A Study on Heat and Mass Transfer of a Plate Heat Exchanger Type Dehumidifier

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Abstract: In this study, experimental investigations have been carried out to examine heat and mass transfer of a heat exchanger type dehumidifier. LiCl aqueous solution is employed as a working fluid. Mass flowrate, concentration of LiCl aqueous solution and relative humidity, velocity of process air were selected as experimental variables. Effects of experimental variables on the dehumidification rate and effectiveness of dehumidification have been examined. As results, it was found that the higher the relative humidity and velocity of process air, the higher the dehumidification rate.

Key Words: **LiCl aqueous solution, dehumidification rate, effectiveness of dehumidification, heat transfer coefficient**

1 INTRODUCTION

With global warming and a shortage of fossil fuels, there has been an increasing emphasis on the need for high-efficiency and eco-friendly air conditioning systems. Vapor compression cooling systems, used in existing personal air conditioning, are known to worsen global warming and ozone depletion. Since process air is cooled below the dew point temperature for dehumidification, such systems do not provide individual control over temperature/ humidity. Thus research is essential to develop eco-friendly systems capable of individual temperature/humidity control.

Liquid desiccant system, one of the air conditioning systems that allow individual control of humidity, reduces the level of humidity in the air using liquid desiccant. These systems effectively remove the latent heat load of humid air. And the sterilizing effect of liquid desiccant helps to prevent air pollution. (Mei and Dai 2008) In addition, solar heat and waste heat can be used as a heat source in regenerator of liquid dehumidifier system. This is more eco-friendly and consumes less energy compared to existing air conditioning systems. (Factor and Grossman 1980, Gandhidasan 2005) Many researchers have thus utilized liquid desiccant in the development of air conditioning systems. (Yin et al. 2009, Zhang et al. 2013)

Liu et al. (2008) presented a mathematical model for coupled heat and mass transfer characteristics between air and liquid desiccant in packed bed dehumidifiers. Tu et al. (2010) analyzed and compared cycle performance between two novel configurations of liquid desiccant air conditioning systems. Jeon et al. (2010) examined how system performance is

affected by the temperature of hot water used in regeneration through cycle analysis of liquid desiccant cooling systems.

For the development of a plate heat exchanger type dehumidifier, we first conducted an experimental study on the heat and mass transfer characteristics of liquid dehumidifiers. Selected variables were velocity and relative humidity of process air, and mass flowrate and concentration of liquid desiccant. And the effects of these variables on the dehumidification rate, effectiveness of dehumidification, and the heat transfer coefficient were examined. LiCl aqueous solution was used as the liquid desiccant.

2 PLATE HEAT EXCHANGER TYPE DEHUMIDIFIER

The plate heat exchanger type dehumidifier used in this study consists of an upper/lower header for cooling water, a LiCl aqueous solution header and five plates. Including the headers, the dehumidifier measures 88 mm in length, 243 mm in width and 695 mm in height. It was made of the ABS (XR-474) resin in consideration of the corrosiveness of LiCl aqueous solution, and the plate surface was grooved and coated with the hydrophilic liquid to enhance a flowability and wettability of LiCl aqueous solution. Process air is in cross flow with LiCl aqueous solution at the plate surface, while the cooling water is in counter flow with LiCl aqueous solution.

