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Dehumidification of Air by Aqueous Lithium Chloride in a Packed Column

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ABSTRACT

A packed bed absorber-stripper system has been designed to dehumidify moist air by contact with aqueous solutions of lithium chloride. The packing material used in the study is 1.6 cm (5/8 inch) polypropylene Flexi rings, which have a surface to volume ratio of 342 m^2/m^3 (104 ft^2/ft^3). The absorber is capable of handling air face velocities from 3362.4 to 6746.4 kg/m^2h and liquid flow rates from 2534.1 to 54648 kg/m^2h. Solutions of 30% and 40% lithium chloride in water were employed as the dehumidifying agent. The minimum liquid flow rate calculated from the equilibrium data would be too low to wet the packing surface completely, and could not be used in the actual operating system. Therefore, liquid flow rates greater than the minimum wetting rate for the packing were used. Measured flooding conditions corresponded closely with exiting empirical correlations. Mass transfer coefficients ranged from 0.062 $kmol/m^3s$ at 40% flooding to 0.166 $kmol/m^3s$ at 80% flooding for the 40% lithium chloride solution. The height of a transfer unit calculated from the experimental data ranged from 0.340 m at a column efficiency of 71.6% to 0.617 m at a column efficiency of 50%.

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INTRODUCTION

Depending on the application, various types of air conditioning systems are available, including solid desiccant based systems, liquid desiccant based systems, and conventional vapor compression refrigeration systems. Although liquid desiccant systems have been used in the past for dehumidification and air conditioning, only limited mass transfer data are available in the open literature.

Several liquid desiccants have been employed for dehumidification of air or other process streams. The most common ones are lithium chloride, lithium bromide, calcium chloride, and the glycols. A summary of studies related to the use of various liquid desiccants is presented in Table 1. Only a few studies are available in the open literature in which a direct comparison of various liquid desiccants is presented. Grover et al. (4) compared, theoretically, the performance of two absorption cooling systems; one employed water-lithium chloride as the desiccant and the other one used water-lithium bromide. According to them, lithium chloride solution is a better absorbent because of its lower corrosivity and fewer health hazards. However, a lithium chloride-water solution has a higher viscosity than a lithium bromide-water solution of comparable concentration, which can reduce the heat transfer rate in the system. Gandhidasan et al. (1) developed several correlations for heat and mass transfer coefficients for a packed column that employed aqueous calcium chloride solution and used ceramic Raschig rings and Berl saddles as packings. Their reason for using calcium chloride was that it was the least expensive and most readily available. However, they did not compare the column performance by using different desiccant solutions .

In a liquid desiccant based system, air is generally introduced at the bottom of a column and a liquid desiccant, such as 40% lithium chloride or 95% triethylene glycol (TEG) solution in water, is fed from the top. To enhance the mass transfer between the air and the liquid, a number of methods can be used, including a column packed with inert packing, a spray column, or a finned tube surface type

Table 1. Liquid Desiccants Used in Absorption/ Regeneration Systems

Study / Liquid Desiccants	Absorption and Regeneration Processes	Heat and Mass Transfer Coefficient
Lithium Chloride	Holland, 1963 (5) Anderson, 1967 (17)* Robinson and Houston, 1980 (27) Grover et al., 1989 (4) Gandhidasan and Satcunanathan, 1983 (11)*	Leboeuf and Lof, 1980 (10)* Lof et al., 1984 (9)* Scalabrin and Scaltriti, 1984 (12)* Kakabaev and Khallyev, 1988 (24)
Lithium Bromide	Van Hatten and Actis Dato, 1981 (30) Esia et al., 1986 (19) Factor and Grossman, 1980 (3)* Grover et al., 1989 (4) Esia et al., 1985 (20)	
Calcium Chloride	Gutkowski and Ryduchowski, 1986 (8) Mullick and Gupta, 1973 (25)	Gandhidasan et al., 1986 (1)* Gandhidasan et al., 1987 (2)*
Triethylene Glycol	Ullah et al., 1988 (13) Johannsen, 1979 (23) Grosso et al., 1980 (21)* Peng and Howell, 1981 (6) Peng and Howell, 1984 (7)	Andrew, 1982 (18)* Howell , 1987 (22) Queiroz et al., 1988 (26)

* study of packed-bed absorber

dehumidifier. All three types of contact-systems are in use commercially .

