Regeneration performance of liquid desiccant on the surface of a plate-type heat exchanger

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Abstract
Recently, there have been many studies on dehumidifiers with a low flow rate of liquid desiccant, in which a plate-type heat exchanger with internal cooling is adopted. If the low flow rate of a liquid desiccant maintains a thin liquid film on the heat exchanger surface, heat and mass transfer performance would improve, the stability of the liquid film would increase, and there would be no entrainment of desiccant droplets. In this study, we built an experimental apparatus to measure the regeneration performance of a liquid desiccant and investigated the wettability of the liquid desiccant along the vertical surface of a plate-type heat exchanger. Liquid desiccant was applied to the top of plate heat exchangers having different groove gaps, on which we had applied a hydrophilic coating to enhance the wettability of the liquid desiccant. In a visualization test, we found that a plate heat exchanger with a 1.0-mm groove gap resulted in the greatest wettability. As the mass flow rate of the supplied liquid desiccant increases, the wettability of the liquid desiccant is enhanced, and the regeneration rate and mass transfer coefficient can also be enhanced. We developed experimental correlations for the heat and mass transfer performances of the heat exchanger.

Key words: Liquid desiccant, Regeneration, Hydrophilic surface coating, Mass transfer coefficient, Heat transfer coefficient, LiCl

Nomenclature
A Heat transfer area, m²
cp Isobaric specific heat capacity, J/kgK
d Channel depth of heat exchanger, m
D Diffusion coefficient, m²/s
g Gravitational acceleration, m/s²
ha Heat transfer coefficient, W/m²K
hm Mass transfer coefficient, kg/m²K
i Enthalpy, J/kg
k Thermal conductivity, W/m K
m Mass flow rate, kg/s
Nu Nusselt number
Pr Prandtl number
Q Heat transfer rate, W
Rea Reynolds number of air side
Ref Film Reynolds number of liquid desiccant
Sc Schmidt number
Sh Sherwood number
t Wall thickness of heat exchanger, m
T Temperature, °C
1. Introduction

Liquid desiccant cooling technology is based on a type of open absorption cycle that absorbs the latent heat of inlet air by a liquid desiccant. It has the advantage of providing efficient cooling with the heat supplied from the community energy supply system including the feed water of the district heating system, industrial waste heat, and other sources (Sur and Das, 2015). In addition, it provides efficient heat and mass transfer as the desiccant comes in direct contact with the air and is capable of eliminating air pollution due to the sterilization effect of the desiccant (Mai and Dai, 2008).

As shown in Fig. 1, in liquid desiccant dehumidification systems, moisture is transferred from the conditioned air to the desiccant in the dehumidifier, and the diluted desiccant from the dehumidifier is regenerated before being reused in the regenerator. For efficient dehumidification or regeneration, the heat and mass transfer performance should be enhanced, and a large contact area between the air and the desiccant is essential. To achieve a low air pressure drop and ensure a large contact area between the air and desiccant, numerous studies have been conducted on several types of dehumidifier, including the spray tower, packed bed tower, and wetted wall column (Jain and Bansal, 2007, Jain et al., 2000).

Since heat and mass transfer occurs at the interface of the liquid desiccant and air, a large contact area can bring high mass transfer by enhancing the wetting of the liquid desiccant on the heat exchanger surface and the air-side mass transfer coefficient. Experiments and analytical studies have been carried out regarding the heat and mass transfer on packed dehumidifier and regenerator (Liu and Jiang, 2008, Yin and Zhang, 2008, Kim et al., 2015).

Carryover of the desiccant is another problem, when the flow rate of the liquid desiccant is increased to secure a large mass transfer surface between the liquid desiccant and air. The liquid film becomes thicker, which induces an unstable wave of liquid film, and small droplets of liquid desiccant may be discharged into the air (Navarro-Peris et al., 2015). An aqueous solution of lithium chloride is normally used as the liquid desiccant, which is highly corrosive. Thus, even small amounts of lithium chloride may corrode surrounding metals. To prevent any carryover of the liquid desiccant, achieving low desiccant flow and identifying the optimal type of contacting equipment are important considerations when designing the dehumidifier and regenerator of a liquid desiccant system.

A low flow rate of the liquid desiccant incurs temperature variations by moisture absorption or evaporation, which reduces the mass transfer performance as well as the performance of the liquid desiccant system. If the liquid desiccant is continually cooled or heated inside a dehumidifier or regenerator by adopting a simultaneous heat and mass transfer exchanger, the drawbacks of a low-flow liquid desiccant can be avoided, and the effectiveness of the dehumidifier and regenerator can be enhanced (Lowenstein et al., 2006, Khan, 1998).

