Building and Environment 143 (2018) 431–442

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Model-based investigation of a heat pump driven, internally cooled liquid desiccant dehumidification system

Jun Liu, Tao Zhang, Xiaohua Liu*

Department of Building Science, Tsinghua University, Beijing, 100084, China

ARTICLE INFO

Keywords:
Liquid desiccant
Internally-cooled
Dehumidification
Heat pump
Heat and mass transfer

ABSTRACT

Liquid desiccant dehumidification system is regarded as a promising and energy-saving solution for dehumidification. A heat pump driven internally cooled desiccant dehumidification system is investigated in this paper. Dehumidifier and regenerator are both internally cooled/heated types compared to previous adiabatic ones, and heating and cooling capacities of a heat pump cycle are utilized for regeneration and dehumidification respectively. System model is established and validated to investigate system performance and effects of different influencing parameters. It's indicated that two main issues, which are restricting the system performance, are encountered, i.e. mismatching property among the three fluids inside the dehumidifier/regenerator and heat offset due to solutions circulating between dehumidifier and regenerator. Heat transfer mismatching ratio (x_t) and mass transfer mismatching ratio (x_ω) are defined to indicate the degree of mismatching property. A lower solution flow rate and a solution-solution heat exchanger with a better recovery efficiency are highly recommended to obtain a better system performance. Further, an improved system with external pre-cooler and pre-heater was proposed to improve the matching property among the three fluids, and COP_{sys} is found to be increased from 5.96 to 6.68 with an increasing ratio of 12%. x_t is found to be reduced from 0.357 to 0.168, and x_ω from 0.282 to 0.127.

1. Introduction

Liquid desiccant dehumidification system has been regarded as a promising and energy-saving substitute to the traditional condensing dehumidification system [1–4]. It has received increasing attention in the air-handling field [5–12]. In traditional liquid desiccant dehumidification systems, adiabatic type of dehumidifier/regenerator is usually utilized, where desiccant is cooled/heated previously and externally by a heat exchanger outside the dehumidifier/regenerator [6]. However, desiccant temperature often tends to rise (decrease) quickly in the dehumidifier (regenerator), resulting in a significant drop in the mass transfer driving force. Internally cooled dehumidifier, which introduces an internal cooling medium to the dehumidifier, is regarded to have advantages in slowing down the increase of temperature and alleviating the decrease of driving force in the dehumidifier. Yin et al. [13] compared the regeneration thermal efficiency and regeneration rate of both internally heated and adiabatic regenerator. The regeneration thermal efficiency was around 0.6–0.7 in internally heated regenerator and only around 0.38 in adiabatic one. Bansal et al. [14] tested the experimental performance of an adiabatic and internally cooled structured packed-bed dehumidifier, showing the moisture removal rate with simultaneous cooling was 30–40% higher than that of adiabatic one.

As a result, it has aroused researchers' increasing interest in the internally-cooled dehumidifier as well as the difference between internally-cooled and adiabatic components [15–25]. Research firstly focused on the experimental performances of internally cooled/heated dehumidifiers/regenerators. Chung et al. [15] experimentally compared air dehumidification performance between spray towers with and without internally-cooled fin coils. Zhang et al. [16] designed and tested the performance of an internally cooled dehumidifier with fin-coil structure, and studied the effects of operational parameters, such as inlet temperature, flow rate of chilled water, and liquid desiccant flow rate. Concerning the corrosion problem, Liu et al. [17] designed and tested an internally cooled dehumidifier made of thermally conductive plastic. Regarding different device structure, Yin et al. [18] tested another internally cooled dehumidifier with a parallel-plate structure, measuring performance under varying air flow rates, water inlet temperatures, and solution inlet temperatures to assess their influence on performance. Bansal et al. [14] designed and tested an internally cooled dehumidifier made of a packed tower with cooling tubes.

Based on the data from previous experimental studies, several heat

* Corresponding author. Dept. of Building Science, School of Architecture, Tsinghua University, Beijing, 100084, China.
E-mail address: lxh@mail.tsinghua.edu.cn (X. Liu).

https://doi.org/10.1016/j.buildenv.2018.07.027
Received 21 April 2018; Received in revised form 17 July 2018; Accepted 18 July 2018
Available online 20 July 2018

and mass transfer models were developed to simulate the performance of internally cooled dehumidifiers. Ren et al. [19] rearranged the heat and mass transfer model and presented a validated analytical model for performance prediction of internally cooled dehumidifiers. Liu et al. [20] established and simplified the heat and mass transfer model of internally cooled dehumidifiers, and adopted the validated model to analyze the influence of different flow types on device performance. Qi et al. [21] developed a simplified numerical model using multiple linear regressions, adopting three kinds of effectiveness—enthalpy, moisture, and temperature—as essential indicators of performance.

Both experimental and simulated studies have pointed out that performance of the internally cooled dehumidifier is significantly affected by its inlet parameters. However, the inlet parameters of an internally cooled/heated dehumidifier/regenerator are often defined and regulated by the system arrangement. As a result, it's of great importance to investigate the combined performance of an entire internally cooled liquid desiccant dehumidification system. Several researchers pioneered in the investigation on the internally cooled system [22–26]. Chen [22] has conducted an experiment to investigate the overall performance of an internally-cooled/heated system. Liquid desiccant was cooled/heated by internal cooling/heating water inside the dehumidifier/regenerator. System performance under various working condition was tested and analyzed, and the heat pump *COP* is around 3.5–4.1 when dehumidifying air from 10.5 g/kg to 8 g/kg. Yamaguchi et al. [23] also tested a similar system dehumidifying air from 14 g/kg to 8 g/kg. The COP_{sys} equals to 2.71 and COP_{hp} equals to 3.82. Juan [24] built up and tested a similar system with *COP* varies from 2.0 to 4.0. Qi et al. [25] presented a multiple regression model for the internally cooled dehumidification system. Further investigations on the energy consumption and optimization strategy of the system are also obtained [26].