A packed-bed absorber has been designed in this project to study the dehumidification of air. The packing material used in the column was 1.6 cm (5/8 inch) polypropylene Flexi rings, having a surface area to volume ratio of 342 m^2/m^3 (104 ft^2/ft^3). Polypropylene Flexi rings are inexpensive and also have good chemical resistance. The performance of the packed column was evaluated under various operating conditions. The parameters that were varied during the experiments included flooding conditions, the temperature and humidity of the inlet air, temperature of the liquid stream and its circulation rate, and the concentration of the desiccant solution. Mass transfer coefficients and the height of the transfer unit were calculated from the experimental data and were compared with literature values.

EXPERIMENTAL SYSTEM

A detailed schematic of the absorption and stripping system that was used in the present study is shown in Figure 1. The absorber is a 15.25 cm (6 inch) I.D. glass column packed with 1.6 cm (5/8 inch) polypropylene Flexi rings. The middle section of the column, containing the packing, has a Teflon support plate that supports the packing and also acts as an air distributor. The top cap has a 5.08 cm (2 inch) side tube for the air outlet. The bottom cap has a 2.54 cm (1 inch) opening for the liquid outlet. The air is introduced in the column through a 3.8 cm (1.5 inch) tube connected to the side of the bottom side spacer. The liquid desiccant is introduced into the column through a 1.9 cm (3/4 inch) diameter line connected to the side of the top side spacers. Both side spacers are made of plexiglass and are inserted between the top or bottom cap and the middle glass column. The stripper design is the same as the absorber. The system can handle air and lithium chloride solution flow rates up to 64 CFM (7687.1 kg/m^2 h or 26.3 lb/ft^2min) and 5 GPM (77718.6 kg/m^2h or