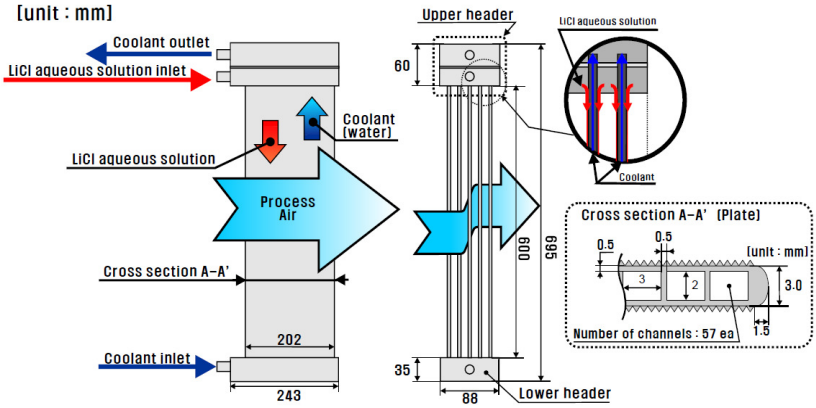


Figure 1 : Plate heat exchanger type dehumidifier

3 EXPERIMENT

3.1 Setup and method

Experimental setup was built to examine the heat and mass transfer characteristics of a plate heat exchanger type dehumidifier. As shown in Figure 2, the experimental setup consists of a LiCl aqueous solution supply unit, test section, process air circulation unit, and cooling water circulation unit. The LiCl aqueous solution supply unit includes a supply bath, solution pump, heat exchanger, constant temperature bath, and return bath. In this unit, high-concentration LiCl aqueous solution is supplied to the LiCl aqueous solution header after adjusting concentration, temperature and mass flowrate of LiCl aqueous solution. Through the distributor at the header, the LiCl aqueous solution flows over the plate surface, and gathers in the return bath as low-concentration absorbing the moisture of process air. The test section is the plate heat exchanger type dehumidifier, which provided measurements for the temperature and concentration of LiCl aqueous solution inlet/outlet, and the inlet/outlet temperature of cooling water. Concentration of LiCl aqueous solution was calculated by temperature (measured by temperature sensor RTD) and density (measured by sampling) of the LiCl aqueous solution. And concentration was measured three times at the inlet and outlet of the test section per each experiment. The process air circulation unit consists of a volumetric air flow meter, blower and duct. Process air flows through the duct connected to

the test section after temperature and humidity values have been set in the constant temperature and humidity chambers. Velocity of process air was adjusted by controlling the rpm of the blower motor. The cooling water circulation unit composed of the constant temperature bath, pump and flow meter supplies the coolant to lower the temperature of the LiCl aqueous solution.

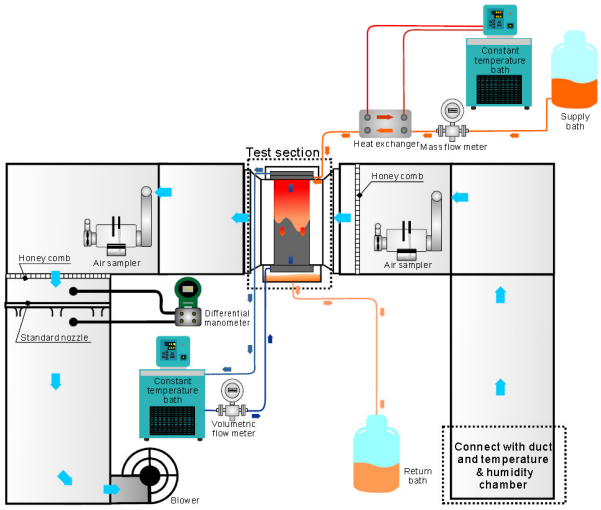


Figure 2 : Schematic diagram of experimental setup

3.2 Experimental conditions

Table 1 shows the normal operating conditions used to examine the heat and mass transfer characteristics of the plate heat exchanger type dehumidifier. The selected variables were velocity and relative humidity of process air, and mass flowrate and concentration of LiCl aqueous solution. The experiments were conducted under a relative humidity of 40 ~ 80% and velocity of 1.0 ~ 2.0 m/s for process air, and a concentration of 41 ~ 45% and mass flowrate of 1.5 ~ 5.5 g/s for LiCl aqueous solution.

Table 1 : Normal operating conditions

Variables		Inlet conditions
LiCl aqueous solution	Temperature, $T_{s,i}$ [℃]	43.0
	Mass flowrate, $\dot{m}_{s,i}$ [g/s]	3.5
	Concentration, C_{in} [%/100]	0.43
Cooling water	Temperature, $T_{w,i}$ [℃]	32.0
	Mass flowrate, $\dot{m}_w$ [g/s]	41.4
Process air	Temperature, $T_{a,i}$ [℃]	35.0
	Velocity, $V_{a,i}$ [m/s]	1.5
	Relative humidity, RH_i [%/100]	0.4

4 DATA REDUCTION

Eq. 1 to 12 are equations used in the analysis of heat and mass transfer characteristics of the plate heat exchanger type dehumidifier. Eq. 1 to 4 are energy balance equation, while Eq. 5 to 7 pertain to mass balance. Eq. 8 to 10 calculate the heat and mass transfer coefficients

of the process air. Eq. 11 gives the effectiveness of dehumidification. As shown in Eq. 12, humidity ratio of process air($\omega_{eq,i}$) in equilibrium state with LiCl aqueous solution at the interface of air and LiCl aqueous solution can be expressed as a function of the inlet temperature and concentration of LiCl aqueous solution.

