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ABSTRACT

In HVAC systems, liquid desiccant systems have attracted research attention in recent years due to their high efficiency in removing latent loads from conditioned buildings while consuming little energy. This paper experimentally investigates the dehumidification performance of the counter-flow type and cross-flow type liquid desiccant system under the same system operation conditions. In this study, Lithium chloride aqueous solution was used as the desiccant solution and CELdek-structured packing was selected. Dehumidification efficiency and moisture-removal rate were adopted as dehumidification performance indices. To investigate the impact of air and solution conditions on the two indices, five parameters—liquid-to-gas ratio, inlet-air temperature and humidity ratios, solution temperature, and concentration—were measured. Experiments were performed inside a test chamber, and the test chamber provided the same summer operation conditions. An 8.1 l/min constant-flow pump was adopted, and mass flow rate of the process air was subsequently determined based on the operation ranges of the liquid-to-gas ratio. Effects of air- and liquid-flow directions on the dehumidification process under various operating conditions were analyzed. Dehumidification efficiency of the counter-flow- and cross-flow-type dehumidifiers varied over the ranges 54.6–78.2% and 50.6%–74.4%, respectively. Similarly, moisture removal rates of the two dehumidifiers varied over ranges 0.39–0.76g/s and 0.36–0.73g/s, respectively. These results indicate that dehumidification performance of both dehumidifiers decreases with increase in inlet-solution temperature. In addition, deviations in dehumidification efficiency and moisture removal rate within 10%, which indicates that there is no significant difference in dehumidification performance between the counter-flow and cross-flow dehumidifiers with increase in inlet-solution temperature.

1. INTRODUCTION

Liquid desiccant cooling systems have been attracted considerable attention as alternative to conventional vapor-compression-based air-conditioning systems due to their advantages in terms of energy-saving potential and ability to provide better indoor-air quality. A liquid desiccant system has proven to be an effective method for moisture control in a humid environment with reduced energy consumption when compared with conventional vapor-compression system (Goetzler et al., 2014, Dieckmann et al., 2004). Moreover, liquid desiccant systems could operate under relatively low regeneration temperature, which indicates their potential to efficiently utilize solar energy, waste heat, and other renewable-energy sources (Lowenstein, 2003).

The dehumidifier is main component in liquid desiccant-based air-conditioning systems, whose heat and mass transfer performance directly impacts the dehumidification process. When the process air comes into the dehumidifier and contacts with a desiccant solution, coupled heat and mass transfer processes occur simultaneously and influence each other. The moisture in the process air is then absorbed by a desiccant solution because of the differences in vapor pressure between the process air and desiccant solution, and heat of vaporization heat is released from the process air and absorbed by the desiccant solution during dehumidification process.

Heat and mass transfer performance inside a dehumidifier is determined by the six parameters—inlet-air temperature and humidity ratios, inlet-solution temperature and concentration, and air and solution mass flow rates. Due to simultaneous occurrence of complex heat and mass transfer processes, it is essential to develop mathematical model of the liquid desiccant dehumidifier to predict system performance and optimize the design operational parameters. A number of mathematical models for different types of dehumidifiers have been developed. However, models developed based on certain assumptions led to disagreement between actual and calculated results; sometimes the differences even exceeded the order of 50%. The reason behind such a deviation is that dehumidification performance of liquid desiccant dehumidifier depends on the configuration of the dehumidifier, the type of desiccant solution, packing material and relative flow direction between the process air and desiccant solution. Therefore, experimental investigation of the dehumidification process becomes necessary to validate and improve the accuracy of numerical models. Experimental study on the liquid desiccant dehumidification systems is helpful to clearly understand coupled heat and mass transfer processes.

Dehumidification process in liquid desiccant systems can be performed through use of various equipment configurations. Dehumidifiers using packed towers with random packing are popular due to their large specific surface area. However, pressure drop on the air side in the random packing configurations is a big concern. Longo and Gasparella (2009) demonstrated that structured packing can significantly reduce air pressure drop by as much as 65–75%. Besides, structured packing is easy to install when compared with the random packing. Therefore, structured packing has been widely employed in various dehumidifier configurations in recent years. In addition, packing wettability has a significant influence on dehumidification performance of liquid desiccant dehumidifiers. Recently, the cellulose fiber paper made of wood material has good absorption of desiccant solutions and provided superior wettability characteristics. Such packing material have, therefore, been widely employed in liquid desiccant research as well as applications (Liu et al., 2006, Gao et al., 2012, Wang et al., 2016).

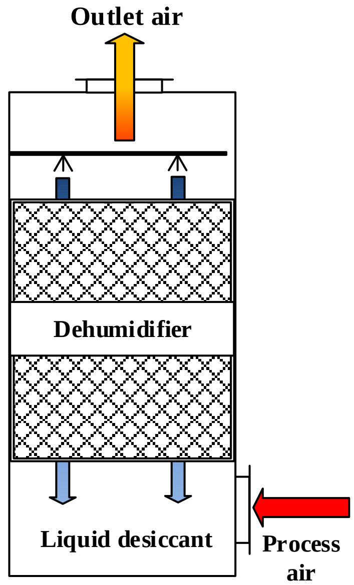
Most of the studies concerning liquid desiccant systems have concentrated on the counter-flow dehumidifier configurations because of their high dehumidification efficiency. Although heat and mass transfer performance of the cross-flow-type dehumidifier is lower compared to that of the counter-flow-type, the cross-flow configuration offers numerous advantages in practical use. The cross-flow configuration is easier to be installed in a restricted space and is maintained well in the field, as it serves to reduce the height of the dehumidification tower and integrates it easily into the duct system. However, compared to counter-flow configuration, there are few studies or experiments have been performed concerning cross-flow-type liquid desiccant dehumidifiers.

The proposed study experimentally compares dehumidification performance of packed-bed cross-flow-type liquid desiccant dehumidifiers against that of the counter-flow configuration under identical operating conditions. Dehumidification experiments were performed with inlet desiccant solution temperatures varying in the range of 15–30 ºC, and inlet-air conditions were set through use of a test chamber based on the average outdoor air conditions in summer. Dehumidification efficiency and moisture removal rate were adopted as performance indices, and influence of differences in flow direction between process air and desiccant solution on dehumidification performance were investigated. Lastly, characteristics of the dehumidification performance have been described.

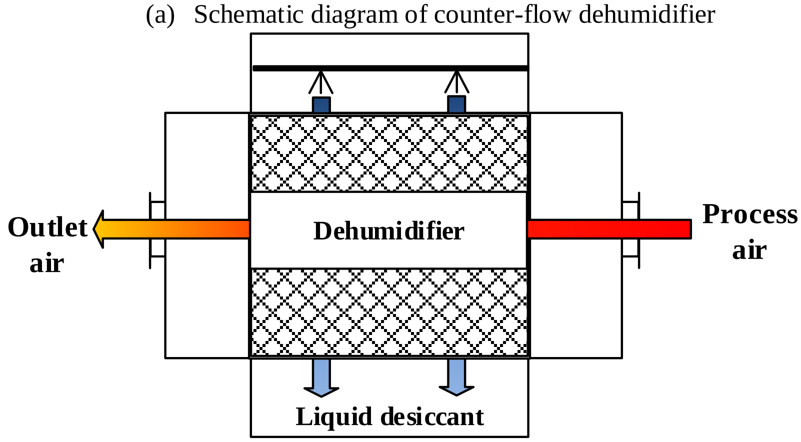
2. EXPERIMENT SETUP

2.1 Configurations of counter-flow- and cross-flow-type liquid desiccant dehumidifiers

The counter-flow and cross-flow packed tower dehumidifiers were selected for the experiment. Schematic diagrams of the two dehumidifiers are shown in Figure 1. In the counter-flow configuration, the desiccant solution was sprayed over the entire surface of the packing material at the top of the dehumidifier, and the process air was pumped and enters from the bottom of the device. In the cross-flow dehumidifier, on the other hand, the dehumidification process occurred when the process air crossed the packing material sufficiently wetted by the desiccant solution.