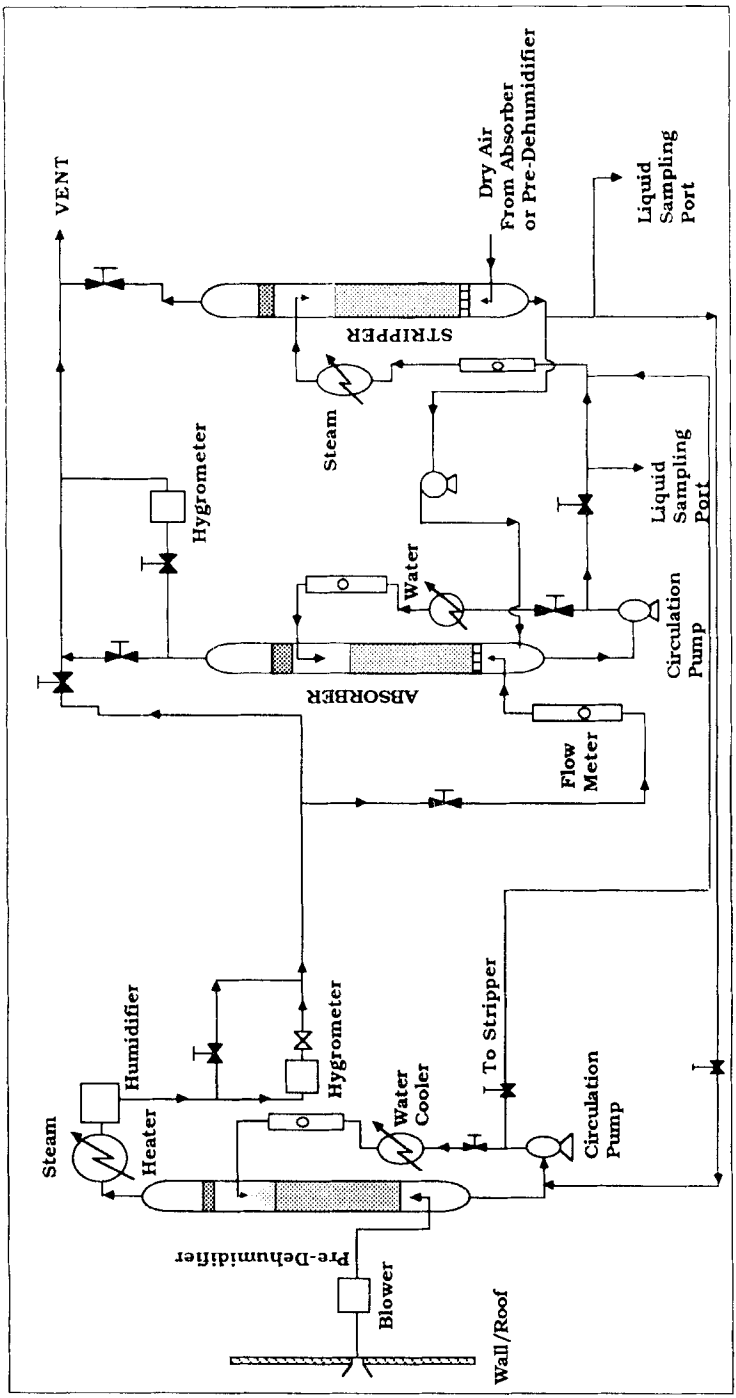

Figure 1. Absorption Stripper System for This Study

265.9 lb/ft^{2}min), respectively. Column pressure drop was less than 3 inches of water per foot of packing height and the total system pressure drop was less than 16 inches of water. The whole bed tended to float as the column approached flooding conditions, due to the light weight of the packing, requiring that special precautions be taken in the design. A metal plate with several holes was put on the top of packings to prevent floating of the bed.

Approximately 51 to 102 m^3/h (30 to 60 CFM) of air was required to operate the absorption column between 50 to 80% of the flooding velocity. Therefore, outdoor air was used in all experimental runs. Because the temperature and relative humidity of outdoor air vary throughout the day, it was first dried by flowing through a dehumidifier and then humidified to the desired level in a plexiglass chamber by spraying water into the flowing air. The humidity and temperature of the flowing air were controlled by monitoring the water temperature and the amount sprayed into the system. With this arrangement, the humidity and temperature of the inlet air could be reproduced.

The humidified air was then introduced in the bottom of the absorber and the liquid absorbent was sprayed on the top of the packing material. The flow rates of both air and liquid were monitored by flowmeters. All of the flowmeters and flow controllers used in this system were calibrated by using standard procedures. Regeneration of the solution was carried out in the stripper and the regenerated solution was cooled and returned to the absorber. Lithium chloride solutions of 30% and 40% were employed in this study.

RESULTS AND DISCUSSION

The minimum liquid flow rate was determined by using the equilibrium curve and was found to be only 0.0095 L/min (0.0025 GPM) at the maximum air flow rate of 108.8 m^3/h (64 CFM). This, however, is significantly lower than the minimum liquid flow rate of 9.82 L/min (2.16 GPM) necessary to wet the packing as found from

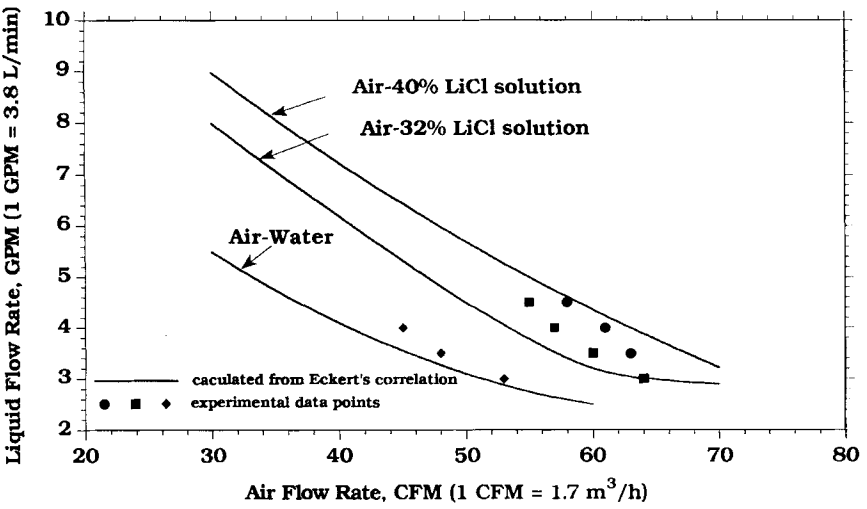

Figure 2. Comparison of Experimental Liquid Flow Rates with Those Predicted Values at the Flooding Condition of the Absorber

the equation given by Leva (15). The operating liquid flow rate used in this study was determined from the correlation of Eckert (14). For a gas flow rate of 51 m^3/h (30 CFM), the liquid flow rate at 40% of flooding was found to be 13.45 L/min (12.3 lb/min ft^2 or 3.55 GPM), which is above the minimum flow rate found from Leva's equation. The flooding condition of the system was calculated by using Eckert's (14) correlation and compared with the experimental data. As can be seen from Figure 2, the measured flooding conditions corresponded closely with the existing correlation. The difference between the experimental data and that calculated from the correlation is less than 10%.

The performance of the absorption system was evaluated by carrying out a series of runs with lithium chloride solutions at two concentrations and different flow rates. Other parameters that were varied during the experimentation included air flow rate, percent flooding, and the temperature and humidity of the inlet air. The operating conditions are presented in Table 2. The efficiency of the

Table 2. Experimental Data of This Study

Percent of Flooding (%)	Air Flow Rate (CFM)	Liquid Flow Rate (GPM)	Air Inlet Temp (°F)	Air Outlet Temp (°F)	Air Inlet Humidity (lb H_2O/lb dry air)	Air Outlet Humidity (lb H_2O/lb dry air)	Liquid Inlet Temp (°F)	Liquid Outlet Temp (°F)	LiCl Conc (% wt)	Equilibrium Humidity (lb H_2O/lb dry air)	Packing Height (cm)	Efficiency (%)	Mass Transfer Coefficient (kmol/m^3s)	Height of Transfer Unit (m)
55	35	3.5	75.9	65.6	0.0139	0.0054	63.6	64.7	40	0.0018	42	70.2	0.1156	0.351
50	35	3.0	74.3	65.3	0.0130	0.0052	63.3	64.5	40	0.0018	42	69.6	0.1132	0.359
47	35	2.5	75.2	66.9	0.0136	0.0057	63.7	65.4	40	0.0018	42	67.0	0.1066	0.381
44	35	2.0	75.3	68.7	0.0139	0.0061	63.6	67.1	40	0.0018	42	64.5	0.0981	0.413
43	28	3.0	76.1	63.1	0.0130	0.0072	61.8	62.4	30	0.0044	42	67.4	0.0857	0.378
54	35	3.0	75.5	63.1	0.0129	0.0074	61.8	62.6	30	0.0044	42	64.7	0.1004	0.404
65	42	3.0	75.3	63.1	0.0129	0.0077	61.8	62.6	30	0.0044	42	61.2	0.1089	0.447
75	49	3.0	74.4	63.2	0.0130	0.0079	61.8	62.9	30	0.0044	42	59.3	0.1203	0.472
86	56	3.0	74.0	63.1	0.0130	0.0080	61.8	62.6	30	0.0044	42	58.1	0.1338	0.486
40	28	3.0	76.8	63.6	0.0131	0.0051	61.8	62.6	40	0.0016	42	69.6	0.0913	0.356
50	35	3.0	76.6	63.5	0.0130	0.0052	61.8	62.6	40	0.0016	42	68.4	0.1100	0.369
60	42	3.0	76.2	62.9	0.0129	0.0051	60.2	62.0	40	0.0014	42	67.8	0.1304	0.374
70	49	3.0	76.6	63.5	0.0130	0.0053	60.8	62.9	40	0.0015	42	67.0	0.1495	0.380
80	56	3.0	76.8	63.6	0.0131	0.0055	61.8	63.0	40	0.0016	42	66.1	0.1661	0.391
40	28	3.0	77.7	74.1	0.0110	0.0065	73.2	73.4	40	0.0027	42	54.2	0.0617	0.526
50	35	3.0	77.9	74.3	0.0107	0.0064	73.2	73.5	40	0.0027	42	53.8	0.0734	0.553
60	42	3.0	77.7	74.3	0.0109	0.0068	73.2	73.4	40	0.0027	42	50.0	0.0788	0.617
40	28	3.0	73.9	59.1	0.0106	0.0040	56.4	57.2	40	0.0013	42	71.0	0.0947	0.343
40	28	3.0	73.5	59.5	0.0130	0.0045	55.7	57.2	40	0.0011	42	71.6	0.0955	0.340
40	28	3.0	76.1	62.6	0.0110	0.0048	60.2	60.7	40	0.0014	42	64.6	0.0803	0.404
40	28	3.0	76.8	63.6	0.0130	0.0051	61.8	62.6	40	0.0016	42	69.6	0.0913	0.356
40	28	3.0	77.7	74.1	0.0110	0.0065	73.2	73.4	40	0.0027	42	54.2	0.0617	0.526
40	28	3.0	77.7	73.9	0.0135	0.0059	72.3	73.2	40	0.0026	42	68.8	0.0910	0.357
40	28	3.0	77.7	73.9	0.0135	0.0059	72.3	72.8	40	0.0026	42	68.8	0.0910	0.357
40	28	3.0	77.9	73.9	0.0136	0.0062	72.3	72.8	38.5	0.0027	42	67.3	0.0864	0.376
50	35	3.0	74.3	65.3	0.0130	0.0052	63.3	64.5	40	0.0018	42	69.6	0.1132	0.359
50	35	3.0	75.0	65.5	0.0130	0.0055	63.3	64.5	40	0.0018	42	67.0	0.1074	0.378
50	35	3.0	76.6	63.5	0.0130	0.0052	61.8	62.6	40	0.0016	42	68.4	0.1100	0.369
50	35	3.0	77.1	63.5	0.0130	0.0054	60.2	62.0	40	0.0015	42	67.8	0.1038	0.391