- Energy balance

$$Q_w = Q_s + Q_a \tag{1}$$

$$Q_w = \dot{m}_w c_{p,w} (T_{w,o} - T_{w,i}) \tag{2}$$

$$Q_s = \dot{m}_{s,i} h_{s,i} - \dot{m}_{s,o} h_{s,o} \tag{3}$$

$$Q_a = \dot{m}_{da} (h_{a,i} - h_{a,o}) \tag{4}$$

- Mass balance

$$\dot{m}_{abs} = \dot{m}_{deh} \tag{5}$$

$$\dot{m}_{abs} = \dot{m}_{s,o} - \dot{m}_{s,i} \tag{6}$$

$$\dot{m}_{deh} = \dot{m}_{da} (\omega_{a,i} - \omega_{a,o}) \tag{7}$$

- Heat and mass transfer coefficients of process air

$$h_a = \frac{Q_{a,sen}}{A_o (T_s - T_a)} \tag{8}$$

$$Q_{a,sen} = \dot{m}_{da} (c_{p,a,o} T_{a,o} - c_{p,a,i} T_{a,i}) \tag{9}$$

$$\beta_a = \frac{\dot{m}_{deh}}{(\omega_a - \omega_{eq}) \rho_a A_o} \tag{10}$$

- Effectiveness of dehumidification

$$\varepsilon_{deh} = \frac{\omega_{a,i} - \omega_{a,o}}{\omega_{a,i} - \omega_{eq,i}} \tag{11}$$

$$\omega_{eq,i} = f(T_{s,i}, C_{s,i}) \tag{12}$$

5 RESULTS AND DISCUSSIONS

Figure 3 presents graphs for energy and mass balance. Most experiments performed in this study gave results within ±20 %. Figure 4 shows how dehumidification rate and effectiveness of dehumidification are affected by varying the velocity of process air in the range of 1.0 ~ 2.0 m/s. The inlet concentration and mass flowrate of LiCl aqueous solution have been fixed at 43 % and 3.5 g/s respectively, and the relative humidity of process air at 40%, 60% and 80%. As the velocity and relative humidity of process air increases, dehumidification rate also rises in the range of about 7.4 ~ 23.8 g/min. This can be interpreted as an increase in the Reynolds number, which results in a higher mass transfer coefficient. An increase in the relative humidity of process air led to an increase in dehumidification rate because of the greater vapor pressure difference of process air and LiCl aqueous solution. On the other

hand, the effectiveness of dehumidification decreased to 23 ~ 49% with an increase in velocity and relative humidity of process air. Figure 5 shows the effect of mass flowrate and concentration of LiCl aqueous solution on dehumidification rate and effectiveness of dehumidification. The relative humidity and velocity of process air at this time is 40% and 1.5 m/s respectively. The higher the concentration of LiCl aqueous solution, the higher the dehumidification rate. The vapor pressure difference of LiCl aqueous solution and process air has increased with the higher concentration since the vapor pressure of LiCl aqueous solution tends to decrease at higher concentrations and lower temperatures. An increase in mass flowrate caused no significant change in dehumidification rate. This is because of increase in the average concentration and the average temperature of LiCl aqueous solution (in the dehumidifier) results in a small change in the vapor pressure of the LiCl aqueous solution. The effectiveness of dehumidification was lesser for a higher concentration of LiCl aqueous solution at the inlet. When the concentration of LiCl aqueous solution was 41 ~ 45%, the effectiveness of dehumidification was about 33 ~ 43%. Thus, we can see that concentration of LiCl aqueous solution has a greater effect than mass flowrate on the effectiveness of dehumidification.

