EMPIRICAL ANALYSIS OF DEHUMIDIFICATION PERFORMANCE OF A PACKED-BED COUNTER-FLOW LIQUID DESICCANT DEHUMIDIFIER

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SUMMARY

Recently, liquid desiccant system integrated with a ventilation system such as a dedicated outdoor air system (DOAS) has been attracting increasing research attention due to its energy saving potentials in controlling latent loads from indoor air in hot and humid climate. This study experimentally investigates the dehumidification performance of a packed bed counter-flow type liquid desiccant system using structured packing material with a specific surface area (229 m^2 m^{-3}). In this study, lithium chloride aqueous solution was used as the desiccant solution and CELdek structured packing was selected. The enthalpy efficiency, dehumidification efficiency, and moisture removal rate were adopted as the dehumidification performance indices. To investigate the impact of air and solution conditions on the three indices, five parameters were measured: the liquid to gas ratio, the inlet air temperature and humidity ratio, and the solution temperature and concentration. Experimental results show that the dehumidification efficiency and enthalpy efficiency varied from 24.32% to 73.45% and from 30.91% to 68.31%, respectively under experimental inlet conditions. Similarly, the range of the moisture removal rate varied from 0.43 g/s to 0.93 g/s. The characteristics of the dehumidification performance in various inlet air and desiccant solution conditions are presented in this paper.

Keywords: liquid desiccant dehumidifier, counter-flow, dehumidification, experimental analysis

1 INTRODUCTION

Air-conditioning systems are designed to provide suitable indoor environment in relation to temperature, humidity, and fresh air. In recent years, independent control of latent loads in buildings has attracted research attention due to its advantages such as energy saving potentials and carbon dioxide emission reduction. Liquid desiccant systems are effective means of controlling moisture in humid air with reduced energy consumption compared to conventional vapor compression systems (Goetzler et al., 2014 and Rambhad et al., 2016). Moreover, liquid desiccant systems can operate in a relatively low regeneration temperature range of 60–75°C, which indicates that liquid desiccant systems have the potential for the efficient use of solar energy, waste heat, and other energy saving sources (Lowenstein, 2003).

The dehumidifier is a key component in a liquid desiccant-based air conditioning system, in which the heat and mass transfer processes directly affect the entire dehumidification performance. When process air flows into the dehumidifier and comes in contact with the desiccant solution, coupled heat and mass transfer processes occur simultaneously, and the heat transfer and mass transfer processes affect each other. The moisture in process air is then absorbed by the desiccant solution because of the vapor pressure difference between process air and the desiccant solution, while vaporization heat is released from humid air to the desiccant solution during the dehumidification process.

The heat and mass transfer performance in a dehumidifier is determined by six parameters: the temperature and humidity ratio of the inlet air, the temperature and concentration of the inlet desiccant solution, and the mass flow rate of the inlet air and desiccant solution. To predict the system performance and optimize the design and operational parameters, reliable mathematical models of the liquid desiccant dehumidifier are essential. A number of heat and mass transfer mathematical models of the dehumidifier have been proposed (Liu et al., 2006; Park et al., 2016). However, the dehumidification performance of a liquid desiccant dehumidifier also varies with the dimension of the dehumidifier, the type of desiccant solution, packing material, and the relative flow direction between the process air and desiccant solution. Therefore, predicting the coupled heat and mass transfer processes in the dehumidifier is so complicated that the theoretical model need to be verified by experimental results. Experimental study on liquid desiccant dehumidifier is also necessary to clearly understand and enhance the coupled heat and mass transfer of a specific type of dehumidifier.

Consequently, this study experimentally investigated the dehumidification performance of a packed bed counter-flow type liquid desiccant system using structured packing material with a specific surface area (229 m^2 m^{-3}). In this study, lithium chloride (LiCl) aqueous solution was used as the desiccant solution. CELdek packing, which is well-known for its wettability (Potnis and Lenz, 1996), was adopted as the packing material. The enthalpy efficiency, dehumidification efficiency, and moisture removal rate were adopted as the dehumidification performance indices. The influence of various inlet parameters on the dehumidification performance was investigated, and the characteristics of the dehumidification performance are described in this paper.