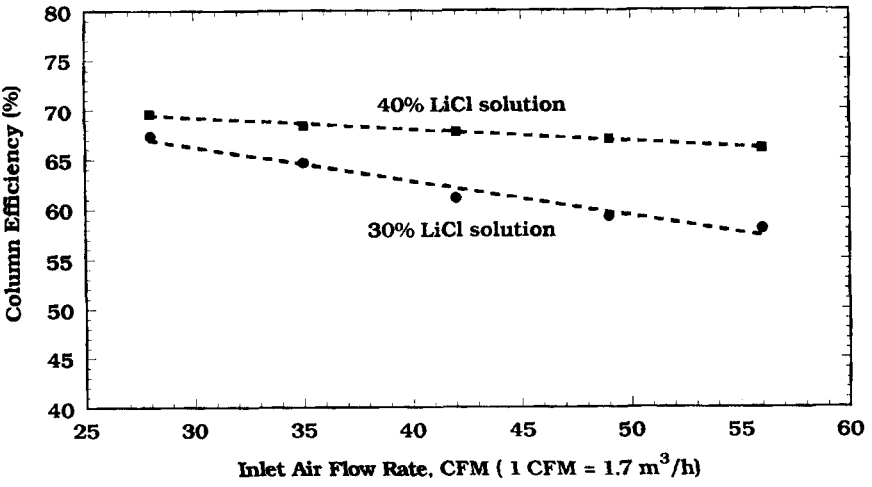

Figure 3. Effect of Inlet Air Flow Rate on Column Efficiency

absorber was calculated as the ratio of the actual change in moisture content of the air leaving the absorber to the maximum possible change in moisture content under a given set of operating conditions. Therefore, the column efficiency, ε, can be expressed as

$$\varepsilon = \frac{W_{in} - W_{out}}{W_{in} - W_{equ}} \qquad (1)$$

where W_{in} and W_{out} are the water contents of the inlet and outlet air streams, respectively. W_{equ} is the water content of the air, which is at equilibrium with the lithium chloride solution at a particular concentration and temperature. The column efficiencies calculated from the experimental data are provided in Table 2 and are plotted versus the inlet air flow rate in Figure 3. As the inlet air flow rate was increased, the amount of moisture to be removed to achieve the same efficiency also increased. Since the packing height and the liquid flow

