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Performance analysis of a novel liquid desiccant-vapor compression hybrid air-conditioning system

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ABSTRACT

LDCH (Liquid desiccant-vapor compression hybrid) air-conditioning systems are popular for reducing energy consumption. This work tests a conventional LDCH air-conditioning experimental setup and establishes the corresponding mathematical model to analyze the effect of the concentrated solution branch in the SSHE (solution–solution heat exchanger) on the cooling capacity of the evaporator; the results show that the percentage of cooling capacity loss of the evaporator exceeds 10% with the small concentration difference of 1.5% in the conventional LDCH air-conditioning system. Afterwards, a new LDCH air-conditioning system is proposed by adopting an auxiliary regenerator to cut down the cooling capacity loss of the evaporator, and the analysis results show that there is a big temperature drop of the concentrated solution branch after being pretreated by the auxiliary regenerator; under the condition of concentration difference of 2.65%, the inlet temperature of concentrated solution branch from the regeneration side in the SSHE can decrease over 6 °C; and the extra heat load entering the dehumidification side from the regeneration side obviously decreases. Consequently, the evaporator only needs to spend 1.5% of its cooling capacity on the compensation for the extra heat load.

1. Introduction

Reducing energy consumption of air-conditioning systems is very important for improvement of building energy efficiency. In a conventional air-conditioning system, air is conditioned by passing it over a cooling coil to achieve both cooling and dehumidification; dehumidification is realized by cooling the air to below its dew point. As a result, the dehumidified air is cooler than the required indoor comfort level, which in turn causes reheating and further energy loss. Meanwhile, since chilled water with a relatively lower temperature is needed, the performance of chillers is decreased. Furthermore, health problems can occur because the condensed water makes the coil surface a breeding ground for bacteria. A Liquid desiccant air-conditioning system has been gaining attentions as an alternative to the conventional dehumidification system. The liquid desiccant system can dehumidify the humid air by the direct contact between the humid air and concentrated solution. The diluted solution after the dehumidification has to be concentrated to use it again. Therefore, the system mainly consists of a dehumidifier and a regenerator. Moreover, the liquid desiccant air-conditioning system can be driven by low-temperature heat source. From this feature, the efficiency of the system is expected to be enhanced by use of the waste heat from a compression heat pump for the regeneration of the diluted solution. In this study, we focus on the LDCH (liquid desiccant-vapor compression hybrid) air-conditioning system consisting of a liquid desiccant system and a vapor compression heat pump [1–3].

Some previous studies on the LDCH air-conditioning system are described as follows. 1) Prior works on developing new systems of LDCH air-conditioning units: Yadav (1995) investigated the effect of operating parameters on the performance of the hybrid solar air conditioning system. The system consists of liquid desiccant cycles and conventional vapor compression. Lithium bromide is used as solution in the liquid desiccant cycle and R-11 is used as refrigerant in the vapor compression system. The results show that the system is more promising under high latent heat load [4]. Ani et al. (2005) established a hybrid system consisting of vapor compression system, liquid desiccant system and solar collector, and investigated

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the optimization of the absorber packing height by experiments [5]. Gasparella et al. (2005) simulated a hybrid system of ground-source heat pump and liquid desiccant. This novel system can save around 30% of the primary energy annually compared with the conventional systems [6]. Zhang et al. (2010 and 2012) proposed a new frost-free hybrid air-conditioning system, which integrated with liquid desiccant dehumidification units. In the system, a heat pump is used for the solution regeneration and pre-cooling in summer. In winter, frosting can be avoided by dehumidifying the air before it enters into the evaporator of the heat pump. The results show that the COP (coefficient of performance) is 30–40% higher than that of the heat pump integrated with an electric heater [7,8]. Mohan et al. (2015) investigated a new liquid desiccant-vapor compression hybrid air conditioner. In this hybrid system, the desiccant dehumidifier is placed after the evaporator, and the regenerator is after the condenser of the AC unit [9].

2) Prior works on seeking methods to improve the designs of configuration: Wu et al. (2006) investigated an internally cooled liquid desiccant dehumidifier. The evaporator of the vapor compression system is set in the dehumidifier to remove the condensing heats of vapor and cool process air, and the condenser equipped in the regenerator is used to heat the regenerating solution [10]. Mohan et al. (2008) investigated the characteristics of absorber and regenerator columns for hybrid liquid desiccant air-conditioning system. The simulation model of countercurrent absorber and regenerator is developed on the basis of heat and mass balance and heat and mass analogy [11].