(a) Schematic diagram of counter-flow dehumidifier



(b) Schematic diagram of cross-flow dehumidifier

Figure 1: Schematic diagram of counter-flow and cross-flow dehumidifiers

Lithium chloride (LiCl) aqueous solution was selected for use as the desiccant solution. As shown in Figure 2, both liquid desiccant dehumidifiers adopted the CELdek structured packing material with 0.70 × 0.35 × 0.35 m with specific surface area 289.1 m^2 m^{-3} and 311.6m^2 m^{-3} for the counter-flow and cross-flow dehumidifier configurations, respectively. The packing consists of corrugated cellulose paper sheets with different flute angles—one steep (60 ºC) and the other flat (30 ºC)—which were bonded together.

(a) Counter-flow (b) Cross-flow (c) CELdek packing material

Figure 2: Packing material used in experiments

As shown in Figure 3, both dehumidifiers consist of strong and weak solution tanks, constant-flow solution pump, variable air-volume fan, air-cooled cooler, and electric heating coil. The test chamber was served by a constant temperature and humidity unit for maintaining target inlet-air conditions. When inlet air passed through the dehumidifier, the strong solution from the strong solution tank was sprayed simultaneously into the dehumidifier. The sprayed solution was collected in the solution sump, and this diluted solution was sent to the weak-solution tank. Outlet air was exhausted into the outside.

(a) Counter-flow dehumidifier (b) Cross-flow dehumidifier (c) Solution cooler/heater

Figure 3: Photographs of experiment rig of the packed-bed counter-flow and cross-flow dehumidifiers

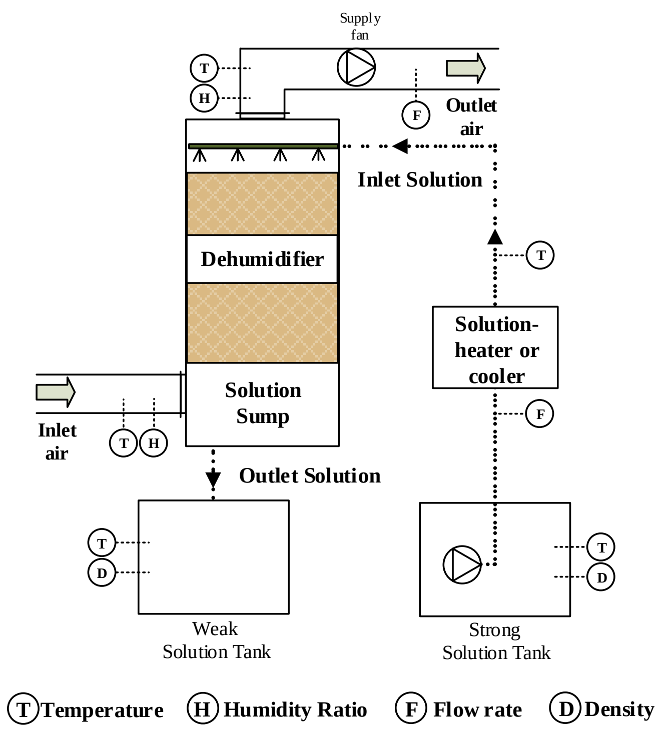
2.2 Experimental conditions and instruments

Experimental data were used to compare dehumidification performance of the counter-flow-type dehumidifier with that of the cross-flow type with respect to five operating parameters—temperature and humidity ratios of the inlet air, temperature and concentration of the inlet solution, and liquid-to-gas (LG) ratio, which could be defined as the mass-flow-rate ratio of desiccant solution to the process air. Table 1 presents the operating range of inlet parameters. Experiments were performed under summer operation conditions because liquid desiccant systems are mostly used under hot and humid conditions. A constant-flow pump delivering 8.1 l/min was adopted, and based on the operational range of the LG ratio, mass flow rate of the process air was determined. The inlet-solution temperature ranged from 15 ºC to 30 ºC, and the tests were performed at 5 ºC intervals with other conditions maintained constant.