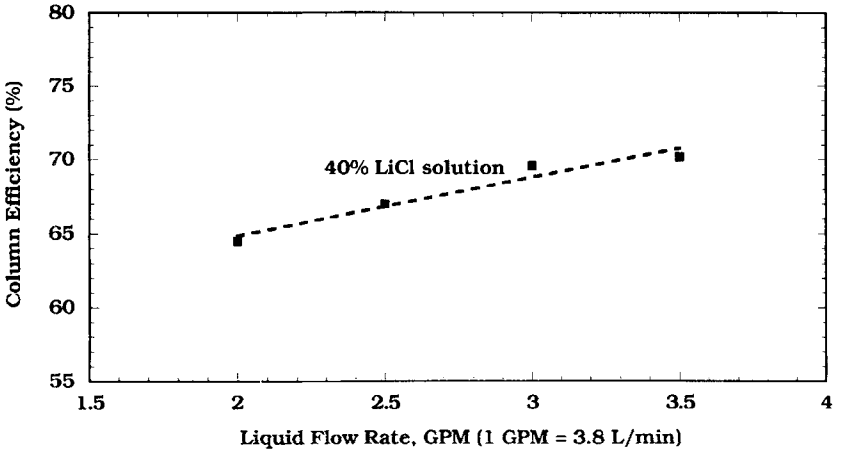

Figure 4. Effect of Liquid Flow Rate on Column Efficiency

rate remained constant, the column efficiency decreased. The column efficiency dropped only 4% for the 40% lithium chloride solution, although the air flow rate increased by a factor of two. The decrease in efficiency was 10% for the 30% lithium chloride solution under the same conditions. The relationship between the column efficiency and liquid flow rate is shown in Figure 4 .

The overall mass transfer coefficient is derived following the procedure given by Hines and Maddox (16). The molar flux in this system is written as the product of an overall mass transfer coefficient and the difference between the bulk and equilibrium concentrations as

$$N_A = \frac{d(G\,y_A)}{a\,dZ} = \frac{K_{GA}}{\beta_{v-v^*}}\left(y - y_A^*\right) \qquad (2)$$

where G is the molar flow rate of air, and the bulk flow concentration factor for transfer through a stagnant film is given by

$$\beta_{v-v^*} = (1-y_A)_{*M} = \frac{(1-y_A^*)-(1-y_A)}{\ell n\left(\frac{1-y_A^*}{1-y_A}\right)} = \frac{y_A - y_A^*}{\ell n\left(\frac{1-y_A^*}{1-y_A}\right)} \qquad (3)$$

By rearranging Eqns (2) and (3) and integrating , the overall mass transfer coefficient can be written as

$$(K_{GA}\, a)_{avg} = \frac{G}{Z}\int_{y_{A,a}}^{y_{A,b}} \frac{(1-y_A)_{*M}}{(1-y_A)}\,\frac{dy_A}{(y_A - y_A^*)} \qquad (4)$$

Most experimental data on packed-bed absorbers are generally given in terms of the height of a transfer unit (HTU) rather than in terms of the mass transfer coefficient, because the HTU is less dependent on liquid or gas flow rates. The HTU is defined as the molar velocity based on total column cross section divided by the overall mass transfer coefficient,

$$H_{OG} = \frac{G}{K_{GA}\, a} \qquad (5)$$

The increase in the overall mass transfer coefficient with increasing air flow rate is shown in Figure 5. The mass transfer coefficients varied linearly with the inlet air flow rates. As expected, mass transfer coefficients were greater for the 40% lithium chloride solution than for the 30% solution. The values of the mass transfer coefficients obtained in this study using polypropylene Flexi rings were higher than those reported by Scalabrin and Scaltriti (12), who used glass Raschig rings and polypropylene Pall rings as packings. Their study was carried out from 10 to 15% of flooding. This is significantly lower than the typical flooding condition, which usually varies from about 50 to 80%. Although Gandhidasan and Satcunanathan (11) reported higher mass transfer coefficients using Berl saddles as the packing, the height of a transfer unit was higher