Internally cooled systems studied in previous researches are mainly driven by cooling water from a cooling tower and hot water from a solar thermal collector. Heat pump cycle is considered to be with advantages in providing both heating and cooling capacities for a liquid desiccant system and there have been more and more studies on liquid desiccant systems combined with heat pump cycles [27–33]. However, there is still lack of study for an internally cooled liquid desiccant dehumidification system driven by heat pump, which is frequently adopted as the heating and cooling sources in an adiabatic liquid desiccant system. In this paper, a heat pump driven, internally cooled desiccant dehumidification system will be analyzed. Numerical heat and mass transfer model of the system is presented and validated with experimental data. The combined operational performance of the system and influence of inlet parameters will be investigated in detail. It's hoped that the present research will be beneficial to improve the performance of the liquid desiccant dehumidification system.

2. System principle

Fig. 1(a) shows the schematic of an internally cooled desiccant dehumidification system driven by a heat pump cycle. The system consists of two operational cycles, i.e. the liquid desiccant cycle and the heat pump cycle. In the liquid desiccant cycle, cool and condensed liquid desiccant (S_3) is sprayed from top of the dehumidifier. Inside the dehumidifier, desiccant directly contacts with fresh air (A_1), realizing heat and mass transfer between air and solution. At the same time, desiccant is cooled through indirect contact with cooling medium that flows inside the tubes. Then the cool, diluted desiccant (S_4) is pumped to the heat exchanger to exchange heat with warm, condensed desiccant (S_2) from regenerator. The warm diluted desiccant (S_1) from the exchanger is then sprayed into the regenerator. Inside the regenerator, desiccant directly contacts with regeneration air (R_1), realizing the regeneration process for solution and completing the liquid desiccant cycle. In the heat pump cycle, internally-cooled dehumidifier is the evaporator, and internally-heated regenerator is the condenser. Cooling capacity of evaporation is utilized to cool the liquid desiccant inside the dehumidifier, and similarly heating capacity of condensation is utilized to heat the liquid desiccant inside the regenerator. Compared to the well investigated adiabatic systems driven by heat pump [27–33], liquid desiccant is completely internally cooled/heated in the current system, resulting in different heat and mass transfer processes and characteristics of system performance.

As shown in Fig. 1, there are three main components in this liquid desiccant dehumidification system, i.e. the internally cooled/heated dehumidifier/regenerator, the solution heat exchanger, and the heat pump cycle (compressor and throttle). Model for each component is adopted from previous researches [16,17,20] as given in the Appendix. Simulation model for the internally cooled dehumidification system is built using the Matlab Simulink platform. The flow chart for system simulation is illustrated in Fig. 2. Further, the system model is validated and compared with experimental data in previous research [22] as shown in Fig. 3 and Table 1. It can be seen that the discrepancies are within ± 10%, thereby validating the accuracy of the proposed system model. In addition, system coefficient of performance, COP_{sys}, is adopted in this paper to evaluate the combined performance of the internally cooled system (Eq. (1)).

$$COP_{sys} = \frac{Q_a}{W_c} = \frac{\dot{m}_a(h_{A1} - h_{A2})}{W_c} \tag{1}$$

where Q_a is the total cooling capacity handled by the system, W_c represents the power consumption of the heat pump, $\dot{m}_a$ indicates the mass flow rate of the processed air, and h_{A1} and h_{A2} are enthalpies of inlet and outlet air of the dehumidifier, respectively. Since the power consumption of pumps for liquid solution is relatively small and varies little among all cases, it is assumed to be negligible in the COP_{sys} calculation.

3. Basic condition analysis

A basic condition is firstly chosen to investigate the performance of this internally cooled system. Inlet parameters of the basic operating condition are listed in Table 2, where inlet air humidity ratio is 20 g/kg, and humidity ratio of the supply air is fixed as 11 g/kg. Values of K_m and K_h are set according to previous research [34]. In addition, flow rate and inlet parameters of the regeneration air were equal to those of the fresh air.

Under the basic condition, outlet temperature and humidity ratio of the air supply were 28.8 °C and 11.0 g/kg. Inlet solution temperature of dehumidifier (t_{s_3}) is 35.9 °C, and the outlet temperature (t_{s_4}) is 31.2 °C. Similarly, inlet (t_{s_1}) and outlet (t_{s_2}) solution temperatures of the regenerator are 38.0 °C and 42.9 °C. Power consumption (W_c) of the heat pump is 4.93 kW, coefficient of performance of the heat pump (COP_{hp}) was 6.85, and COP_{sys} is 5.96. Other simulation results are listed in Table 3 and Fig. 1(b).

As the liquid desiccant is internally cooled, temperature of outlet solution (31.2 °C) from the dehumidifier is lower than that of the inlet solution (35.9 °C). And it's vice versa for solution in the internally-heated regenerator. As a result, temperature difference (11.7 °C) between outlet solutions from dehumidifier (31.2 °C) and regenerator (42.9 °C) is significant, and much larger than that in an adiabatic system. This further results in an evident heat offset for solutions circulating between the internally-cooled dehumidifier and internally-heated regenerator. Concerning this issue, heat offset amount in the current system can be calculated as Eq. (2).

$$Q_{offset} = Q_e - Q_a = c_{ps}\dot{m}_s(t_{S_3} - t_{S_4}) \tag{2}$$

where Q_e is the cooling capacity of evaporator.

Further, heat transfer efficiency of the solution heat exchanger can be expressed as: