (%)
SF	Solar fraction
$T_{rw,i}$	Regenerative water entering temperature (°C)
T_{zone}	Zone dry-bulb temperature (°C)

conditioning have been carried out with various thermal storage means, like chilled water storage [19,20], absorbent storage [21] and refrigerant storage [22].

Besides using the working pair of H_2O–LiBr, attention has also been paid to the alternative of ammonia-water (NH_3–H_2O) in solar cooling [23–25]. Lin et al. [26] developed a two-stage air-cooled NH_3–H_2O absorption chiller, which could have COP of 0.34 when it was driven by the 85 °C hot water generated from solar energy. Du et al. [27] built a solar NH_3–H_2O absorption air-conditioning prototype with cooling capacity of 2 kW, it is technically feasible and has opened a way to develop low-cost small solar cooling system for residential use. To enhance the COP of solar NH_3–H_2O absorption air-conditioning, the idea of diffusion-absorption refrigeration cycle was introduced by using an auxiliary inert gas to both refrigerant and absorbent, like hydrogen or helium for the working pair of NH_3–H_2O [28,29].

In this study, the advancement of solar absorption air-conditioning using NH_3–H_2O is proposed through better integration of the components of refrigeration cycle. The rest of this paper is structured in the following way. Section 2 brings out the integration strategies for solar absorption air-conditioning using the working pair of NH_3–H_2O. Section 3 presents the dynamic simulation and modeling details of the proposed integrated system design alternatives for the energy study around a year. Section 4 states the metrics of performance evaluation and analysis. Section 5 discusses the results and highlights the effective integrated system design of solar absorption air-conditioning. Section 6 is conclusion and recommendation.

2. Integrated strategies for solar absorption air-conditioning design

The technical feasibility of the solar thermal air-conditioning systems depends strongly on the COP of the chiller and the thermal output of the solar collectors. Based on the previous studies [30,31] in the hot and humid climate, it was found that the basic AAS (absorption air-conditioning system), which consisted of H_2O–LiBr absorption chiller powered by solar energy through the evacuated tube collectors, could offer substantial energy saving compared to the conventional CAS (compression air-conditioning system) using electrical vapor compression chiller. A typical system schematic diagram of the AAS is shown in Fig. 1, including the absorption chiller, the solar energy collection and regenerative water supply for the generator, the chilled water supply from the evaporator, the cooling water supply for the condenser and the absorber, and the air handling unit for the building zone.

As low-pressure water is used as the refrigerant in H_2O–LiBr absorption chiller, the size of the equipment would be large and causing spatial demand. To improve the system effectiveness, three integration strategies are supposed in this study. To realize the new approaches, the alternative working pair of NH_3–H_2O is adopted for the absorption chiller. The target is to directly provide air-conditioning for buildings in the hot-humid climate. Although COP of the NH_3–H_2O absorption chiller is generally lower than that of the H_2O–LiBr one, however, it is unlikely to apply the proposed strategies in the H_2O–LiBr absorption system. Since its evaporator and condenser are grouped together with the absorber and generator respectively, in order to facilitate the migration of refrigerant within the system. The details of the three integration alternatives are discussed as follows. The respective changes of air states in the systems are shown in Fig. 2.

2.1. Integrated absorption air-conditioning unit

The first integration strategy is to convert the evaporator into a direct-expansion supply air coil, and the system becomes an IAAU (integrated absorption air-conditioning unit), which can provide direct supply air for the conditioned space of building zone. The schematic diagram of the solar-driven IAAU is illustrated in Fig. 3. The mixed air (MA_{IAAU}) entering the supply air coil is composed of the FA (fresh air) and the RA (return air) with the state conditions indicated in Fig. 2. The SA (supply air) leaving the supply air coil is used to handle both the sensible and latent loads of the building zone. The GV (generator valve) is on/off type and controlled by the zone thermostat, and it opens when the absorption refrigeration is in operation. The SAF (supply air fan) runs continuously during the entire daily occupied period. The RWP (regenerative water pump) and the CWP (cooling water pump) are energized when the absorption cycle starts, and the cooling tower is additionally controlled according to the cooling water temperature leaving the IAAU. The operation of the HWP (hot water pump), used to convey the solar heat to the storage tank, is governed by a differential thermostat which ensures that the water leaving the solar collector is higher than that inside the hot water tank within the daily operation schedule. Evacuated tubes are employed as the solar collectors.

In fact, there has been encouragement to apply the air- or water-cooled compression chillers with the refrigerant of ammonia because of their potentially higher coefficient of performance [32,33]. Due to the nature of low toxicity of ammonia, it is aware that there is risk in using a direct-expansion cooling coil with the refrigerant of ammonia in the supply air stream. However in this study, the focus was emphasized on energy analysis of the advanced system design of solar air-conditioning system primarily. For the sake of safety in practical operation, ammonia leakage detection and fail-safe activation can be included in the proposed systems, which are commonly found in the ammonia-related industrial applications.

2.2. Integrated absorption-desiccant air-conditioning unit

To further enhance the system performance, the second integration strategy is to integrate the components of the absorption refrigeration cycle with the desiccant cooling. This is different from the hybrid design which to make use of a separate absorption