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Performance investigation of a counter-flow heat pump driven liquid desiccant dehumidification system

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A B S T R A C T

Liquid desiccant dehumidification is an energy-efficient approach for humid air handling process. Increasing attention has been paid to heat pump driven liquid desiccant (HPLD) systems in China. The current research focuses on a counter-flow HPLD system. The configuration of this HPLD system is introduced and theoretical models of key components are analyzed. Based on the simulation model, operating performances with varying input parameters are obtained. Effects of input NTU_m, NTU_{evap} and required ω_{sa} are drawn from the simulated results. NTU_m of the packed tower is a key parameter, which affects Q_{fa}/Q_e indicating the heat recovery performance and COP_{hp} indicating the energy performance of heat pump. As NTU_m is not sufficient, heat-cold offset resulted from solutions circulating between dehumidifier and regenerator severely affects the system performance. Then adding a solution heat exchanger is regarded as an appropriate approach to improve the performance. Besides, adopting a multi-stage heat pump cycle helps to improve the match properties between solution and refrigerant. It's treated as an approach to improve the energy efficiency of this counter-flow HPLD system to a certain extent. The present study is expected to be beneficial to design an optimized HPLD system.

1. Introduction

The major tasks of air-conditioning systems are to control both the indoor temperature and humidity. Reducing the energy consumed by the air handling process has a significant impact on the energy conservation of buildings [1]. Liquid desiccant dehumidification is regarded as an energy-efficient approach of satisfying air humidity control requirement. Nowadays it is playing an increasingly important role in application. In contrast to conventional condensing dehumidification methods, liquid desiccant approaches show superiorities in utilizing renewable energy or low-grade energy [2–5]. Solar energy, industrial waste energy, and even condensing heat of a vapor compression cycle are all appropriate heating sources for solution regeneration.

Increasing attention has been paid to air handling processes using liquid desiccant and many processes or systems have been proposed, including different approaches for desiccant regeneration [2–11]. Experimental results could be obtained for the dehumidification/regeneration process between air and solution or the entire air handling system. Key issues influencing the coupled heat and mass transfer processes were tested by Martin et al. [6], Jain et al. [7] and Mohan et al. [8]. System models can also be built with the help of numerical methods, and the operating parameters can then be simulated to investigate performance discrepancies. Das et al. [11] proposed six potential standalone liquid desiccant cycles and investigated the performances for selecting a best configuration. The major differences for various cycles are the different utilization approaches of indoor exhaust air. The simulated results showed that liquid desiccant cycles using indoor exhaust air for heat recovery with the outdoor air or for indirect evaporative cooling to cool the outdoor air is superior to other cycles in energy performances.

The dehumidifier/regenerator is one of the key components in liquid desiccant air-conditioning systems. According to the flow arrangement between air and solution, it is usually classified as the parallel-flow type, the counter-flow type and the cross-flow type. As to the cross-flow type, it has advantages in terms of reducing height and convenient for actual application. Both tested and calculated results on cross-flow dehumidifier/regenerator have been carried out by researchers [12–15]. A multi-stage air handling processor using liquid desiccant with cross-flow pattern is

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attracting more and more attention in China. Zhao et al. [16] introduced a kind of two-stage air handling processor using liquid desiccant to satisfy indoor humidity control for an office building. Its energy performance was also tested. While for the counter-flow dehumidification/regeneration process, it's believed that it's superior to the cross-flow type in terms of higher mass transfer efficiency and simpler configuration. Analysis on influencing factors including air and solution flow rates, solution concentration, inlet solution temperature and so on have been conducted [17–20]. Wang et al. [17] focused on a chiller driven counter-flow dehumidifier of liquid desiccant dehumidification system and strategy was proposed to optimize the operating solution temperature and flow rate. However in that investigated system, additional hot water rather than the condensing heat of the heat pump cycle was utilized as the heating source for solution regeneration. The issues of how to select appropriate operating parameters and how to pursue a process with better energy efficiency are at the center of current research efforts. Besides, counter-flow type is an essential condition for constructing an ideal dehumidification process using liquid desiccant as analyzed by Li et al. [21].