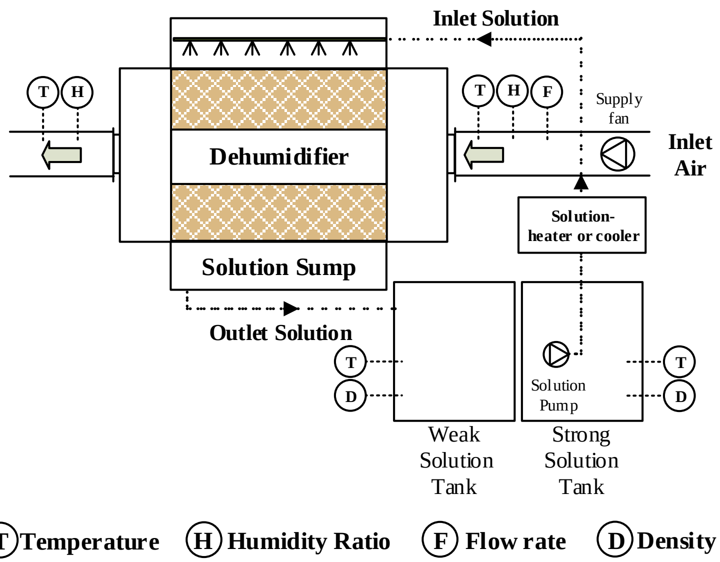
Table 1: Experimental conditions

Parameters		Average	Range
Inlet air	Temperature [°C]	27.9	27.7–28.1
	Humidity ratio [g/kg]	18.34	17.70–18.95
Inlet solution concentration [%]		35.68	35.04–36.32
Air flow rate [kg/s]		0.0651	0.0649–0.0653

For analyzing dehumidification performance of counter-flow- and cross-flow-type dehumidifier and that of the cross-flow, the measurement parameters for the test were the inlet air dry-bulb temperature and humidity ratio, the outlet air dry-bulb temperature and humidity ratio, air volume flow, the solution density, and the inlet and outlet solution temperatures; measuring points for the counter-flow and cross-flow dehumidifier configurations are shown in Figure 4. Inlet and outlet dry-bulb temperatures and humidity ratios were measured using a humidity/temperature probe, and temperature of the desiccant solution was measured using a k-type immersion thermometer. Concentration of the desiccant solution was determined by measuring solution density through use of a density meter (Conde, 2003). Mass flow rate of dehumidified air was determined using the velocity of outlet air measured by means of a vane sensor. Table 2 lists the range and accuracy of each sensor.



(a) Counter-flow liquid desiccant dehumidifier



(b) Cross-flow liquid desiccant dehumidifier

Figure 4: Configuration of experimental setup and sensing points

Table 2: Sensor characteristics

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

2.3 Dehumidification performance indices

Dehumidification efficiency and moisture removal rate were adopted to describe combined heat and mass transfer performances of the two dehumidifiers. Dehumidification efficiency are defined as the ratio of variance in the actual humidity ratio of air passing through the dehumidifier to that observed under ideal conditions, as described in Equation 1. The moisture removal rate of air can be calculated by Equation 2. Knowing these two indices along with air and solution inlet conditions, the leaving air and solution conditions could be determined, which are essential in determining the performance of the dehumidifier and hybrid systems.

$$\varepsilon_{deh} = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{a,eq}} \quad (1)$$