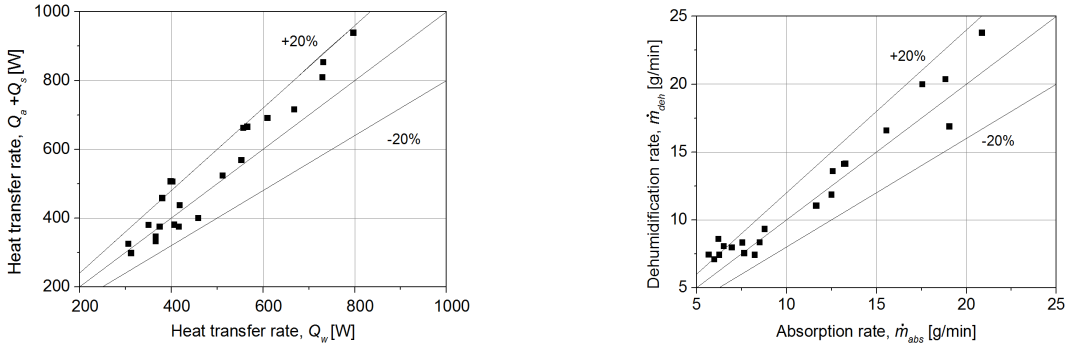


Figure 3 : Energy and mass balance

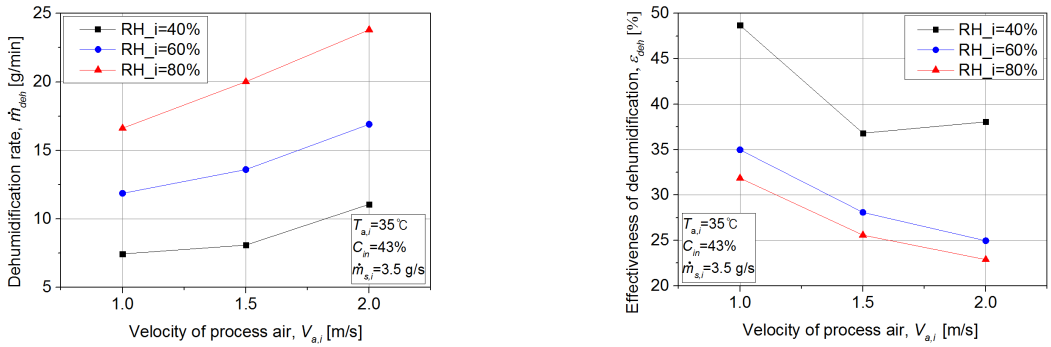


Figure 4 : The effect of velocity and relative humidity of process air on dehumidification rate($\dot{m}_{deh}$) and effectiveness of dehumidification(ε_{deh})

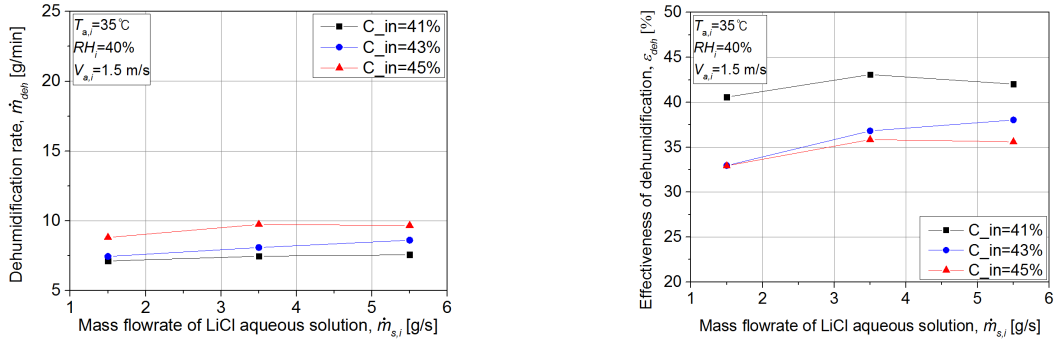
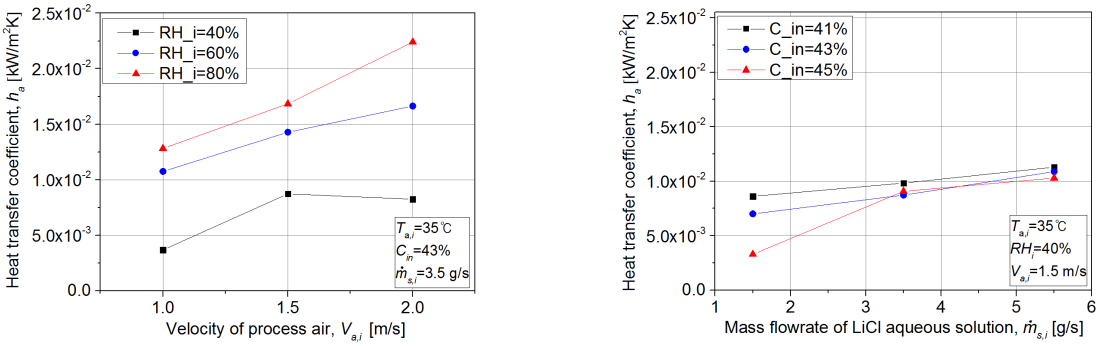


Figure 5 : The effect of mass flowrate and concentration of LiCl aqueous solution on

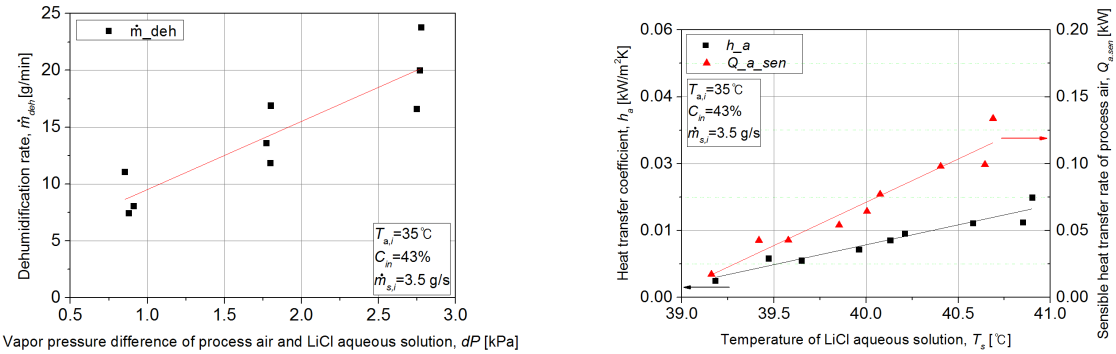
dehumidification rate($\dot{m}_{deh}$) and effectiveness of dehumidification(ε_{deh})

Figure 6 illustrates the effect of velocity and relative humidity of process air, and concentration and mass flowrate of LiCl aqueous solution on the air side heat transfer coefficient. Figure 7(a) shows the effect of vapor pressure difference between process air and LiCl aqueous solution on dehumidification rate, while Figure 7(b) gives the effect of average inlet/outlet temperature of LiCl aqueous solution on air side heat transfer coefficient and sensible heat transfer rate of process air. As shown in Figure 6(a), the heat transfer coefficient rises with an increase in velocity and relative humidity of process air. When the velocity of process air is 1.0 ~ 2.0 m/s, ranges for the heat transfer coefficient were 3.68 ~ 8.25 W/m^{2}K, 10.75 ~ 16.64 W/m^{2}K, and 12.82 ~ 22.41 W/m^{2}K for a relative humidity of 40%, 60% and 80%, respectively. The increase in heat transfer coefficient with velocity of process air can be attributed to the higher Reynolds number of process air. As can be seen from figure 7(a) dehumidification rate increases with the increase in the vapor pressure difference between the process air and the LiCl aqueous solution. And as dehumidification rate increases, the increased heat of absorption causes the high average temperature of LiCl aqueous solution in the dehumidifier. This in turn results in a higher temperature of process air and also a greater sensible heat transfer rate of process air. But it was found that the temperature difference between the LiCl aqueous solution and the process air is nearly constant for all cases. Thus, the air side heat transfer coefficient (refer to Eq. (8)) increases under the conditions of high average temperature of the LiCl aqueous solution (same as the conditions of greater dehumidification rate, e. g., as the inlet relative humidity or the velocity of process air increases) as shown in figure 7(b). The heat transfer coefficient was not significantly affected by changes in mass flowrate and concentration of LiCl aqueous solution, and this can be seen in Figure 6(b). The velocity and relative humidity of process air at this time is 1.5 m/s and 40% respectively. The heat of absorption was not able to change the temperature of LiCl aqueous solution due to the small difference in dehumidification rate resulting from changes in LiCl aqueous solution concentration.



(a) (b)

Figure 6 : The effect of (a) velocity and relative humidity of process air (b) concentration and mass flowrate of LiCl aqueous solution on air side heat transfer coefficient(h_a)



(a) (b)

Figure 7 : The effect of (a) vapor pressure difference of process air and LiCl aqueous

solution on dehumidification rate($\dot{m}_{deh}$) (b) temperature of LiCl aqueous solution on air side heat transfer coefficient(h_a) and sensible heat transfer rate($Q_{a,\,sen}$) of process air

6 CONCLUSION

This study examined the heat and mass transfer characteristics in a plate heat exchanger type dehumidifier for application to liquid dehumidifier systems. The experimental variables were relative humidity and velocity of process air, and mass flowrate and concentration of LiCl aqueous solution. The results can be summarized as follows.

(1) Dehumidification rate increases with an increase in velocity and relative humidity of process air, but effectiveness of dehumidification decreases. When process air had a velocity of 1.0 ~ 2.0 m/s and relative humidity of 40 ~ 80%, the dehumidification rate and effectiveness of dehumidification were 7.4 ~ 23.8 g/min and approximately 23 ~ 49%, respectively.

(2) Changes in the mass flowrate and concentration of LiCl aqueous solution were found to have minimal effect on dehumidification rate. The effectiveness of dehumidification increases with a decrease in the concentration of LiCl aqueous solution.

(3) As the velocity of process air increases, the air side heat transfer coefficient becomes greater. For a relative humidity of 40%, 60%, and 80% at the inlet of process air, ranges for the air side heat transfer coefficient were 3.7 ~ 8.3 W/m^{2}K, 10.8 ~ 16.6 W/m^{2}K, and 12.8 ~ 22.4 W/m^{2}K, respectively.

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