The desiccant solution supplied to the regenerator must be maintained as a thin liquid layer on the entire heat
exchanger surface, so in this study, we sought to improve the wettability of the liquid desiccant through hydrophilic surface treatment and a shape-changing surface. The purpose of this study is to analyze the wettability performance and its effect on the heat and mass transfer characteristics of LiCl aqueous solution on a plate-type heat exchanger with grooves. We investigated the effects of the desiccant aqueous solution flow rate as well as air flow rate on the regeneration performance. Due to the complexity of the combined heat and mass transfer processes in the regenerator, we established a numerical model to analyze the heat and mass transfer processes, based on our experimental results.

2. Plate heat exchanger in regenerator

As shown in Fig. 2, heating water flows inside channels in the plate heat exchanger, and regeneration occurs when desiccant solution is supplied to the outside surface of the heat exchanger from top to bottom through a gap between the header and heat exchanger, while air is supplied in the vertical direction of the flowing desiccant solution. To enhance
the wettability of the liquid desiccant on the surface of the heat exchanger, we made V-shaped grooves on the heat exchanger surface-parallel to the direction of flow of the liquid desiccant, and coated the porous layer to improve wettability. Figure 2 illustrates the structure of the heat exchanger. We used three heat exchangers, with different groove pitches of 0.5, 1.0, and 1.5 mm. The heat exchangers were manufactured in a drawing process and the base material consisted of high thermally resistant ABS polymer.

We applied a porous coating to the surface of the heat exchanger to enhance the wettability of the liquid desiccant. This acrylic epoxy resin with alumina oxide powders (average diameter of 50 µm) coat the surface of the heat exchanger, and then an additional sulfonic hydrophilic polymer coating is applied on the surface of the heat exchanger [Lee et al. 2016]. Figure 3 shows SEM images of the porous hydrophilic surface treatment. More particles were filled in the groove, which can reduce the depth of groove. The wettability of liquid desiccant seems to be enhanced by two main causes. Firstly, surface wettability is mainly improved by porous coating due to capillary effect on voids between particles. Secondly, the grooves on the surface of the heat exchanger serve not only to sustain the liquid film on the heat exchanger surface but also to distribute the liquid desiccant evenly on the top of heat exchanger surface. The grooves build gaps between header and heat exchanger surface, where liquid desiccant is distributed on heat exchanger surface. The porous coating was not applied to this distributing part to bind header on heat exchanger securely. Thus, small change of groove shape by porous coating is assumed to influence little effect on wettability of liquid desiccant.

We carried out a wettability visualization test of the liquid desiccant on the surface of the plate heat exchanger. We supplied a 40% LiCl liquid solution mixed with a fluorescent substance to the top of the vertically installed plate heat exchanger [Chang et al., 2014]. Figure 4 shows the results of the heat exchanger visualization test with respect to groove pitch. We found that the wettability on the heat exchanger surface was highest in the heat exchanger with a 1.0-mm groove pitch. Figure 5 shows the results of the wettability visualization test for the heat exchanger with a groove pitch of 1.0 mm when we varied the flow rates of the supplied liquid desiccant between 30, 60, and 90 g/min, and the wettability of the liquid desiccant on the surface increased with an increase in the supply of the liquid desiccant.
3. Regeneration performance

Figure 6 shows a schematic diagram of the experimental apparatus used to investigate the regeneration performance of the LiCl aqueous solution. The experimental apparatus consists of the LiCl solution loop, water heating circulation loop, test section, and measurement devices. We installed one heat exchanger plate at the test section, and the width and height of the heat exchanger were 200 mm and 600 mm, respectively. Experiments were conducted inside the thermal chamber where the temperature and humidity are controlled precisely. In front of the test section, we installed an air sampler to measure the dry and wet bulb temperatures of the inlet air. Gear pumps that circulate the LiCl aqueous solution and a thermostatic bath that controls the inlet temperature of LiCl aqueous solution are located in the LiCl solution loop. To measure the concentration of the LiCl aqueous solution, we measured the refractive indexes of the solution sampled at the inlet and outlet of the test section, and calculated the concentration using the correlation of the refractive index and the concentration of the LiCl solution.