2 METHODS

2.1 Experimental setup of counter-flow liquid desiccant dehumidifier

The schematic of the experimental setup is shown in Figure 1. LiCl aqueous solution was used as the desiccant solution. CELdek structured packing with overall height, width, and length of 0.70 m, 0.35 m, and 0.35 m, respectively was used in the dehumidifier with a specific surface area of 229 m^2 m-^{3} and flute height of 7 mm. In this research, the dehumidifier system consists of strong and weak solution tanks, a constant flow pump, a variable air volume fan, air-cooled cooler, and an electric heating coil. The test chamber was served by a constant temperature and humidity unit to maintain the target inlet air conditions. When the inlet air flows through the dehumidifier, strong solution from the strong solution tank was sprayed simultaneously. The sprayed solution was collected in the solution sump, and this diluted solution was transferred to the weak solution tank. The outlet air was exhausted to the outside.

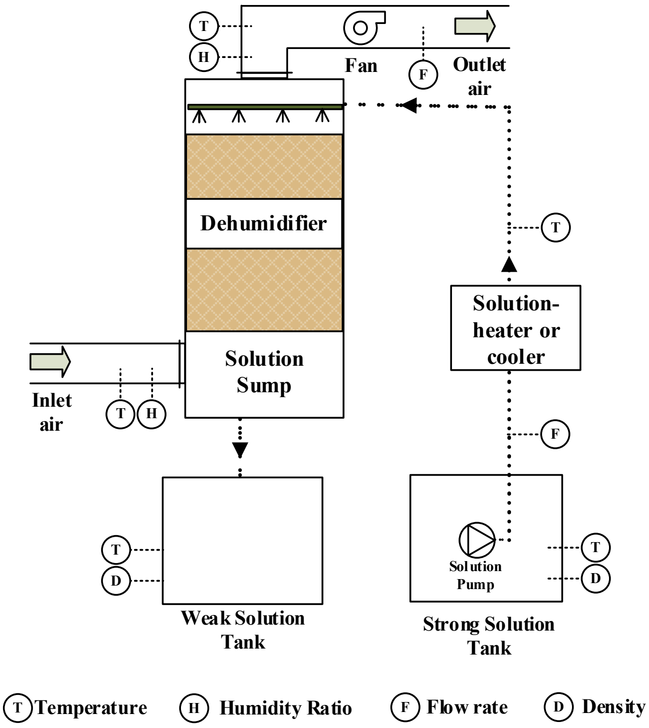

Figure 1. Schematic design of experiment for the packed bed counter-flow dehumidifier

2.2 Experimental conditions and instruments

In this study, 32 sets of experiments were carried out to investigate the dehumidification performance of the packed bed counter-flow type liquid desiccant dehumidifier. The measured values were used to analyze the dehumidification performance variation of the absorber with respect to five operating parameters: the temperature and humidity ratio of the inlet air, the temperature and concentration of the inlet solution, and the liquid to gas (LG) ratio, which is defined as the mass flow rate ratio of the desiccant solution to the process air. Table 1 presents the operating range of the inlet parameters. The experiment was conducted in summer conditions because liquid desiccant systems are mostly used in hot and humid conditions. In this study, a constant flow pump with a flow rate of 8.1 l/min was adopted in the dehumidifier. Therefore, based on the operating ranges of the LG ratio, the mass flow rate of the process air varied from 0.065 kg/s to 0.112 kg/s.

Experimental test was carried out to analyze the dehumidification performance of the packed bed counter-flow type liquid desiccant dehumidifier with CELdek structured packing material. The measurement parameters for the test were the inlet air dry-bulb temperature and humidity ratio, outlet air dry-bulb temperature and humidity ratio, air volume flow, solution density, and inlet and outlet solution temperatures; the measurement points are shown in Figure 1. The inlet and outlet dry-bulb temperature and humidity ratio were measured using a humidity/temperature probe. The temperature of the desiccant solution was measured using a k-type immersion thermometer. The concentration of the desiccant solution was determined by measuring the density of the solution with a density meter. The mass flow rate of the dehumidified air was determined by the velocity of the outlet air, which was measured using a vane sensor. Table 2 lists the range and accuracy of each sensor.

Table 1. Operating ranges of experimental conditions

Parameter	Symbol	Low	High
Inlet air temperature [°C]	$T_{a,in}$	27	33
Inlet air humidity ratio [kg/kg]	$\omega_{a,in}$	0.0107	0.0201
Inlet solution temperature [°C]	$T_{s,in}$	15	30
Inlet solution concentration [%]	$X_{s,in}$	32.1	38.4
Liquid to gas ratio [-]	LG	1.5	2.5

Table 2. Specifications of different measuring devices

Variable	Device	Characteristics		
Dry-bulb temperature and humidity ratio of humid air	High-precision humidity/temperature probe	Range	Temperature	-20–60 ℃
			Humidity	0–100%
		Accuracy	Temperature	±0.2 ℃ (<30 ℃)
				±0.5 ℃ (>30 ℃)
			Humidity	±(1.8%RH +0.7% of m.v.)
Air flow rate	Differential pressure sensor	Range	Pressure	0–1250 Pa
		Accuracy		±0.30%
Solution temperature	K-type immersion temperature probe	Range	Temperature	-60–1000 ℃
		Accuracy		±1.5 ℃
Solution flow rate	Ultrasonic flow meter (TFM 100)	Range	Velocity	0–32 m/s
		Accuracy		±1.00%
Solution density	Glass hydrometer	Range	Density	1.00–1.4 kg/m^3
		Accuracy		±2 kg/m^3

2.2 Dehumidification performance indices

The dehumidification efficiency, enthalpy efficiency, and moisture removal rate are adopted to describe the combined heat and mass transfer performances of the dehumidifier. The enthalpy and dehumidification efficiency are defined as the ratio of the actual enthalpy or the humidity ratio variance of air passing through the dehumidifier to the variance under ideal conditions, as given in Equations 1 and 2, respectively. The moisture removal rate of air can be calculated as given in Equation 3. Knowing these three indices and the inlet air and solution conditions, the outlet air and solution conditions can be determined, which are essential to determine the performance of the dehumidifier and the hybrid system.

$$\varepsilon_{ent} = \frac{h_{a,in} - h_{a,out}}{h_{a,in} - h_{a,eq}} \tag{1}$$

$$\varepsilon_{deh} = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{a,eq}} \tag{2}$$

$$\dot{m}_{deh} = \dot{m}_a\left(\omega_{a,in} - \omega_{a,out}\right) \tag{3}$$

In Equation 2, the equilibrium humidity ratio ($\omega_{a,eq}$) can be defined using the solution pressure (P_s) and the atmospheric pressure (P_{atm}) as given in Equation 4. To obtain the solution pressure (P_s) at saturation condition of the desiccant solution, a second order polynomial proposed by Fumo and Goswami (2002) was used.

$$\omega_{a,eq} = 0.622 \times \frac{P_s}{P_{atm} - P_s} \tag{4}$$

3 RESULTS AND DISCUSSION

The effects of five inlet parameters of the air and desiccant on the dehumidification performance were experimentally investigated. The five inlet parameters are the inlet air temperature, inlet air humidity ratio, inlet desiccant solution temperature, inlet desiccant solution concentration, and the mass flow rate ratio between the process air and desiccant solution. The inlet conditions of the air and desiccant solution are listed in Table 3. The effect of each factor on the dehumidification efficiency, enthalpy efficiency, and moisture removal rate is analyzed.

Table 3 Experimental inlet conditions of air and desiccant solution

Case	Air			Desiccant solution			Liquid to gas ratio
	$T_{a,in}$ [°C]	$\omega_{a,in}$ [kg/kg]	$\dot{m}_a$ [kg/s]	$T_{s,in}$ [°C]	$X_{s,in}$ [%]	$\dot{m}_{s,in}$ [kg/s]	LG [-]
2 (a)	-	0.01462-0.01653	0.1050-0.1070	15.2-18.3	32.1-31.2	0.167-0.168	1.56-1.60
2 (b)	27.2-30.2	-	0.1030-0.1067	14.9-18.5	31.8-31.2	0.167-0.168	1.62-1.63
2 (c)	27.2-31.2	0.01561-0.01783	0.0850-0.1023	-	32.1-33.1	0.167-0.168	1.64-1.97
2 (d)	26.8-30.2	0.01691-0.01830	0.0910-0.1052	16.8-19.5	-	0.167-0.168	1.59-1.84
2 (e)	27.8-31.3	0.01129-0.01965	-	15.8-22.5	30.6-35.4	0.167-0.168	-

3.1 Influence of inlet parameters on dehumidification performance

The effects of the five inlet parameters of the air and desiccant on the dehumidification efficiency, enthalpy efficiency, and moisture removal rate are shown in Figure 2 and Figure 3, respectively. Under the given experimental inlet conditions, the dehumidification efficiency and enthalpy efficiency varied from 24.32% to 73.45% and from 30.91% to 68.31%, respectively. Similarly, the range of the moisture removal rate is from 0.43 g/s to 0.93 g/s. Figure 2 shows that the increase in the inlet air humidity ratio and the LG ratio increases the dehumidification efficiency, while the increase in the inlet air and inlet desiccant solution temperature decreases the dehumidification efficiency. For the enthalpy efficiency, the positive influencing parameter is the inlet air temperature, while the negative influencing parameters are the inlet desiccant temperature and the LG ratio. Figure 3 shows that the inlet air and desiccant solution temperature have negative effects on the moisture removal rate, while the other three parameters have positive effects on the moisture removal rate. Decreasing the LG ratio, that is, increasing the inlet air flow rate, increases the mass transfer coefficient between air and the desiccant solution. However, the dehumidification efficiency decreases with decreasing LG ratio because of the shorter contact time. Increasing the inlet desiccant solution temperature can lead to higher surface vapor pressure of the desiccant solution, which reduces the mass transfer potential between air and the desiccant solution and then reduces the dehumidification efficiency and the moisture removal rate. In contrast, increasing the inlet desiccant solution concentration increases the moisture removal rate due to the decrease in the surface vapor pressure. However, a higher desiccant solution concentration leads to a higher surface tension, which reduces the wettability of the desiccant solution (Moon et al., 2009). This effect counteracts the increase in the mass transfer potential, which results in minimal change in the dehumidification efficiency.

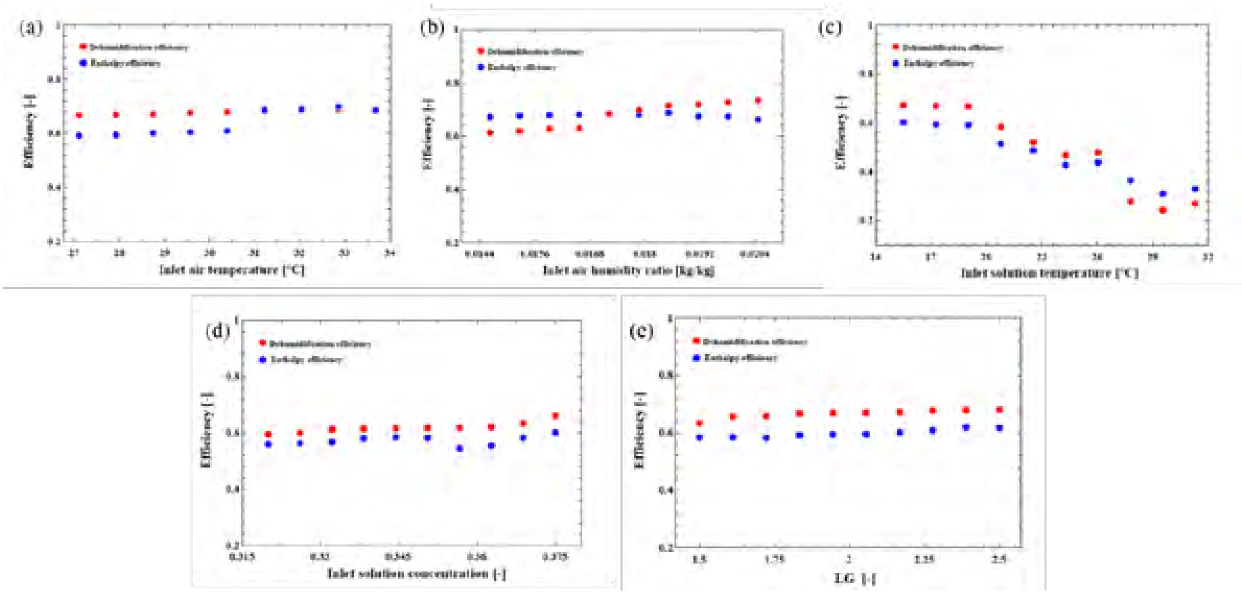

Figure 2. Influence of inlet parameters on dehumidification efficiency and enthalpy efficiency

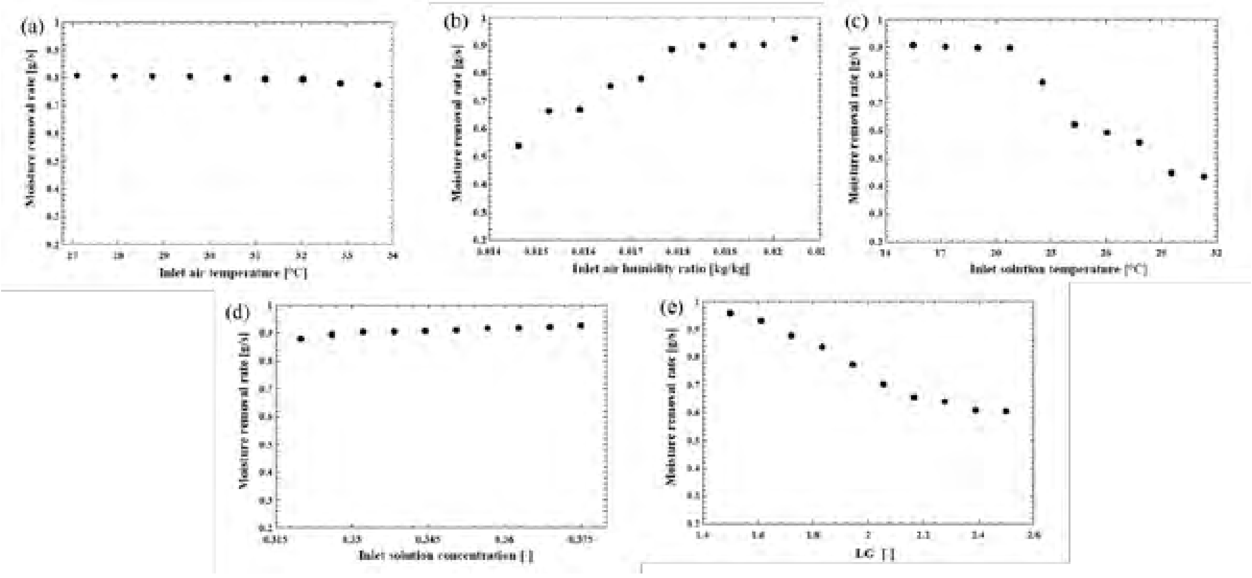

Figure 3. Influence of inlet parameters on moisture removal rate

4 CONCLUSIONS

This study experimentally investigated the dehumidification performance of packed bed counter-flow type liquid desiccant system using CELdek packing material with a specific surface area (229 m^2 m^{-3}). The experiment was conducted in summer conditions because liquid desiccant systems are mostly used in hot and humid conditions. In this study, a constant flow pump with a flow rate of 8.1 l/min was adopted in the dehumidifier. The enthalpy efficiency, dehumidification efficiency, and moisture removal rate were adopted as dehumidification performance indices. These indices were used to analyze the characteristics of the dehumidification performance in various inlet air and desiccant solution conditions. The main conclusions of the study are summarized below.

The dehumidification efficiency and enthalpy efficiency were mainly influenced by the inlet air temperature, the inlet solution temperature, and the LG ratio. Experimental results also indicate that the air inlet humidity ratio influences only the dehumidification efficiency, while the desiccant concentration influences only the enthalpy efficiency. In terms of the moisture removal rate, the inlet air and desiccant solution temperature have negative influence on the moisture removal rate, while the other three parameters have positive influence on the moisture removal rate. This study also shows that this type of dehumidifier operates more effectively when air with high humidity ratio is used; hence, this compact dehumidifier is suitable for humid regions. The dehumidification efficiency is sensitive to a wide range of desiccant inlet temperatures, which indicates that the desiccant inlet temperature is a suitable control variable for adjusting the supply air humidity.

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