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Mass Transfer Correlation for Dehumidification of Air in a Packed Absorber with an Inverse U-Shaped Tunnel

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Mass Transfer Correlation for Dehumidification of Air in a Packed Absorber with an Inverse U-Shaped Tunnel

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ABSTRACT

The mass transfer performance in a packed pilot absorber with an inverse U-shaped tunnel to prevent the carryover of solution is discussed in this study. The empirical correlation for the overall gas-phase volumetric mass transfer coefficient ($K_y a$) is determined. The correlation is given in dimensionless form by

$$\mathrm{Sh}'_G = 8.9 \times 10^{-8} \, (p_{soln}/P)^{-0.57} \, \mathrm{Sc}_G^{1/3} \mathrm{Re}_G^{1.53}$$

and the modified Sherwood number (Sh'_G) is defined in this study for the overall volumetric mass transfer coefficient. The vapor pressure of the working solution (p_{soln}) is used to represent the characteristics of different working solutions at their operating concentrations and temperatures. This will overcome the disadvantages of the traditional convective mass transfer relationships which use such indirect parameters as the viscosity, density, or concentration to represent the working solutions in their correlations. Because the liquid desiccant solution works on the principle of absorption and has the property of absorbing moisture from air, the vapor pressure of the inlet liquid solution is lower than that of the air stream, and dehumidification take place. Therefore, the driving force of dehumidification in the absorber is dependent on the vapor pressure of the working solution. Our data showed that the mass transfer coefficients varied significantly with the vapor pressures of the working solutions. The correlated equation shown above fitted the experimental data very well, and the average value of the errors between predictions and experimental data is about 4%.

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INTRODUCTION

Absorption–dehumidification systems are widely used in industry and in residential life (1). Constant system performance during long-term operation and the prevention of carryover are the most important factors in designing a system. For commercial systems such as the Niagara "Hygrol" system and some other commercial units (2), the packed towers are combined with an air tunnel design to prevent the carryover of solutions. A packed pilot tower with an inverse U-shaped tunnel to prevent carryover was built in this study to obtain practical pilot data on the mass transfer coefficient. The mass transfer coefficient or the height of a transfer unit is an important parameter in the design of absorbers. These parameters also provide a means to compare system performance under different operating conditions. However, correlations predicting the gas-phase mass transfer coefficients in packed towers are less reliable than those in wetted-wall towers. Table 1 shows the previous published dimensionless correlations for the mass transfer coefficients in different absorbers. A more recent correlation was developed by Chung et al. (3) for dehumidification of air in a traditional packed column. Their correlation obeys the relationship of convective mass transfer (4) as well as the earlier correla-

TABLE 1
Previous Published Dimensionless Correlations for

Author	Experimental setup	Correlation	Mass transfer coefficient in Sherwood number	Column diameter (cm)
Gilliland and Sherwood, 1934 (18)	Cocurrent and countercurrent wetted-wall column	$Sh_G = 0.023\ Re_G^{0.83}\ Sc_G^{0.44}$	k_c (m/s)	2.67
Kafesjian et al., 1961 (19)	Countercurrent wetted-wall column	$Sh_G = 0.0065\ Re_G^{0.83}\ Re_L^{0.15}$	k_c (m/s)	2.54
Onda et al., 1968 (5)	Countercurrent packed column	$Sh_G = 5.23\ Re_G^{0.7}\ Sc_G^{1/3}$	$k_y a$ (kmol/m^{3}s)	15
Braun and Hilby, 1970 (20)	Cocurrent and countercurrent wetted-wall column	$Sh_G = 0.18\Phi\ Re_G^{0.4}\ Re_L^{0.16}\ Sc_G^{0.44}\ (1 + 6.4X^{-0.75})$	k_c (m/s)	4
Chung and Luo, 1996 (14)	Countercurrent packed column	$Sh'_G = 1.326 \times 10^{-4}\ (1 - x)^{-0.94}\ (L'/G')^{0.27}\ (Sc_G)^{1/3}\ (Re_G)^{1.16}$	$K_y a$ (kmol/m^{3}s)	15
Nielsen et al., 1998 (21)	Cocurrent wetted-wall column	$Sh_G = 0.00031\ Re_G^{1.05}\ Re_L^{0.207}\ Sc_G^{0.5}$	k_c (m/s)	3.26