Table 1 shows the experimental conditions used to investigate the heat and mass transfer characteristics of a plate heat exchanger. We maintained the inlet air temperature and relative humidity at 35 °C and 40%, respectively. The inlet temperature and concentration of the LiCl aqueous solution were 68 °C and 40%, respectively. We varied the solution flow rates within a range of 30 to 80 g/min and the air flow rates within a range of 6 to 58 CMH, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Conditions</th>
<th>Conditions</th>
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</thead>
<tbody>
<tr>
<td>Solution inlet temperature</td>
<td>°C</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Solution flow rate</td>
<td>g/min</td>
<td>30–80</td>
<td></td>
</tr>
<tr>
<td>Solution concentration</td>
<td>%</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Hot water temperature</td>
<td>°C</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Hot water flow rate</td>
<td>g/min</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Air inlet temperature</td>
<td>°C</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Air inlet flow rate</td>
<td>CMH</td>
<td>6–58</td>
<td></td>
</tr>
<tr>
<td>Air inlet relative humidity</td>
<td>%</td>
<td>40</td>
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The regeneration rate of the liquid desiccant can be measured from the mass flow rate difference between the inlet and outlet liquid desiccant, as in Eq. (1). The regeneration rate can be also obtained from the air side, using Eq. (2), which should coincide with the regeneration rate of the liquid desiccant determined by Eq. (1).

\[
\dot{m}_{\text{reg}} = \dot{m}_{s, i} - \dot{m}_{s, o} \\
\dot{m}_{\text{reg}} = \dot{m}_{a, o} \omega_{a, o} - \dot{m}_{a, i} \omega_{a, i}
\]  

(1)  

(2)

The heating water heats the liquid desiccant for regeneration, heating rate can be calculated using Eq. (3). The increases in the enthalpy of the liquid desiccant and air are obtained by Eqs. (4) and (5), respectively. The energy supplied by the heating water corresponds to the sum of the enthalpy increases in the liquid desiccant and air.

\[
\dot{Q}_w = \dot{m}_w \left( C_{p,w,i} T_{w, i} - C_{p,w,o} T_{w, o} \right) \\
\dot{Q}_s = \dot{m}_{s,i} C_{p,s,i} T_{s,i} - \dot{m}_{s,o} C_{p,s,o} T_{s,o} \\
\dot{Q}_a = \dot{m}_{a,o} \omega_{a,o} - \dot{m}_{a,i} \omega_{a,i} \\
\dot{Q}_w = \dot{Q}_s + \dot{Q}_a
\]  

(3)  

(4)  

(5)  

(6)

The energy and mass balances obtained from the experimental results are shown in Fig. 7. The experimental results show that the heat and mass balances match to within ± 20%, which verifies the confidence level of the experimental results.

We used three groove pitches of 0.5 mm, 1.0 mm, and 1.5 mm of the plate heat exchangers. Figure 8(a) shows the effect of the air flow rate on the regeneration rate for the different groove pitches. We found that the regeneration rate increases as the air flow rate increases, as expected. This is because the mass transfer coefficient between the air and the liquid desiccant becomes larger with an increase in the air flow rate.

We carried out experiments on the regeneration performance by varying the supplied flow rate of the liquid desiccant, while the air flow rate was held constant at 6 CMH. From the results of our visualization test, we found that a higher flow rate of the LiCl solution increases the wettability of the liquid desiccant on the heat exchanger surface. The regeneration rate of the liquid desiccant increases with an increase in the mass flow rate of the supplied liquid desiccant, as shown in Fig. 8(b). We consider the increase in the mass transfer performance to be mainly due to the enhanced wettability. We also found the regeneration rate associated with the 1.0-mm groove pitch to be better than that of the other two groove pitches.

![Fig. 7 Heat and mass balances of experimental data](image-url)
5. Heat and mass transfer model for regeneration process

Figure 9 shows a schematic of the heat and mass transfer process on the finite volume in the regenerator. The desiccant, flowing across the direction of the air flow, is distributed over the surface of the heat exchanger by gravity and releases moisture as it comes into contact with the air. The assumptions for the present model are (1) the local heat and mass transfer coefficients are uniform throughout the finite volume; (2) the contribution of conduction or diffusion to the total heat or mass transfer can be neglected in the flow directions; and (3) since the liquid desiccant film is very thin, the temperature of the liquid desiccant film surface is equal to the average temperature of the desiccant.