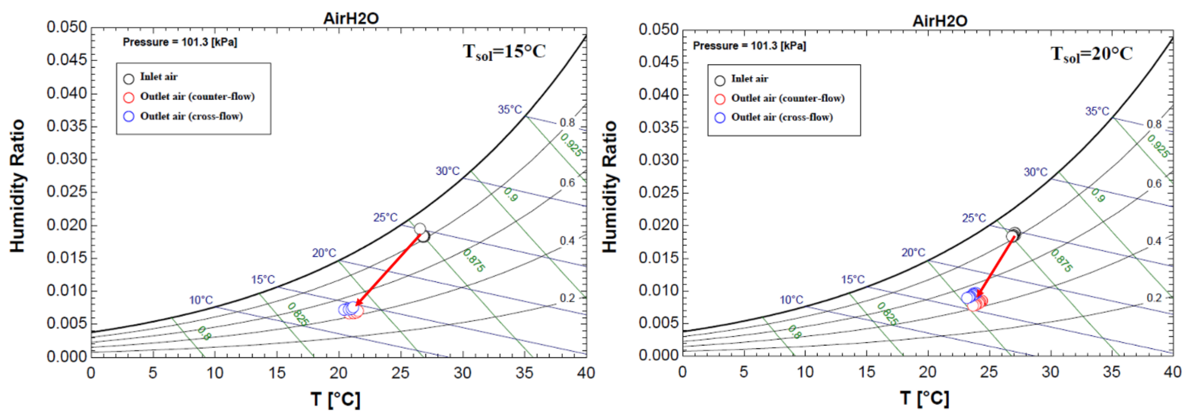
$$\dot{m}_{deh} = \dot{m}_{a}(\omega_{a,in} - \omega_{a,out}) \quad (2)$$

In Equation 1, the equilibrium humidity ratio ($\omega_{a,eq}$) can be defined using solution (P_s) and atmospheric pressures (P_{atm}), as described in Equation 3. To determine the solution pressure (P_s) under saturation condition of the desiccant solution, the second-order polynomial suggested by Fumo and Goswami (Fumo and Goswami, 2002) was used.

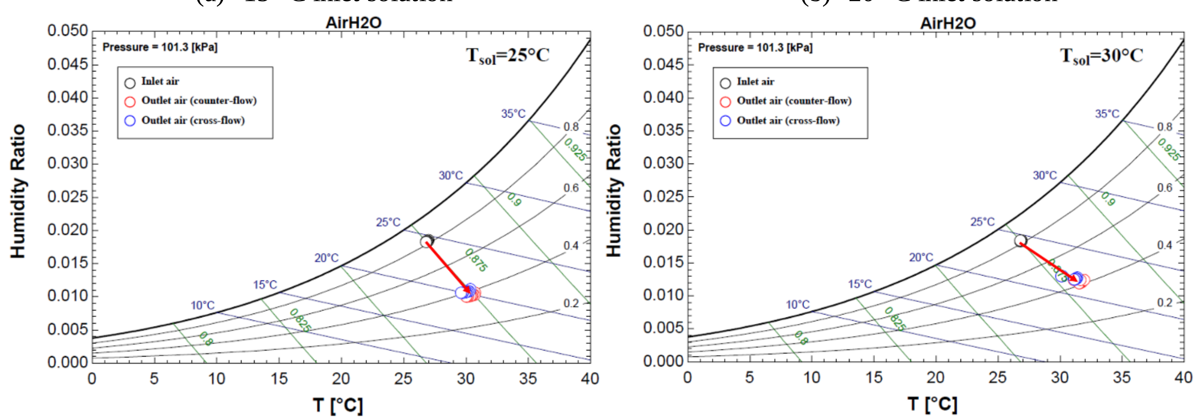
$$\omega_{a,eq} = 0.622 \times \frac{P_s}{P_{atm} - P_s} \tag{3}$$