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tion of Onda (5). Both correlations are applicable for packed absorbers. However, the Onda correlation has no parameter to represent the characteristics of the working solutions. It can not identify a system with different concentrations or temperatures for a working solution at the same operating conditions and obtain the same predicted values. The correlation of Chung et al. tried to improve the disadvantages of the Onda correlation by using a solution concentration parameter to represent the working solution. With this improvement the Chung correlation can successfully identify a system using 30 and 40 wt% lithium chloride solutions at the same operating conditions. However, on the basis of the principles of absorption dehumidification, the mass transfer rate is dependent on the vapor pressure difference between moist air and the desiccant solution. If the vapor pressures of the desiccant solutions are available, these correlations may be correlated by using a more direct parameter of vapor pressure to represent the characteristics of the working solution. The vapor pressure of a solution varies with the composition, concentration, and temperature of the solution. A single vapor pressure parameter of the working solution represents the variations of composition, concentration, or temperature of the solution in a correlation. Therefore, when the vapor pressure of a working solution is known, the correlation may use the vapor pressure to represent

Mass Transfer Coefficients in Different Absorbers

Column/packed height (cm)	Column material	Temperature (°C)	Pressure (atm)	Re_G/Re_L	Chemical system
117	Glass	25–56	0.145–3.06	2,000–27,000/ 1,000	Evaporation of water and eight different organic liquids
101.6	Stainless	—	—	2,000–17,000/ 25–1,200	Evaporation of water
10, 15, 20	Acryle-resin pipe	20–25	—	1–1,000/1–40	Absorption of moisture by calcium chloride
20, 140	Glass	—	—	1,000–14,000/ 800–2,800	Absorption of ammonia in dilute sulfuric acid
42	Glass	16–24	1	12,901–13,945/ 120,538–242,435	Absorption of moisture by lithium chloride
500	PVC	50	1	7,500–18,300/ 4,000–12,000	Absorption of sulfur dioxide by sodium hydroxide

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the characteristics of that working solution. However, this is rarely found in the open literature.

Grover et al. (6) compared the performance of two absorption systems theoretically by using water–lithium chloride and water–lithium bromide solutions. According to them, lithium chloride solution is a better absorbent because of its lower corrosivity and fewer health hazards. However, a water–lithium chloride solution has a higher viscosity than a water–lithium bromide solution of comparable concentration, and this reduces the heat transfer rate in the system. Gandhidasan et al. (7) studied a packed tower with a water–calcium chloride solution. Their reason for using calcium chloride was that it was the least expansive and most readily chemical available. The transfer of moisture from air to a water–calcium chloride solution is not better than that to aqueous lithium chloride or lithium bromide solutions. Therefore, a tower packed with 5/8-in. polypropylene Pall rings was used in this project to study the absorption of water vapor from moist air by contacting the air with aqueous solutions that contained from 37.5 to 42.5 wt% lithium chloride. The absorber was capable of handling air flow rates from 10 to 15 kg/min and liquid flow rates from 10 to 16 kg/min. With these flow rates and the proper design, the tower can be operated at 50 to 80% flooding, which is good for most absorption processes in packed towers (8). Since literature data about this type of pilot absorber are limited, a discussion on mass transfer performance is presented in this study.

THEORY

The driving force in a packed dehumidification tower is the vapor pressure difference between the inlet air and the liquid desiccant. As long as the air vapor pressure is higher than the liquid vapor pressure, dehumidification takes place (7). On the basis of the same operating conditions, the lower the vapor pressure of the liquid desiccant, the drier is the outlet air. Therefore, the mass transfer coefficient for the absorber can be determined by the vapor pressure of the liquid desiccant.

