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Analysis of Mass Transfer Performance in an Air Stripping Tower

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ABSTRACT

The carryover of working solution in a traditional stripping tower is of serious concern in real applications. A U-shaped spray tower to prevent carryover has been designed to study the stripping of water vapor from aqueous desiccant solutions of 91.8 to 95.8 wt% triethylene glycol. In this study, water vapor was removed from the diluted desiccant solution by heating the solution and stripping it with the ambient air. Therefore, the solution was concentrated to a desired concentration. This spray tower was capable of handling air flow rates from 3.2 to 5.13 kg/min and liquid flow rates from 1.6 to 2.76 kg/min. Since the literature data on air stripping towers are limited, studies on the mass transfer coefficient and other mass transfer parameters were carried out in this study. Under the operating conditions, the overall mass transfer coefficient calculated from the experimental data varied from 0.053 to 0.169 mol/m^3·s. These corresponded to heights of a transfer unit of 2.3 to 0.71 m, respectively. The rates of stripping in this spray tower were typically varied from 2.28 to 12.15 kg H_2O/h. A correlation of the mass transfer coefficient for the air stripping process was also developed in this study.

INTRODUCTION

The industrial importance of the stripping or desorption process is similar to that of absorption. Examples of desorption processes in industrial applications were provided by Shah and Sharma (1), Doraiswamy and Sharma (2),

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and Astarita et al. (3). In most cases the stripping process involves simultaneous physical absorption for continuous operation. This type of system is called an absorption–stripping system. Studies on the absorption process or its mass transfer performance are available in the open literature. However, studies on the stripper of the absorption–stripping system are rare. In 1990, Patnaik et al. (4) investigated the mass transfer performance of the regeneration of aqueous lithium bromide in a solar open-cycle absorption–stripping system. The influence of temperature on the mass transfer rate of the absorption and stripping processes was carried out both experimentally and theoretically by Khudenko et al. (5). The computer simulation was in good agreement with their experimental data. On the other hand, in order to avoid the carryover of liquid particles, a gas–liquid contact device with a "U-shaped" air tunnel and eliminators was designed and tested by Chung and Wu (6). There is nothing significantly different in mass transfer between U-shaped units and traditional spray columns, but U-shaped units are more effective in preventing carryover. As shown in Table 1, although spray towers, packed towers, and falling film systems are usually used in absorption–stripping systems, data of mass transfer performance of spray towers are limited in the open literature, especially for stripping process in the spray tower. Therefore, the mass transfer performance of the air stripping process in a spray tower is discussed in this study.

TABLE 1
Recent Studies on the Absorption and Stripping Systems

Type of gas-liquid contact device	Absorption process or mass transfer performance	Stripping process or mass transfer performance
Spray tower	Chung and Wu, 1998 (6)	
	Scalabrin and Scaltriti, 1985 (12)	
	Scalabrin et al., 1988 (13)	
Packed tower	Ertas et al., 1997 (14)	Patnaik et al., 1990 (4)
	Kinsara et al., 1996 (15)	Lof et al., 1984 (9)
	Khan, 1996 (16)	Khan, 1994 (16)
	Chung, 1994 (17)	Ertas, 1994 (19)
	Khan, 1994 (18)	Elasyed et al., 1993 (20)
	Ertas et al., 1994 (19)	Ertas et al., 1993 (23)
	Elasyed et al., 1993 (20)	
	Chung et al., 1992 (21)	
	Ertas et al., 1990 (22)	
Falling film	Park et al., 1994 (24)	Peng and Howell, 1984 (8)
	Hernandez et al., 1997 (25)	Gandhidasan, 1995 (28)
	Zheng and Worek, 1992 (26)	Park et al., 1995 (29)
	Zografos and Marasla, 1991 (27)	Gandhidasan and Al-Farayedhi, 1994 (30)

In the absorption–stripping process, the heat needed to regenerate the working solution is the major energy consumer of the whole system. Therefore, Hollands (7), Peng and Howell (8), and Lof et al. (9) tried to use solar energy as the heat source for regenerating the working solutions. In their studies the design of the absorption–stripping systems focused on lowering energy consumption and preventing carryover of the working solution.

Packed towers are generally used in liquid desiccant dehumidification systems for working solutions of lower viscosity. The most commonly used desiccants of lower viscosity are aqueous inorganic solutions of lithium chloride, lithium bromide, and calcium chloride. Desiccants of higher viscosity are aqueous organic solutions of triethylene glycol (TEG) and propylene glycol (PG), which are good for use in spray towers. Both of them are used widely in the air-conditioning systems. However, crystallization of the inorganic desiccant occurs when the concentration is higher than 40 wt%, and corrosion has been observed of the metallic absorbers. Therefore, aqueous TEG solutions were used in this study.

In the spray tower, the liquid desiccant was sprayed by nozzles as fine particles. Air was introduced at the top of the tower to contact the liquid particles cocurrently. Parameters varied during the experiments included the temperature and humidity of the inlet air, the temperature and concentration of the desiccant solution, and the flow rates of the air and solution. The overall mass transfer coefficient, the height of a transfer unit, and the rate of stripping in the spray tower were calculated from the experimental data. These mass transfer parameters are important for designing a spray tower. However, these experimental data are limited in the open literature.

EXPERIMENTAL SYSTEM

The flow diagram of the stripper/regeneration system is shown in Fig. 1. The design of a “U-shaped” air tunnel with eliminators in the spray tower to allow air and solution cocurrent contact neglects carryover of the solution. The detailed design of the tower geometry and the advantages of the tower design were discussed in a previous work (6). However, the application of the spray tower in this study is stripping, which is used to regenerate the working solution for most absorption–stripping systems. The stripper can handle air flow rates from 3.2 to 5.13 kg/min and liquid flow rates from 1.6 to 2.76 kg/min. Full-cone spray nozzles were used in this study. The flow rates of the nozzle varied from 1.5 to 3 L/min at different pressures. These corresponded to spray angles of 55 to 70°, respectively. The diameters of the liquid particles formed by the nozzles were 290–410 μm. The heat source for regenerating the solution was a 80-L insulated water tank with a 2-kW electric heater. Aqueous TEG solutions of 91.8 to 95.8 wt% were employed. The concentration of the solution was measured by a refractometer. A Rotronic IDL 20K hygrometer

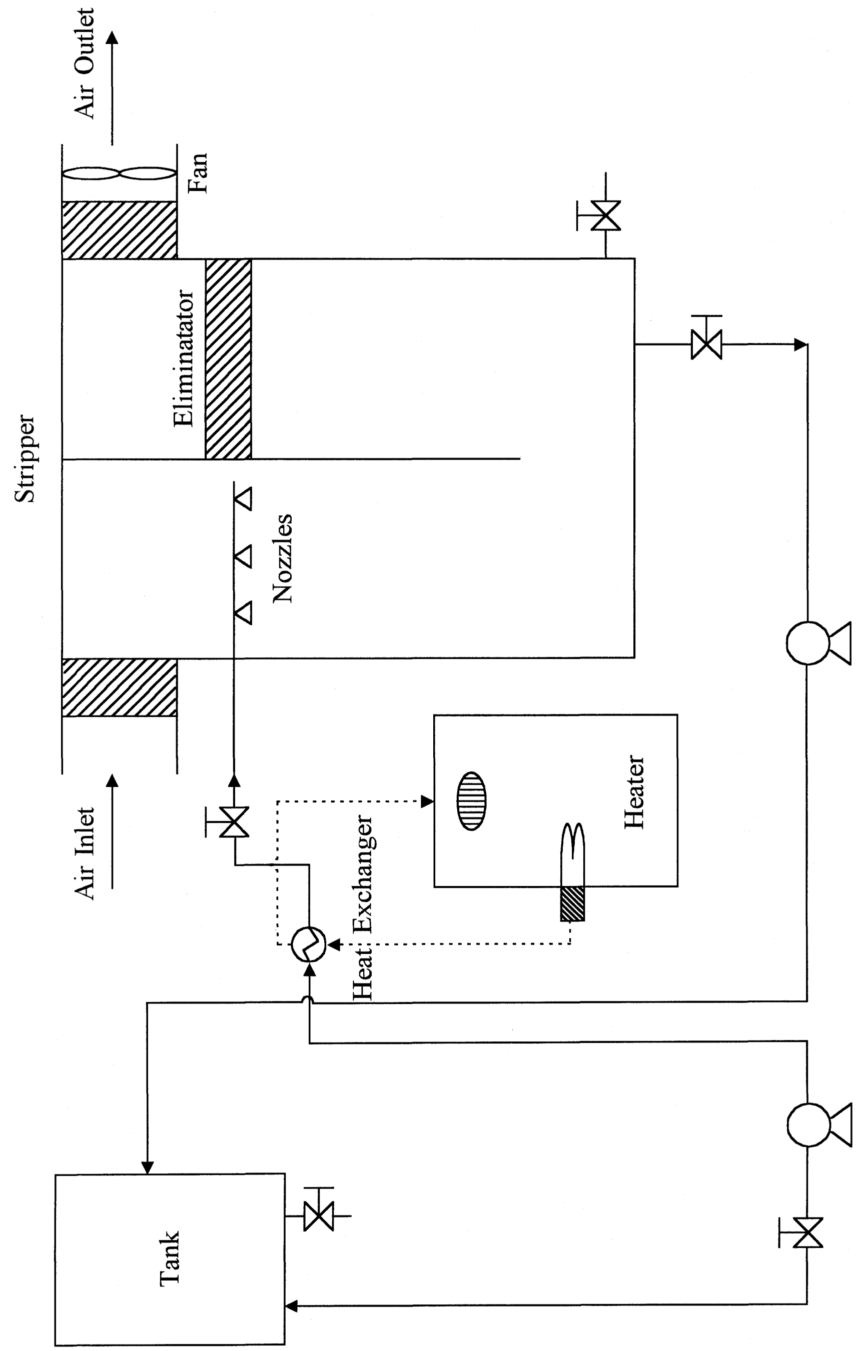

FIG. 1 Stripper/regeneration system for this study.

with two humidity probes, which can measure the relative humidity from 0 to 100% RH at −20 to 60°C, was used. The accuracy of this hygrometer is about ±0.2% RH. The air flow rates were controlled by a transistor inverter on the 0.5 HP blower. The liquid flow rates were measured by a rotameter, and the air flow rates were measured by a hot-wire flowmeter. The flow meters and flow controllers used in this study were calibrated by standard procedures.

RESULT AND DISCUSSION

The mass transfer performance of the stripper/regeneration system was evaluated by carrying out a series of experimental runs. The parameters that were varied during the experimentation including the air flow rate, the liquid flow rate, the temperature and humidity of the inlet air, the temperature of the inlet desiccant solution, and the concentration of the solution. The operating conditions are presented in Table 2. The rate of stripping was proportional to the difference between the outlet and inlet air humidities. Therefore, the rate of stripping, E, can be calculated by

$$E = (W_{out} - W_{in}) \times G_{air}$$

where W_{out} and W_{in} are the water contents of the outlet and inlet air streams, respectively, and G_{air} is the air mass flow rate. The rates of stripping calculated from the experimental data are provided in Table 2. When the solution concentration decreases, the rate of stripping is increased significantly (Fig. 2a) since the lower the solution concentration, the larger is the amount of water contained in the solution. Therefore, a larger amount of water is able to evaporate from a solution of lower concentration. In stripping processes, the growth of gas bubbles in the liquid can partially increase the turbulence or destroy the boundary layer and increase the diffusional mass transfer. In addition, a sufficiently large increase in temperature causes a significant decrease of gas solubility in the liquid phase. In this regard the stripping process reveals a higher driving force of mass transfer with increasing temperature. Generally speaking, the higher the inlet liquid temperature is, the higher the mass transfer rate in the stripper will be. Therefore, the rate of stripping in Fig. 2(b) increases as the inlet liquid temperature increases. As shown in Fig. 2(c), when the liquid flow rate is kept constant, the rate of stripping increases as the air flow rate increases. Similarly, when the air flow rate is kept constant, the rate of stripping increases as the liquid flow rate increases (Fig. 2d). The increases of air flow rate and liquid flow rate are similar to increasing the amount of stripping air and the amount of water vapor evaporation in a certain operating time. Therefore, more stripping air and/or evaporating water cause more water vapor removal in a stripper. However, the loading of water vapor in stripping air and the rate of water evaporation are also dependent on the temperature; this is shown in Fig. 2(b). In Fig. 2(e) the rate of stripping is not

TABLE 2
Experimental Data of This Study

Air flow rate (kg/min)	Liquid flow rate (kg/min)	Air inlet tempe-rature (°C)	Air outlet tempe-rature (°C)	Air inlet humidity (g H_2O/Kg dry air)	Air outlet humidity (g H_2O/kg dry air)	Liquid inlet tempe-rature (°C)	Liquid outlet tempe-rature (°C)	Tempe-rature below the fin (°C)	TEG concen-tration (wt%)	Equili-brium humidity (g H_2O/kg dry air)	Spary tower height (cm)	Rate of stripping (kg H_2O/h)	Mass transfer coefficient (kmol/m^3-s)	Height of transfer unit (m)
5.13	2.76	36.2	51.4	20.1	44.0	75.0	64.6	67.9	95.8	46.3	70	7.35	0.124	0.96
5.13	2.76	36.5	50.9	20.1	51.0	75.1	60.2	66.0	94.0	64.0	70	9.51	0.148	0.80
5.13	2.76	36.7	50.7	20.5	56.3	75.0	59.1	64.7	92.5	86.0	70	11.01	0.164	0.73
5.13	2.76	37.2	50.8	21.0	60.5	75.0	58.7	63.9	91.8	95.0	70	12.15	0.169	0.71
5.13	2.76	29.5	43.8	19.4	26.8	60.1	50.6	56.0	93.7	34.8	70	2.28	0.053	2.30
5.13	2.76	29.8	46.6	19.5	32.4	65.0	53.8	59.4	93.7	43.5	70	3.97	0.083	1.46
5.13	2.76	30.2	48.8	19.5	37.8	70.1	56.8	62.4	94.0	52.0	70	5.63	0.107	1.12
5.13	2.76	30.6	51.5	19.9	49.0	75.2	60.3	65.5	94.5	58.5	70	8.95	0.143	0.83
3.20	2.76	33.5	50.4	19.0	48.4	75.0	63.0	66.4	95.0	54.0	70	5.65	0.093	0.80
3.85	2.76	34.1	50.6	19.5	49.0	75.1	61.3	65.3	95.3	51.0	70	6.81	0.110	0.81
4.49	2.76	34.0	50.0	19.5	48.4	75.1	60.9	65.1	95.0	54.0	70	7.78	0.127	0.82
5.13	2.76	33.9	49.6	19.0	46.0	74.9	60.4	64.9	94.5	59.0	70	8.31	0.142	0.84
5.13	1.60	35.7	44.9	19.7	30.5	75.0	61.7	67.1	95.8	46.3	70	3.32	0.072	1.69
5.13	1.99	35.9	47.1	19.9	34.5	75.1	60.2	67.5	95.6	46.5	70	4.49	0.090	1.35
5.13	2.37	36.0	49.1	19.1	37.5	75.1	62.5	67.0	95.5	48.5	70	5.66	0.109	1.10
5.13	2.76	36.2	51.8	19.3	45.5	75.0	63.7	66.9	95.5	48.5	70	8.06	0.136	0.87
5.13	2.76	36.2	51.8	19.3	45.5	75.0	63.7	66.9	95.5	48.5	70	8.06	0.136	0.87
5.13	2.76	35.6	50.7	20.3	41.5	75.0	60.6	67.2	95.3	51.0	70	6.50	0.114	1.04
5.13	2.76	36.6	51.2	21.4	46.3	75.2	61.3	68.1	95.0	54.0	70	7.70	0.123	0.97
5.13	2.76	36.9	50.9	21.5	45.0	75.2	62.7	67.6	95.5	48.5	70	8.31	0.129	0.93
5.13	2.76	36.3	50.9	22.0	47.5	74.9	61.2	66.4	95.5	48.0	70	7.85	0.124	0.96

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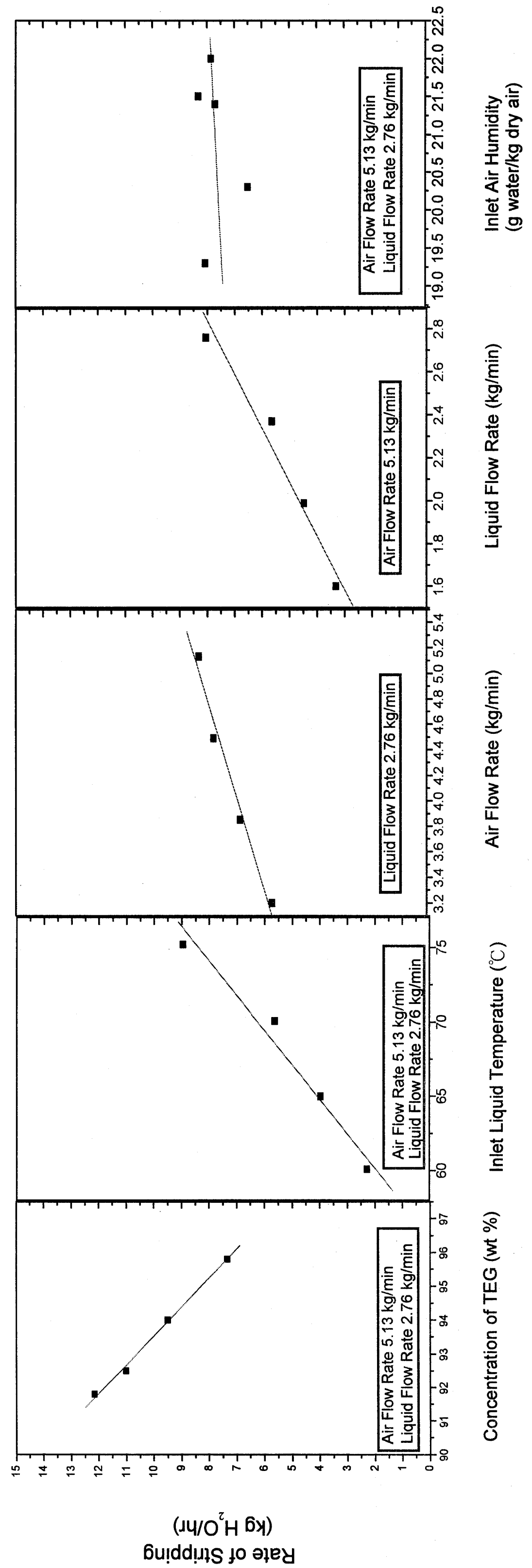

2(a) 2(b) 2(c) 2(d) 2(e)

FIG. 2 Effect of various operating conditions on the rate of stripping.

significantly influenced by the air humidity because the amount of water vapor removal during the stripping process is much higher than the inlet air water content (similar to the ambient air humidity). The effect on the humidity of stripping air is almost negligible in this study.

The overall mass transfer coefficient was derived from Geankoplis (10). The rate of mass transfer due to the molar fraction in the water vapor being transferring can be obtained as follows:

$$(K_{\mathrm{G}}a)_{\mathrm{avg}} = \frac{G}{Z}\int_{y_{\mathrm{a,in}}}^{y_{\mathrm{a,out}}} \frac{(1-y_{\mathrm{a}})_{*\mathrm{M}}}{(1-y_{\mathrm{a}})} \frac{dy_{\mathrm{a}}}{(y_{\mathrm{a}}-y_{\mathrm{a}}^{*})}$$

where G is the molar flow rate of air, and the bulk flow concentration factor is given by

$$(1-y_{\mathrm{a}})_{*\mathrm{M}} = \frac{(1-y_{\mathrm{a}}^{*})-(1-y_{\mathrm{a}})}{\ln(1-y_{\mathrm{a}}^{*}/1-y_{\mathrm{a}})}$$

where y_{a}^{*} is the equilibrium total molar fraction of an air–water mixture at different temperatures and concentrations of the TEG solution. The stripping of water vapor takes place when the partial pressure of the fluid is higher than the partial pressure of the gas on the interface. In general, the process of stripping is best known in the diffusional transfer region for which the same mass transfer models can be used as for the absorption process. This means that in many ways the stripping process following the mechanism of diffusion is the reverse of physical absorption [Zarzycki and Chacuk (11)]. Therefore, the above equation is applicable for both absorption and stripping processes. However, the limitations of the integration for absorption and stripping are reversed.

As expected, the effect of various operating conditions on the overall mass transfer coefficients shown in Fig. 3 is similar to the effect on the rate of stripping in Fig. 2. An increase in the overall mass transfer coefficient with an increase of air or liquid flow rates is observed in Figs. 3(c) and 3(d). As mentioned earlier, improvement in the gas–liquid contact is observed with an increase of gas and/or liquid flow rates. This will result in an increase of the overall mass transfer coefficient. As shown in Fig. 3(a), water vapor removal from a solution of higher concentration is lower. Because the water content in a solution of higher concentration is lower, the amount of water evaporation is limited. The overall mass transfer coefficient decreases when the solution concentration is increased. However, an increase in the TEG solution temperature increases the amount of water vapor evaporation from the solution. This results in an increase of the overall mass transfer coefficient (Fig. 3b). There is no significant effect of inlet air humidity on the overall mass transfer coefficient in Fig. 3(e).

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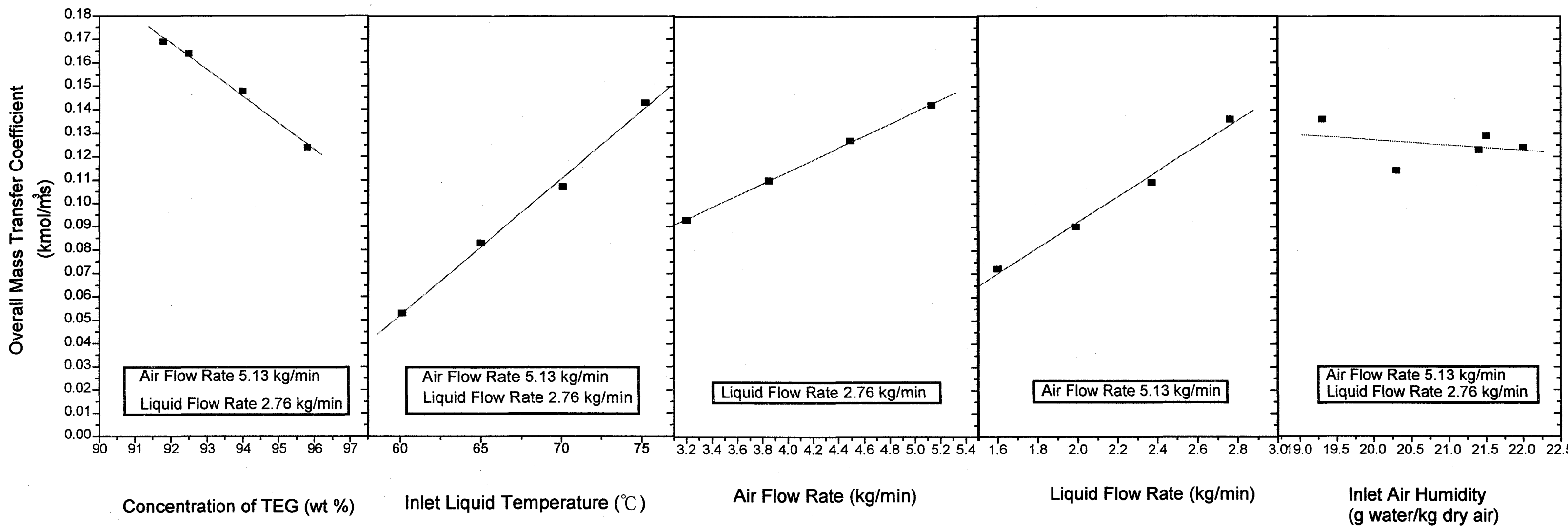

3(a) 3(b) 3(c) 3(d) 3(e)

FIG. 3 Effect of various operating conditions on the mass transfer coefficient.

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Most experimental data on gas–liquid contact devices are generally given in terms of the height of a transfer unit (HTU) rather than in the mass transfer coefficient, because the HTU is less dependent on gas or liquid flow rates. This provides a means to evaluate system performance under different operation conditions. Therefore, the height of a transfer unit, H_{OG}, in a spray tower is calculated in comparison with the HTU in a packed tower. The definition of the height of a transfer unit is

$$H_{OG} = G/(K_G a)_{avg}$$

Based on the above definition, the effect of various operating conditions on the height of a transfer unit shown in Fig. 4 is contrary to the effect on the overall mass transfer coefficient shown in Fig. 3 since an increase of the overall mass transfer coefficient results in a decrease of the value of HTU. The lower the value of HTU, the higher the mass transfer performance expected in the stripper. As noted in Fig. 4(c), the HTU values are almost constant for different air flow rates because an increase in the air flow rate results in an increase of the overall mass transfer coefficient (Fig. 3c). The variation in the ratio of air flow rate to the overall mass transfer coefficient is minor. Therefore, the HTU values are almost constant in Fig. 4(c).

As noted in Table 1, studies of mass transfer performance as well as of mass transfer correlation of the air stripping process are rare in the open literature. However, a generalized correlation is needed for design purposes. The driving force in the air stripping process is the difference between the vapor pressure of solution and the partial pressure of water vapor in the stripping air. Therefore, the mass transfer coefficient for the stripper can be determined by this pressure difference. The mass transfer coefficients are correlated in terms of the vapor pressures and the process variables by the Buckingham Pi method. Variables that affect the gas-phase mass transfer coefficient include vapor pressures, flow rates of air and liquid, physical properties of air and liquid, column diameter, and diffusion coefficient of water in air. A mass transfer correlation obtained from dimensional analysis is given as

$$\frac{K_G a M d_c^2}{D_V \rho_V} = 1.70 \times 10^{-3}\,\mathrm{Re_G Re_L^{0.85} Sc_G^{1/3}} \left(\frac{P_{sol} - P_A}{P_A}\right)^{0.5}$$

The left-hand-side of the above equation is a modified Sherwood number for the overall volumetric mass transfer coefficient. Deviations between the predicted and experimental data are summarized in Fig. 5. The new correlation for mass transfer coefficients predicted the experimental data with an average error of 10.5%.

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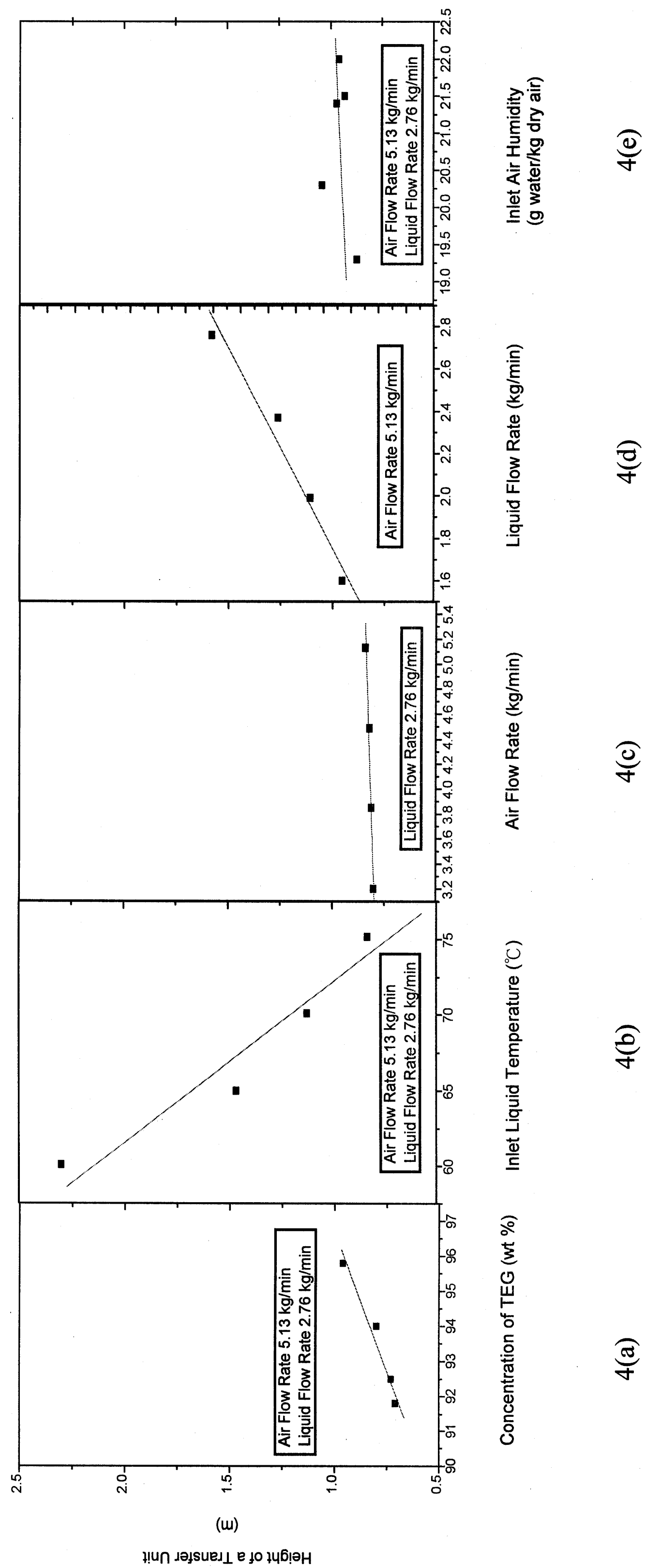

FIG. 4 Effect of various operating conditions on the heights of a transfer unit.

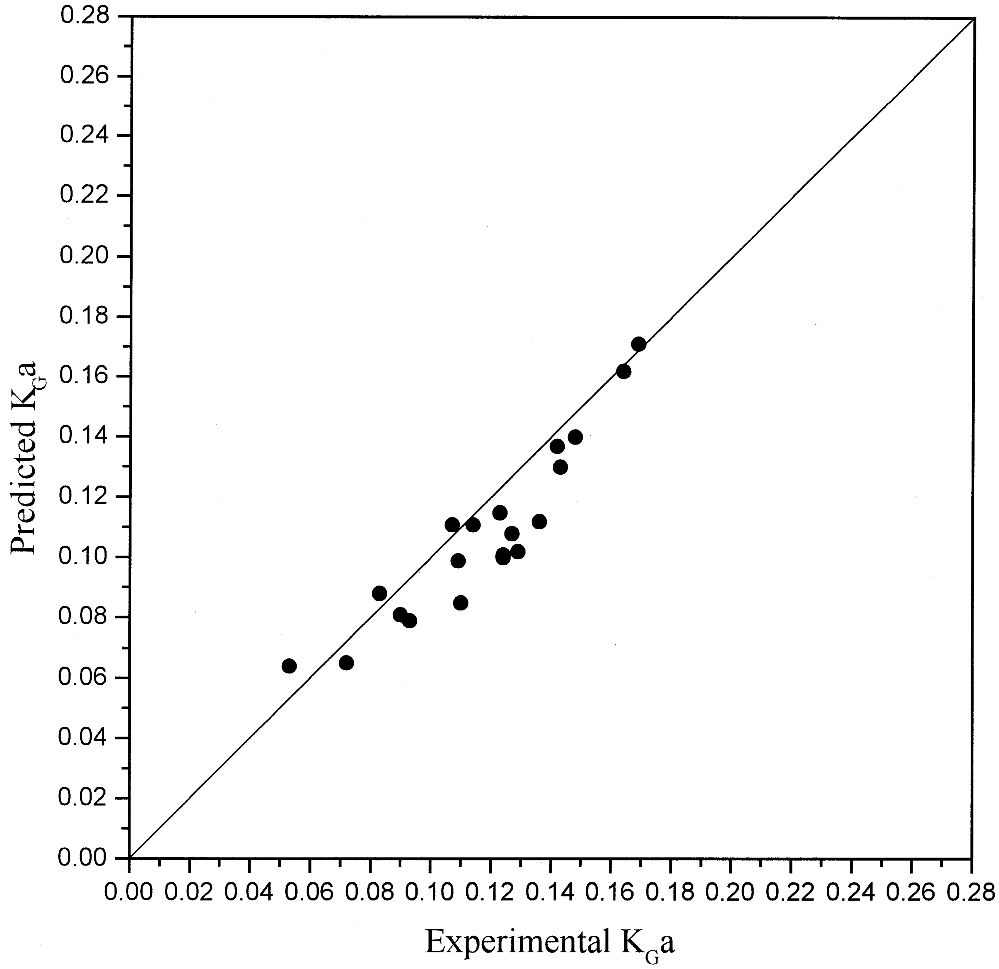

FIG. 5 Comparison between the predicted and experimental mass transfer coefficients.

CONCLUSIONS

A "U-shaped" stripping tower has been designed and successfully tested for regenerating the working solution. A U-shaped tunnel with eliminators prevents the carryover of solution which may contaminate the environment and waste the working solution. The main purpose of this design is similar to that of traditional spray columns which use filters in the outlet of the air stream. However, this design is more effective in preventing carryover. The effect of this design on mass transfer performance is negligible. Most mass transfer occurs in the left chamber of the U-shaped unit, while the right chamber eliminates the carryover of the working solution. There is nothing significantly different in the mass transfer between the U-shaped units and the traditional erect columns. Therefore, the mass transfer correlation of the air stripping process derived in this study is also applicable for other traditional spray columns.

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This study shows that the rate of stripping increases as either the air flow rate increases or the liquid flow rate increases. The overall mass transfer coefficients increase with increases of the air and liquid flow rates. As expected, increasing the liquid temperature significantly improves the stripping performance. In addition, lowering the TEG concentration increases the overall mass transfer coefficient and decreases the required height of a transfer unit. In addition, the effect of inlet air humidity is negligible in this stripping process. Since there are a limited number of studies on mass transfer performance in the open literature, the results of this work provide useful data and correlation to the design and improvement of the stripper in absorption–stripping systems.

NOMENCLATURE

d_c	column diameter (m)
D_v	diffusisity (m^2/s)
E	rate of stripping (kg H_2O/h)
G	air molar flow rate (kmol/$m^2\cdot$s)
G_{air}	air mass flow rate (kg/$m^2\cdot$s)
H_{OG}	height of a transfer unit (m)
$K_G a$	overall volumetric mass transfer coefficient (kmol/$m^3\cdot$s)
M	molecular weight of transferred material (kg/kmol)
P_{sol}	vapor pressure of the solution (mmHg)
P_A	partial pressure of water vapor in the air (mmHg)
Re_G	Reynolds number of the gas, $\rho_v u_v d_c/\mu_v$
Re_L	Reynolds number of the liquid, $\rho_L u_L d_c/\mu_L$
Sc_G	Schmid number of the gas, $\mu_v/\rho_v D_v$
u_v	air velocity (m/s)
u_L	liquid velocity (m/s)
W_{in}	water content of air at the inlet of the stripper (kg water/kg dry air)
W_{out}	water content of air at the outlet of the stripper (kg water/kg dry air)
y_a^*	the mole fraction of water vapor in the air in equilibrium with the TEG solution at the particular concentration and temperature (kmol H_2O/kmol air)
$y_{a,in}$	the mole fraction of water vapor in the inlet air stream (kmol H_2O/kmol air)
$y_{a,out}$	the mole fraction of water vapor in the outlet air stream (kmol H_2O/kmol air)
Z	height of the tower (m)
ρ_v	density of the gas (kg/m^3)
ρ_L	density of the liquid (kg/m^3)
μ_v	viscosity of the gas (kg/m$\cdot$s)
μ_L	viscosity of the liquid (kg/m$\cdot$s)

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