3. EXPERIMENT RESULTS

Dehumidifier performance can be expressed in terms of dehumidification efficiency and moisture removal rate using Equation 1 and 2, respectively. Figure 5 shows measured data corresponding to inlet and outlet air conditions on a psychrometric chart based on different inlet-solution temperatures in the ranges of 15–30 °C. Experimental data were measured at 30-second intervals under operating conditions listed in Table 1. Figure 4 demonstrates that humidity ratio of the air passing through the cross-flow dehumidifier was slightly higher compared to that passing through the counter-flow dehumidifier. In addition, the difference between humidity ratios of the two dehumidifiers was observed to have steadily decreased with increase in inlet-solution temperature, thereby indicating that dehumidification performance in liquid desiccant dehumidifier decreases with increase in inlet-solution temperature. Outlet-air temperature was observed to have increased above the 25 °C value of the inlet-solution temperature because endothermic energy played a dominant role compared to the effect of solution temperature.



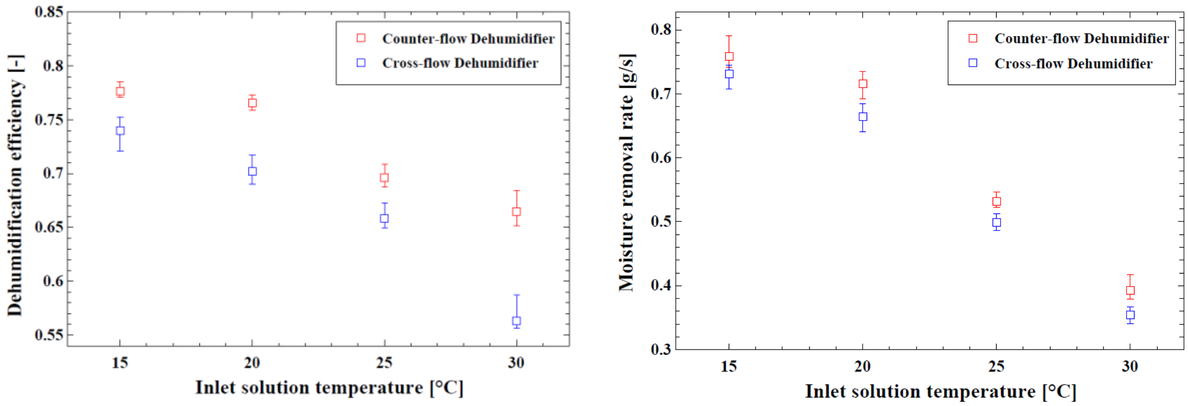
(a) 15 °C inlet solution (b) 20 °C inlet solution



(c) 25 °C inlet solution (d) 30 °C inlet solution

Figure 5: Experimental data representing inlet- and outlet-air conditions on psychrometric chart

Based on measured data shown in Figure 5, dehumidification efficiency and moisture removal rate were calculated using Equations 1–3. Figure 6(a) represents the effect of differences in flow direction between air and the desiccant solution on dehumidification efficiency. From the Figure 6(a), it can be inferred that dehumidification efficiency decreases with increase in inlet-solution temperature in both dehumidifiers. Experimental results demonstrate that dehumidification efficiency of the counter-flow dehumidifier is higher compared to that of cross-flow dehumidifier. Deviation of dehumidification efficiency with discrepancies in flow direction between air and the desiccant solution was observed to be 3.9%, 8.4%, 5.9%, and 7.4% at inlet-solution temperatures of 15 ºC, 20 ºC, 25 ºC, and 30 ºC, respectively. Figure 6(b) represents the effect of discrepancies in flow direction between air and desiccant solution on moisture removal rate. Similar to Figure 6(a), the moisture removal rate decreases with increase in inlet-solution temperature, and results also indicate that the range of variation in moisture removal rate with increase in solution temperature slightly larger compared to the variation in dehumidification efficiency. Deviations in dehumidification efficiency with differences in flow direction between air and desiccant solution measured 4.0%, 7.1%, 5.7%, and 7.7% at inlet-solution temperatures of 15 ºC, 20 ºC, 25 ºC, and 30 ºC, respectively. In summary, dehumidification performance of both dehumidifiers was observed to decrease with increase in inlet-solution temperature. In addition, deviation in dehumidification efficiency and moisture removal rate 3.9% to 8.4% and 4.0% to 7.7% for the counter-flow and cross-flow dehumidifier types, respectively, thereby demonstrating that there exists no significant difference between dehumidification performance of the two dehumidifier types with increase in inlet-solution temperature. The average dehumidification efficiency and moisture removal rate of the counter-flow and cross-flow dehumidifiers are summarized in Table 3.