The mass transfer coefficients were correlated in terms of the vapor pressure and the process variables by the Buckingham Pi method. Variables that affect the gas-phase mass transfer coefficient include vapor pressure of liquid, total pressure of absorber, air flow rate, physical properties of both air and liquid, packing volume and size, and diffusion coefficient of water in air. The mass transfer correlation obtained from the dimensional analysis is given as

$$\frac{K_y a M_t d_p^2}{D_G \rho_G} = \alpha \left(\frac{p_{soln}}{P} \right)^{\beta} Sc_G^{\gamma} Re_G^{\delta} \tag{1}$$

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where α, β, γ, and δ are constants and are obtained by nonlinear regression of the experimental data. The modified Sherwood number (Sh'_G) is defined for the overall volumetric mass transfer coefficient and can be written as

$$Sh'_G = \frac{K_y a M_t d_p^2}{D_G \rho_G} \tag{2}$$

Therefore, the dimensionless mass transfer correlation of Eq. (1) can be simplified as follow:

$$Sh'_G = \alpha \left(\frac{p_{soln}}{P} \right)^{\beta} Sc_G^{\gamma} Re_G^{\delta} \tag{3}$$

The corrected value for constant γ has been shown theoretically and experimentally to be $\frac{1}{3}$ in this type of correlation (9). The value of constant γ was also shown experimentally to be $\frac{1}{2}$ for wetted-wall absorbers (10). However, based on *exact boundary layer analysis* and *approximate integral analysis* (11), the value of constant γ was obtained to be $\frac{1}{3}$ theoretically. The experimental tests in this study and previous studies of the packed absorbers were as consistent as the theoretical value.

The vapor pressures of the commercial desiccant solutions were available as experimental data or predicted equations in the literature. Basically, the liquid desiccant solutions can be classified into aqueous inorganic salt solutions of LiCl, LiBr, and $CaCl_2$ and into aqueous organic solutions of glycols. The experimental vapor pressures of the aqueous inorganic salt solutions are available in the studies (12–14). The vapor pressures of the aqueous organic solutions are available in reports of the Dow Chemical Company (15) and Chung and Luo (14).

The Antoine equation is one of the most popular equations for predicting the vapor pressure of a solution and is usually correlated as

$$\ln(p_{soln}) = A - \frac{B}{T + C} \tag{4}$$

The variables *A, B,* and *C* vary with the aqueous desiccant solutions used, and they can be expressed as functions of the solution concentration. Some variables of the Antoine equation were available in the literature for part of the inorganic salt solutions (12, 13, 14, 16).

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The design of the inverse U-shaped tunnel in the absorber to allow air and solution counter flow-contact

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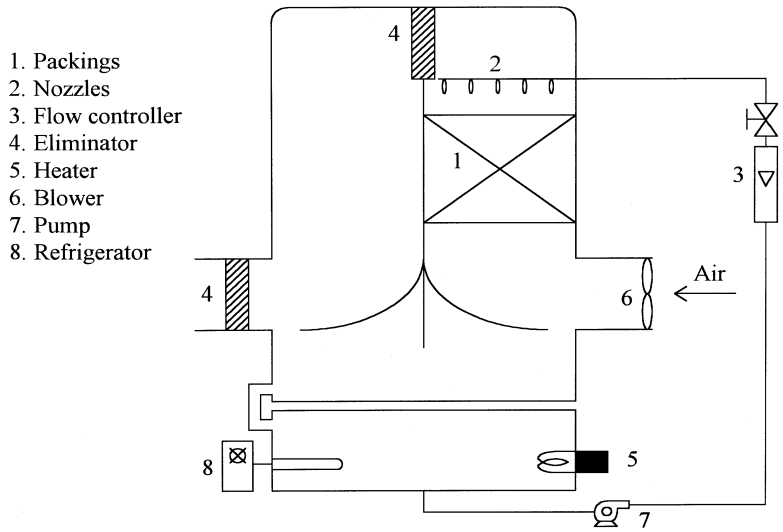

FIG. 1 Experimental setup of this study.

increases the absorption rate and reduces the carryover of the solution. The moist air was introduced to the bottom of the packing materials, and the working solution was sprayed on the top of the packings. The flow rates of air were controlled by the transistor inverter on a 1 HP blower, and liquid was monitored by the flowmeter. After the moist air and desiccant solution achieved intimate contact within the packing materials, air was passed through the inverse U-shaped tunnel. The high efficiency eliminators in the tunnel and gravity prevented the air from carrying the solution particles. The humidities of the inlet and outlet air streams in the absorber were measured by chilled mirror dew point meters (accuracy: $\pm 2^{\circ}$C dew point, General Eastern, Model M4-RH). The concentration of the solution was measured by a refractometer. The liquid flow rates were measured with a rotameter, and the air flow rates were measured with a hot-wire flowmeter.

When the concentration of LiCl solution had been changed to a significant difference, (generally 1 wt% of the original concentration), the absorption process was stopped and the regeneration was carried out by turning on the electric heater in Fig. 1. Almost 180 Liters of the LiCl solution were used in this system to extend the length of time needed for LiCl concentration to change by 1 wt%. In this system it took more than 30 minutes for the solution concentration to change 1 wt%. The system reached steady-state in each experimental run in less than 20 minutes. Therefore, the variation of solution concentration during the experimental runs was negligible.

RESULTS AND DISCUSSION

The performance of the inverse U-shaped absorber was evaluated by a series of experimental runs with aqueous solutions that contained from 37.5 to 42.5 wt% lithium chloride. Other parameters that were varied during the experimentation included air and liquid flow ratio, temperature and humidity of the air, and temperature of the desiccant solution. As noted, the vapor pressure of a desiccant solution varies with the composition, concentration, and temperature of the solution. These parameters can be represented by a single parameter, the vapor pressure, of a solution. The operation conditions are presented in Table 1.

The overall mass transfer coefficient was derived by following the procedure given by Geankoplis (17). 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

$$N_A = \frac{d(Gy_A)}{adZ} = \frac{K_y}{\beta_{v-v^*}}(y - y_A^*) \tag{5}$$

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

$$\beta_{v-v^*} = (1 - y_A)_{*M} = \frac{(1 - y_A^*) - (1 - y_A)}{\ln\left(\frac{1 - y_A^*}{1 - y_A}\right)} = \frac{y_A - y_A^*}{\ln\left(\frac{1 - y_A^*}{1 - y_A}\right)} \tag{6}$$

By rearranging Eqs. (5) and (6) and integrating, the overall volumetric mass transfer coefficient can be written as

$$(K_y a)_{avg} = \int_{y_{A,a}}^{y_{A,b}} \frac{(1 - y_A)_{*M} dy_A}{(1 - y_A)(y_A - y_A^*)} \tag{7}$$

The liquid flow rates in this absorber and most commercial units are based on calculation of the wetting rate, which is much higher than the minimum liquid flow rate determined from the equilibrium calculation. Therefore, Fig. 2 shows almost no detectable influence of solution flow rate on the mass transfer coefficient, and it is not necessary to consider the solution flow rate parameter for the mass transfer correlation developed in this study. However, an increase in the overall mass transfer coefficient with increasing air flow rate is observed in Fig. 3. The mass transfer coefficient varied linearly

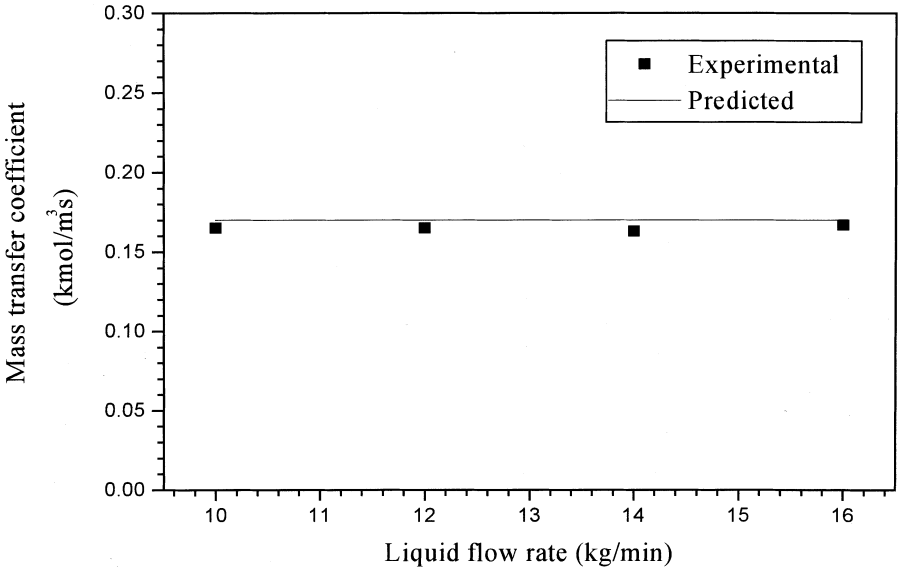

FIG. 2 Effect of liquid flow rate on mass transfer coefficients.

with the inlet air flow rate. Since the molar flux of this system is proportional to the air flow rate, the mass transfer coefficient is also proportional to the air flow rate. Most of the experimental mass transfer coefficients in the literature also involve variation of the solution concentration or of the

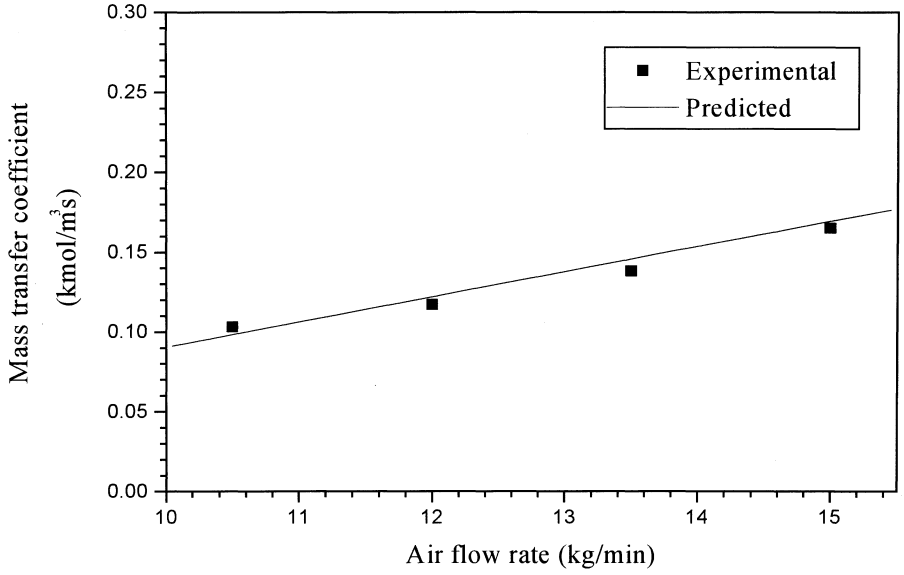

FIG. 3 Effect of air flow rate on mass transfer coefficients.

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temperature. As mentioned earlier, the vapor pressure of the solution varied with the composition, concentration, and temperature of the solution. Therefore, in this study a single parameter, the vapor pressure, was chosen to represent the characteristics of the working solutions. Figure 4 shows that the overall mass transfer coefficients were significantly affected by the vapor pressures of the solution. A nonlinear relationship between the overall mass transfer coefficient and the vapor pressure of the solution was obtained in this study.

The constants α, β, γ, and δ of the correlation given by Eq. (3) were obtained from a nonlinear regression of the experimental data in Table 2. These experimental data for the inverse U-shaped absorber with $\frac{5}{8}$-inch polypropylene Pall rings were used to obtain the constants α, β, γ, and δ. The dimensionless correlation for the gas-phase overall volumetric mass transfer coefficient ($K_y a$) is given as

$$\mathrm{Sh}'_{\mathrm{G}} = 8.9 \times 10^{-8} \, (p_{\mathrm{soln}}/P)^{-0.57} \mathrm{Sc}_{\mathrm{G}}^{1/3} \mathrm{Re}_{\mathrm{G}}^{1.53} \tag{8}$$

The predicted values from Eq. (8) are also compared with the experimental data in Figs. 2–4. The correlation provided good estimations of the data. The average error value between predictions and experimental data was about 4%. It should be noted that Eq. (8) is a function of the properties of the working solution and the packing and tower geometries. Therefore, the correlation can be extended to predict other systems.

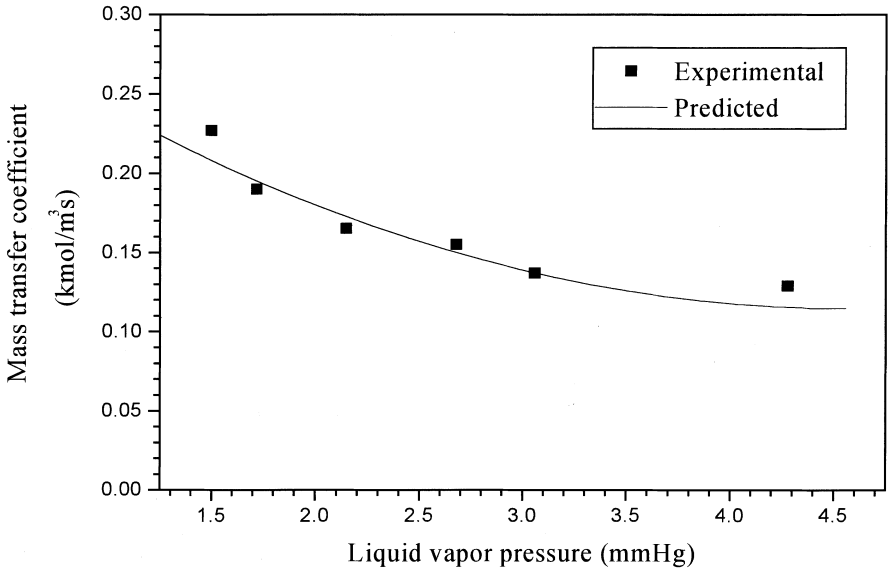

FIG. 4 Effect of liquid vapor pressure on mass transfercoefficients.

TABLE 2
Experimental and Predicted Mass Transfer Coefficients of This Study

Air flow rate (kg/min)	Liquid flow rate (kg/min)	Liquid (LiCl) conc. (%wt)	Liquid inlet temperature (°C)	Liquid vapor pressure[a] (mmHg)	Air inlet temperature (°C)	Air inlet humidity (g water/kg dry air)	Air outlet humidity (g water/kg dry air)	Experimental mass transfer coefficient ($kmol/m^3 \cdot s$)	Predicted mass transfer coefficient ($kmol/m^3 \cdot s$)
15.0	10.0	40.0	15.0	2.15	27.5	15.0	8.8	0.165	0.170
15.0	12.0	40.0	15.0	2.15	26.0	15.0	8.8	0.165	0.170
15.0	14.0	40.0	15.0	2.15	25.0	14.8	8.8	0.163	0.170
15.0	16.0	40.0	15.0	2.15	26.5	15.0	8.7	0.167	0.170
10.5	10.0	40.0	15.0	2.15	29.0	14.8	9.2	0.103	0.099
12.0	10.0	40.0	15.0	2.15	29.5	15.2	9.4	0.117	0.121
13.5	10.0	40.0	15.0	2.15	28.5	14.5	8.8	0.138	0.145
15.0	10.0	40.0	15.0	2.15	27.5	15.0	8.8	0.165	0.170
15.0	10.0	40.0	10.0	1.50	28.5	14.0	6.6	0.227	0.210
15.0	10.0	40.0	15.0	2.15	27.5	15.0	8.8	0.165	0.170
15.0	10.0	40.0	20.0	3.06	28.5	14.0	9.2	0.137	0.139
15.0	10.0	40.0	25.0	4.28	28.5	14.0	9.8	0.129	0.115
15.0	10.0	42.5	15.0	1.72	30.0	15.0	8.2	0.190	0.194
15.0	10.0	40.0	15.0	2.15	27.5	15.0	8.8	0.165	0.170
15.0	10.0	37.5	15.0	2.68	25.5	15.0	9.0	0.155	0.150

[a] Patil et al. (1990).

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CONCLUSIONS

A packed absorber with an inverse U-shaped tunnel has been designed, and it tested well for the dehumidification of air in this study. The mass transfer performance of the absorber was discussed with the gas-phase overall volumetric mass transfer coefficient parameter. A correlation of the mass transfer coefficient was developed by using the vapor pressure of the desiccant solution, which is one of the most direct parameters for representing the rate of absorption dehumidification. This concept can be used to modify other mass transfer correlations in the literature. It may increase the accuracy and the application range of these correlations. The relationship of the convective mass transfer for absorption dehumidification can be rewritten as

$$\mathrm{Sh_G} = f\left(\mathrm{Sc_G}, \mathrm{Re_G}, \frac{p_{\mathrm{soln}}}{P}\right) \tag{9}$$

This relationship should be applicable for other dehumidification absorbers such as wetted-wall towers and spray towers because these absorbers are also based on the principles of convective mass transfer.

NOTATION

a	specific interfacial surface for contact of a gas with liquid (m^2/m^3)
a_c	correction factor for the interfacial area [R_A ($d_c - 2\delta_L$)/d_c]
d_c	absorber inner diameter (m)
d_p	packing diameter (m)
D_G	diffusion coefficient (m^2/s)
G	molar flow rate of air ($kmol/s \cdot m^2$)
H	humidity (kg water/kg dry air)
k_c	gas-phase mass transfer coefficient (m/s)
$k_y a$	gas-phase volumetric mass transfer coefficient ($kmol/s \cdot m^3$)
$K_y a$	gas-phase overall volumetric mass transfer coefficient ($kmol/s \cdot m^3$)
L	height of the wetted-wall column (m)
M_t	molecular weight of the transferred component (kg/kmol)
N_A	flux of species A at the interface ($kmol/s \cdot m^2$)
p_{soln}	vapor pressure of the solution (kPa)
P	total pressure of the absorber (kPa)
R_A	ratio of the interfacial area in the presence of waves to the plane interfacial area
$\mathrm{Re_G}$	gas-phase Reynolds number ($d_p \rho_G V/\mu_G$)
$\mathrm{Re_L}$	liquid-phase Reynolds number ($d_p \rho_L V/\mu_L$)
$\mathrm{Sh_G}$	gas-phase Sherwood number ($k_c a_c d_c/D_G$)
$\mathrm{Sc_G}$	gas-phase Schmidt number ($\mu_G/D_G \rho_G$)

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Sh'_G gas-phase Sherwood number for volumetric mass transfer coefficient ($k_y a M_t d_p^2/D_G \rho_G$ or $K_y a M_t d_p^2/D_G \rho_G$)
T solution temperature (K)
V gas flow rate (m/s)
y_A mole fraction of water vapor in the bulk phase (kmol/kmol of 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)
X dimensionless height (L/d_c)
Z height of packings (m)

Greek Letters

δ_L mean liquid film thickness (m)
ρ_G density of gas (kg/m^3)
ρ_L density of liquid (kg/m^3)
μ_G viscosity of gas (kg/ms)
μ_L viscosity of liquid (kg/ms)
Φ relative absorption rate [$1 - (1 - H)^a$; $a = 1.8X^{0.33}Re_G^{0.0625}$]

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