Recently heat pump driven liquid desiccant (HPLD) systems have become more and more popular, due to their significant advantages of compact size and high efficiency. The HPLD system is considered as an option for utilizing liquid desiccant dehumidification where there is no available low-grade heat, with benefits in ease of operation and maintenance. Both the cooling capacity from an evaporator and heat from a condenser are utilized in this kind of system. The cooling capacity is used to cool the desiccant to enhance its dehumidification ability in dehumidifier and the heat is used to regenerate the solution. Condensing heat of the heat pump cycle could be utilized in different ways in different HPLD systems [22–25]. As analyzed in previous research [25], it's recommended to use the condenser to heat inlet solution rather than inlet air in the regenerator to obtain a better mass transfer performance. One of the key issues in studies on HPLD systems is to remove the extra condensing heat efficiently, as the amount of condensing heat is always greater than that actually needed for desiccant regeneration. For example, an auxiliary air-cooled or water-cooled condenser after the solution-cooled condenser of a HPLD system was suggested by researchers [22,25], to extract the extra condensing heat.

However there is still lack in investigation on HPLD systems with counter-flow pattern. In the present study, performance of a novel counter-flow HPLD system will be investigated. Configuration of this counter-flow HPLD system is introduced and then its simulation model is built and validated. Energy performances with varying input parameters and optimizing approaches will be obtained based on simulated results. It is hoped that the results of this research will be helpful for design and optimization of the HPLD systems.

2. System configuration and theoretical models of the HPLD system

2.1. Operating principle of the HPLD system

Fig. 1 illustrates the operating schematic of a counter-flow HPLD system. The system mainly consists of two kinds of components. One is the packed tower for dehumidification and regeneration, i.e. the dehumidifier and regenerator where coupled heat and mass transfer processes occur between solution and air. The other is a heat pump cycle, including compressor, evaporator, condenser and so on. As shown in Fig. 1, fresh air is cooled and dehumidified by cold solution spraying in dehumidifier, and then flows out becoming supply air. Indoor exhaust air is heated and humidified by hot solution in regenerator, becoming exhaust air in the end. Counter-flow pattern is selected between solution and air both in dehumidifier and in regenerator. In the coupled heat and mass transfer processes between air and liquid desiccant, fresh air is cooled and dehumidified from a_{in} to a_{out}, and indoor exhaust air is heated and humidified from state r_{in} to r_{out}. For the circulating solution in this HPLD system, evaporator of the heat pump acts as an external cooling source and provides cooling capacity to cool solution from state S_4 to S_1. Similarly, condenser of the heat pump cycle acts as the external heating source and solution is heated from S_2 to S_3 after flowing through the condenser.

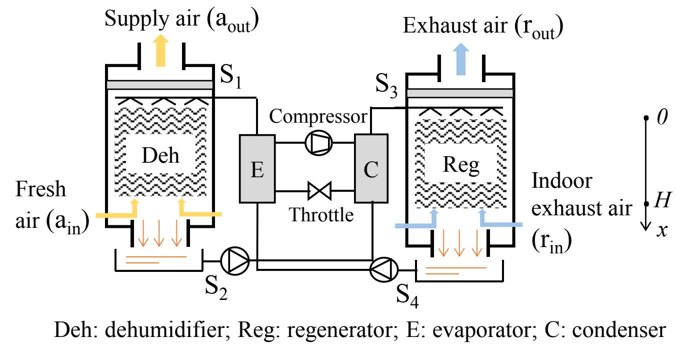

Fig. 1. Schematic diagram of the counter-flow HPLD system.

The system performance can be evaluated by the performance indexes including COP_{hp} and COP_{sys}, which are calculated by Eqs. (1) and (2) respectively. Taking the power consumption of circulating pumps, COP'_{sys} could be determined as Eq. (3).

$$COP_{hp} = \frac{Q_e}{P_{com}} \tag{1}$$

$$COP_{sys} = \frac{Q_{fa}}{P_{com}} \tag{2}$$

$$COP'_{sys} = \frac{Q_{fa}}{P_{com} + P_{pump}} \tag{3}$$

where Q_{fa} is the cooling capacity obtained by the fresh air; Q_e is the cooling capacity provided by evaporator; P_{com} and P_{pump} are power consumptions of the heat pump cycle and spraying pumps, respectively.

In order to facilitate performance analysis, combine Eqs. (1) and (2) to yield:

$$COP_{sys} = \frac{Q_{fa}}{Q_e} COP_{hp} \tag{4}$$

The COP_{sys} will be greater than COP_{hp}, if $Q_{fa}/Q_e > 1$; otherwise, the COP_{sys} will be lower than COP_{hp}.

2.2. System modeling

Based on the operating schematic mentioned above, theoretical models of key components for this HPLD system are introduced as follows.

a) Dehumidifier and regenerator

For the coupled heat and mass transfer processes in the dehumidifier and regenerator with counter-flow configuration, energy