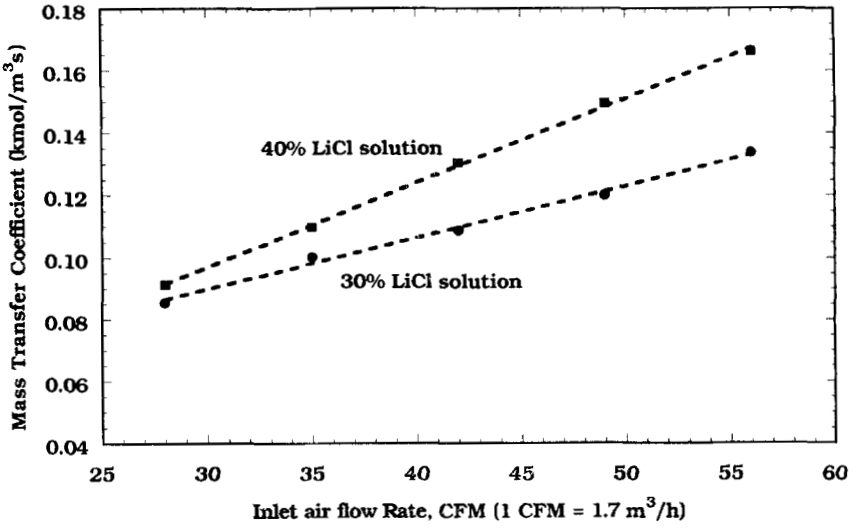

Figure 5. Effect of Inlet Air Flow Rate on Mass Transfer Coefficient

than that obtained in the present study. The H/D (packing height/column diameter or nominal size) ratio in their system was less than one. Therefore, all of the packing surface in their study may not have been utilized for gas-liquid contact. Although the packing volume in their system was about 30 times greater than for this system, the values of the mass transfer coefficient were the same order of magnitude. The comparison with literature data is shown in Table 3.

The liquid flow rate did not appear to have a significant effect on the overall mass transfer (see Figure 6) because the liquid flow rate used in the absorber is significantly larger than the minimum liquid flow rate determined from the equilibrium calculation.

The height of a transfer unit calculated at various flooding conditions is shown in Figure 7. The different flooding conditions were obtained by increasing the air flow rate while the liquid flow rate

Table 3. Comparison of Mass Transfer Coefficients with the Literature Data

	Packings	LiCl Conc	Gas Flow Rate & Temperature Range	Liquid Flow Rate & Temperature Range	Nature of Study	Mass Transfer Coefficients ($kmol/m^3s$)	Height of Transfer Unit (m)
This Study	5/8" Polypropylene flexi rings	30-40%	3362-6746 $kg/h\text{-}m^2$ 22.7-25.5 °C	31212-54648 $kg/h\text{-}m^2$ 12.7-22.7 °C	Mass Transfer Coefficients	0.0617-0.1661	0.3-0.4
Gandhidasan et al. (1983)	1.5" Berl saddles	41%	345.73 $kg/h\text{-}m^2$ 25-41 °C	933.5 $kg/h\text{-}m^2$ 24-40 °C	Tower Performance	0.21-0.42	0.5-0.6
Scalabrin and Scaltriti (1984)	4 x 6 glass Raschig rings and 3/4" ceramic Pall rings	40%	1648-9889 $kg/h\text{-}m^2$ 18.5-24.9 °C	2604-6617 $kg/h\text{-}m^2$ 16.7-34.8 °C	Mass Transfer Coefficients	0.0004-0.0011 0.0003-0.0009	- -
Lof et al. (1984)	1" Raschig rings	26-35%	3355-5599 $kg/h\text{-}m^2$ 60-105°C	2173-4273 $kg/h\text{-}m^2$ 34-39°C	Heat Transfer Correlation under regeneration conditions	0.16-0.31	-

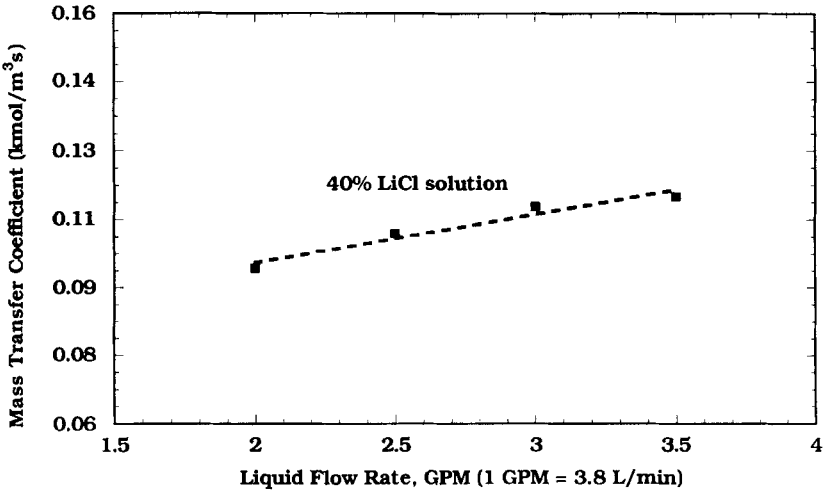

Figure 6. Effect of Liquid Flow Rate on Mass Transfer Coefficient

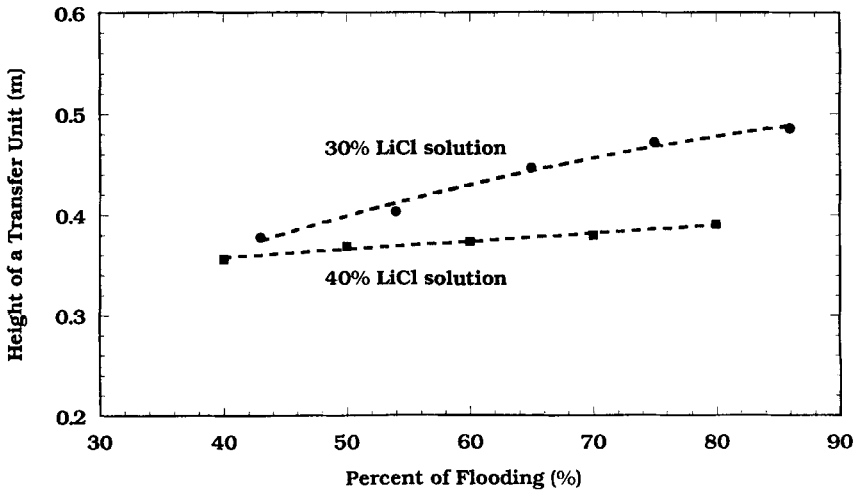

Figure 7. Change in Height of a Transfer Unit at Different Percent of Flooding

was maintained at the same level. Although the height of the transfer unit increased for the 30% lithium chloride solution with an increase in air flow rate, it remained nearly constant for the 40% lithium chloride solution. Since the contact time decreased as the inlet air flow rate increased and less time was available to reach equilibrium, the air flow rate played an important role in the case of the 30% solution. However, this effect is negligible for the 40% solution.

As shown in Table 2, a slight difference in the inlet liquid temperature caused a significant difference in the outlet humidity. As expected, the column operates more effectively with lower liquid temperature. The mass transfer coefficients are higher for the higher liquid concentrations. This can be attributed to the increased water uptake by the lithium chloride solution. Also, the effects of the inlet humidity concentration on the mass transfer coefficient were more pronounced at higher system temperatures.

CONCLUSIONS

A packed bed absorber-stripper system has been designed and tested successfully for dehumidification of air. Measured flooding conditions corresponded closely with existing empirical correlations. For a given height of packing, the column efficiency increased as either the air flow rate decreased or the liquid flow rate increased. The mass transfer coefficients increased with increasing air and liquid flow rates. As expected, lowering the liquid temperature improved the column performance significantly. The experimental data suggest that Flexi rings provide better contact than ceramic Raschig rings, Pall rings, and Berl saddles. The values for the height of transfer unit in this system using Flexi rings are in the range of 0.36 to 0.39 m for 40% lithium chloride solution, which is lower than that reported by Scalabrin and Scaltriti (12), who used Raschig rings and Pall rings, and Gandhidasan and Satcunanathan (11), who used Berl saddles as packings.

NOMENCLATURE

a	Specific interfacial surface for contact of a gas with liquid, m^2/m^3.
ε	Efficiency of the packed bed absorber, %.
G	Superficial mass velocity of air, kmol/s m^2.
K_{GA}	Overall gas phase mass transfer coefficient, kmol/s m^2.
N_A	Flux of species A at the interface, kmol/s m^2.
W_{in}	Water content of air at the inlet of the absorber, kg moisture/kg dry air.
W_{out}	Water content of air at the outlet of the absorber, kg moisture/kg dry air.
W_{equ}	Minimum possible water content at the outlet of the absorber, kg moisture/kg dry air.
y_A	Mole fraction of water vapor in the bulk phase, kmol/kmol gas mixture.
$y_{A,a}$	Mole fraction of water vapor at the top of the column, kmol/kmol of gas mixture.
$y_{A,b}$	Mole fraction of water vapor at the bottom of the column, kmol/kmol of gas mixture.
y_A^*	Equilibrium mole fraction of water vapor in the air, kmol/kmol of gas mixture.
Z	Height of packing, m.

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