The heat transfer rate from the heating water to the liquid desiccant can be represented by Eqs. (7)–(10), as shown below. The heat and mass transfer occur at the same time, and the heat transfer rate from the liquid desiccant to the processed air can be represented by Eq. (11), shown below. We divided the test section of the plate heat exchanger into 10 x 30 finite volumes, as shown in Fig. 9. The regeneration and heat transfer rates can be obtained using the combined heat and mass transfer model which accounts mass transfer resistance of liquid film and air.

\[
d\dot{Q}_w = U(T_w - T_s) dA
\]

\[
\frac{1}{U} = \frac{1}{h_w} + \frac{t}{k_{HX}} + \frac{\delta}{k_s}
\]

\[
\delta = \left(\frac{3\Gamma \mu \rho^2}{\beta g}\right)^{1/3}
\]

We have the following equations:

\[
d\dot{Q}_w = U(T_w - T_s) dA
\]

\[
\frac{1}{U} = \frac{1}{h_w} + \frac{t}{k_{HX}} + \frac{\delta}{k_s}
\]

\[
\delta = \left(\frac{3\Gamma \mu \rho^2}{\beta g}\right)^{1/3}
\]

Fig. 9 Schematic of the heat and mass transfer process on the finite volume in the regenerator
In this study, we obtained the heat and mass transfer coefficients on a grooved-plate heat exchanger by comparing the experimental data of the regeneration and heat transfer rates with the results of the numerical model. Uncertainties in heat transfer coefficient and mass transfer coefficient were estimated based on the method by Moffat (1988). For heat transfer rate greater than 100 W (typically, air flow rate greater than 30 CMH), uncertainties in heat transfer coefficient and mass transfer coefficient were in the range of 15 - 18% and 8 – 9%, respectively. For heat transfer rate less than 60 W (typically, air flow rate less than 10 CMH), uncertainties in heat transfer coefficient and mass transfer coefficient ranged from 20 to 23% and 10 – 11%, respectively.

We developed the heat and mass transfer correlations in Eqs. (12) and (13) based on the numerical model and experimental results for the 1.0-mm groove pitch case. As shown in Fig. 8, the regeneration rate, which is affected by the mass transfer characteristics of the air and the liquid desiccant, depends on the mass flow rate of the liquid desiccant as well as the air flow rate, and the heat transfer rate between the air and the liquid desiccant shows a similar trend to that of the mass transfer. Thus, we used regression analysis to develop heat and mass transfer correlations as functions of the Reynolds numbers of the air and film Reynolds number of the liquid desiccant, as follows. The developed correlations predict the heat and mass transfer coefficients within ±20% and ±10% error bounds, respectively, as shown in Fig. 10. Heat transfer coefficients less than 5 W/m²K were obtained from the experimental data of low heat transfer rate and low air flow rate region, which have relatively larger experimental measurement error. Thus developed heat transfer correlation has greater error more than 20% and has a tendency of overpredicting heat transfer coefficient in the range less 5 W/m²K.

As shown in Fig. 11, the heat and mass transfer model developed in this study can predict the regeneration performance, within a 10 - 20% margin of error, of the experimental data under various operating conditions.

\[
\begin{align*}
\text{Nu} & = 0.04607 \text{Re}_a^{0.6606} \text{Re}_s^{0.3217} \text{Pr}_a^{0.4} \\
\text{Sh} & = 0.7351 \text{Re}_a^{0.06716} \text{Re}_s^{0.5966} \text{Sc}_a^{0.4}
\end{align*}
\]

6. Conclusion

In this paper, we described our experimental study on the regeneration performance of a plate-type heat exchange dehumidifier. Based on our results, we can draw the following conclusions: To enhance the wettability of the liquid desiccant on the surface of the heat exchanger, we applied V-shaped grooves onto the heat exchanger surface, where a porous layer had also been coated to improve the wettability. A heat exchanger groove pitch of 1.0 mm produced better
regeneration performance than groove pitches of 0.5 mm and 1.5 mm, which rely on the better wettability of the liquid desiccant on the heat exchanger surface. As the air and liquid desiccant flow rates increased, the regeneration rate of water from a LiCl aqueous solution increased. We developed heat and mass transfer correlations as functions of the Reynolds numbers of the air and liquid desiccant. On the whole, the proposed correlations can predict the heat and mass transfer performance within 10 to 20% error bound, even though heat transfer correlation has greater error more than 20% and has a tendency of overpredicting heat transfer coefficient in the range less 5 W/m²K.

Acknowledgments

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