3) Prior works about examination, test and simulation of system performance: Bergero and Chiari (2010 and 2011) examined the performance of an air dehumidification system integrated with a vapor compression inverse cycle. Air is dehumidified in an air-solution membrane contractor and cooled by a vapor compression cycle; lithium chloride solution is cooled by a vapor compression unit and regenerated in another membrane. The results show 60% energy savings at high latent heat load compared with a traditional direct expansion air conditioning system [12,13]. Yamaguchi et al. (2011) conducted the performance evaluation test of a hybrid liquid desiccant air-conditioning system consisting of a conventional liquid desiccant system and a vapor compression heat pump. The main feature of this system is that the absorber and regenerator are integrated with the evaporator and condenser, respectively. The results showed that the COP of the system was 2.71 [14]. Zhao et al. (2011) investigated the real operating performance of the temperature and humidity independent control air-conditioning system. The system is composed of a two stage total heat recovery device and a two-stage air handling device coupled with refrigeration cycles. The total heat recovery device is used to recover the energy from return air to decrease the energy consumption in the fresh air handling process. In the heat pump driven air handling device, the diluted solution from the dehumidification module is heated by the exhaust heat from the condenser, and the hot concentrated solution from the generation module is cooled by the evaporator [15]. Lazzarin and Castellotti (2007) conducted energy savings of a novel desiccant air-handling unit with that of a traditional mechanical dehumidifier. In the air-handling unit, the diluted desiccant solution is regenerated using the thermal energy supply from a primary heat pump condenser, while air regeneration is used a secondary heat pump condenser [16]. Li et al. (2005) carried out numerical simulation to predict the performance a new type of fresh air processor system in different meteorological conditions. The system is combined of liquid desiccant total heat recovery device and a refrigeration cycle, and divided into two parts, the first part is appeared in the middle solution for the purpose of total heat recovery and the second part appeared in the left and right side where liquid desiccant exchanges sensible heat with the refrigeration cycle [17].

4) Prior works on removing the superfluous heat capacity of the condenser: the amount of heat from the condenser in a LDCH air-conditioning system is often more than the heat needed in desiccant regeneration process. To remove the superfluous condensing heat, Zhang et al. (2012) used two different methods for removing the extra heat. In the first method, they used a water-cooled assistant condenser; in the second method, they added an air-cooled assistant condenser. The coefficient performance of the system with the water-cooled condenser was approximately 35% higher than the basic system [18]. Niu et al. (2012) studied the capacity matching of a new hybrid liquid desiccant air conditioning system, which consisted of a liquid desiccant dehumidification and a heat pump system with double condensers. The results show that the system with a double-condenser is a feasible configuration for achieving capacity matching [19]. Chen et al. (2014) proposed a novel temperature and humidity independent control air-conditioning system based on liquid desiccant. In the system, an air-cooled condenser works in series with a solution-cooled condenser, and the refrigerant from compressor rejects its condensation heat firstly to the solution-cooled condenser and then to the air-cooled condenser. This makes capacity matching between the dehumidification and regeneration processes more efficient [20].

However, these reviewed studies above had paid few attentions to the heat exchanging process between the concentrated solution from regeneration side and the diluted solution from the dehumidification side. In a LDCH air-conditioning system, the SSHE (solution–solution heat exchanger) lies between the concentrated solution branch from regeneration side and the diluted solution branch from dehumidification side, and the concentrated solution branch from the regeneration side is pre-cooled in the SSHE before entering the dehumidification side, but the temperature of concentrated solution branch leaving from the SSHE is still higher than the temperature of solution in dehumidification side. Therefore, the concentrated solution branch delivered from the SSHE will increase the additional consumption of cooling capacity of the evaporator, and this process becomes energy inefficient. Consequently, the effect of concentrated solution branch on the heating exchanging process of the SSHE deserves a further investigation.

Obviously, the temperature and the flow rate of concentrated solution branch are the key factors which heavily influence the additional consumption of cooling capacity of the evaporator. One of the novelties of this work is that the effect of concentrated solution branch fluid on the heat exchanging process of the SSHE is analyzed based on a conventional LDCH air-conditioning experiment setup. A further contribution is that a new LDCH air-conditioning system is proposed to reduce the additional consumption of evaporating load of heat pump. The results can help to design energy-efficient LDCH air-conditioning systems.

2. Description of a conventional LDCH air-conditioning system

2.1. Working principle

The schematic of a conventional LDCH air-conditioning system is shown in Fig. 1, which consists of regeneration module, dehumidification module, SSHE, and a vapor compression heat pump. The desiccant solution is concentrated in the regenerator after being heated by the condenser of heat pump; the desiccant solution imbibes water from the processed air in the dehumidifier after being cooled in the evaporator. In other words, the condenser of