(a) Dehumidification efficiency (b) Moisture removal rate

Figure 6: Effect of difference in flow direction between air and desiccant solution on dehumidification performance

Table 3: Average dehumidification efficiency and moisture removal rate of counter-flow and cross-flow dehumidifiers

Solution Temperature [ºC]	Counter-flow dehumidifier				Cross-flow dehumidifier			
	Dehumidification efficiency [%]		Moisture removal rate [g/s]		Dehumidification efficiency [%]		Moisture removal rate [g/s]	
	Average	Range	Average	Range	Average	Range	Average	Range
15	77.7	77.4–78.2	0.76	0.75–0.81	74	73.6–74.4	0.73	0.71–0.77
20	76.6	74.3–77.3	0.72	0.68–0.76	70.2	68.7–71.7	0.67	0.62–0.72
25	69.6	68.4–70.4	0.53	0.52–0.54	65.8	63.6–65.5	0.5	0.48–0.51
30	56.5	54.6–58.4	0.39	0.37–0.42	52.3	50.6–54.0	0.36	0.32–0.40

4. CONCLUSIONS

The study experimentally compares dehumidification performance of packed-bed cross-flow and counter-flow liquid desiccant dehumidifiers under identical operating conditions. Dehumidification experiments were performed with the inlet-solution temperature varying in the range of 15–30 ºC, and inlet air conditions were set, through use of a test chamber, based on average outdoor air conditions in summer. Dehumidification efficiency and moisture removal rate were adopted as performance indices, and the influence of difference in direction between the process air and desiccant solution on dehumidification performance was investigated. Following dehumidification performance characteristics were observed.

Dehumidification efficiency of the counter-flow- and cross-flow-type dehumidifiers were observed to vary over the ranges 54.6–78.2% and 50.6%–74.4%, respectively. Similarly, moisture removal rates of the two dehumidifiers varied over ranges 0.39–0.76g/s and 0.36–0.73g/s, respectively. These results demonstrate that dehumidification performance of both dehumidifiers decreases with increase in inlet-solution temperature. In addition, deviations in dehumidification efficiency and moisture removal rate ranged between 3.9–8.4% and 4.0–7.7%, respectively for the counter-flow- and cross-flow-type dehumidifiers, which indicates that there is no significant difference in dehumidification performance between the counter-flow and cross-flow dehumidifiers with increase in inlet-solution temperature.

Experimental results demonstrate that differences in flow direction between air and the desiccant solution have little effect on dehumidification performance under identical operating conditions. However, a major limitation of this study is that the proposed performance comparison analysis could only be performed with respect to varying inlet-solution temperatures. In addition, the proposed study compares the counter-flow and cross-flow dehumidifiers only in terms of dehumidification performance. To facilitate design optimization of liquid desiccant dehumidifiers, however, it is essential to compare the two dehumidifier configurations in terms of practical aspects. Therefore, further investigations, which consider energy consumption of counter- and cross-flow dehumidifiers, are required, since greater tower heights result in higher energy consumption.

NOMENCLATURE

$\dot{m}_a$	Air flow rate	(kg/s)
$\dot{m}_{deh}$	Moisture removal rate	(g/s)
P_{atm}	Atmospheric pressure	(kPa)
P_s	Vapor pressure of solution	(kPa)

Greek Symbols

ε	Efficiency	(-)
ω	Humidity ratio	(kg/kg)

Subscript

a	Air
deh	Dehumidification
eq	Equilibrium
in	Inlet
out	Outlet

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