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Effect of interfacial phenomena on mass transfer performance of an absorber packed closely with cylindrical packing

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HIGHLIGHTS

- An absorber packed closely with cylindrical packing was designed in this study.
- The wetting of packing surface is a key factor for absorber performance.
- The Marangoni effect can be triggered in the system with continuous liquid phase.
- The surface stress increases significantly as TEG concentration exceeds 92 wt.%.
- The larger flow rate of TEG solution weakened the Marangoni effect.

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ABSTRACT

The mass transfer performance is usually affected by the wetting of the packing surface with absorbent solution, and the wetted surface can be affected by interfacial disturbances resulting from the gradient in surface tension between water vapor and absorbent solution. In order to discuss the effects of interfacial phenomena on mass transfer performance of water vapor absorbed by triethylene glycol (TEG) and lithium bromide (LiBr) solutions, an absorber packed closely with cylindrical packing was designed in this study and the packing material was polyvinyl chloride. In addition, the interfacial behaviors were observed from water droplet positioned on the surface of absorbent solution, and the surface stress was defined and calculated to analyze how mass transfer performance was affected by the stress. Experimental results show that surface stress increases with increases in concentration of TEG solution. The surface stress increases significantly when the concentration of TEG solution exceeds 92 wt.% The area of packing wetted by TEG solution increases as the concentration of TEG solution and humidity increase. Therefore, the mass transfer performance also increases with the higher concentration and higher humidity.

1. Introduction

A face of contact by two or more phases is called an interface. The behaviors of mass transfer and fluid flow are always affected by the components and density of the interface. One such effect is Marangoni convection, which results from the gradient in surface tension. The gradient in surface tension can be affected by changes in temperature and concentration. Table 1 shows some studies related to interfacial flow, induced by changes in temperature or concentration. Table 1 also reveals that the Marangoni effect can be triggered in mass transfer systems with continuous liquid phases. The Marangoni effect can also be induced spontaneously by mass and heat transfer processes. For example, the mass transfer performance of carbon dioxide absorbed into and desorbed from organic solvents was discussed by Sun et al. [5]. Their experimental results showed that the mass transfer performance was enhanced by interfacial disturbance caused by the process of carbon dioxide absorbing into and desorbing from organic solvents. Similar to the spontaneous Marangoni effect, which results from the concentration gradient, the thermal Marangoni effect can also be triggered spontaneously, such as in the evaporation of water, as discussed by Chang and Velev [9]. As long as the gradient in surface tension is high enough, the Marangoni effect will be induced. In addition to liquid droplets used in horizontal absorption cell, vapor can also contribute to a absorption system to produce the gradient. In order to discuss the interfacial disturbance resulting from the gradient in surface tension independently, a horizontal absorption system was developed by Wu et al. [2], Agble and Mendes-Tatsis [3], Kang and Kashiwagi [4], and Sun et al. [5] to reduce external interference. Other mass transfer processes, such as condensation, discussed by Vemuri et al. [8], and evaporation, discussed by Chang and Velve [9], can apply the Marangoni effect to increase mass transfer as a result of sufficient

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Table 1
Interfacial flow induced by vapor or additives.

System	Solutions	Vapor or additives	Authors
Horizontal absorption cell	EG (or DiEG) + $C_{12}E_{10}$($C_{12}E_4$)	Water vapor	Cachile et al. [1]
	55 wt.% LiBr	*n*-octanol droplet	Wu et al. [2]
	Water	Orgarnic droplet	Agble and Mendes-Tatsis [3]
	Water	*n*-octanol vapor	Kang and Kashiwagi [4]
	Methanol, toluene, chlorobenzene, and isobutanol	CO_2	Sun et al. [5]
Wetted wall column	53.5 wt.% LiBr	*n*-octanol vapor	Kashiwagi et al. [6]
Bubble absorber	Water	Hexanol, octanol	Kim et al. [7]
Steam condensation	Water	2-ethyl-1-hexanol	Vemuri et al. [8]
Evaporation	Water	Temperature	Chang and Velev [9]

difference in surface tension. On the basis of the concept that the Marangoni effect triggered in the system with continuous liquid phase, the aim of this study is to design an absorber with close cylindrical packing and to examine the effects of interfacial phenomena on mass transfer performance. In addition, the wetting of the packing surface with absorbent solution is also discussed in relation to the concentration of TEG solution and ambient humidity.

Zarzycki and Chacuk [10] pointed out that interfacial tension or lateral stress is an important factor that affects mass transfer mechanisms of absorption, distillation, and extraction. The gradients resulting from the differences between concentration and temperature are called solutal and thermal Marangoni effects respectively. If the Marangoni effect is induced by adding a surface additive, it is called an artificial Marangoni effect; if the Marangoni effect is induced by a mass transfer process, it is called a spontaneous Marangoni effect. Table 2 shows the types of differences of surface tension and the methods by which they have been induced in the open literature. For a single-component liquid, the density and surface tension are dependent on temperature. The liquid layer was heated from the bottom by Kamotani and Masud [16] and from the centerline by Kalitzova-Kurteva et al. [17] to activate fluid flow. Since the density and surface tension were changed by changes in temperature, the induced fluid flow was called the artificial thermal Marangoni effect. Table 2 shows that the artificial Marangoni effect is often applied to absorption systems. Spontaneous Marangoni effects have been found in absorption, distillation, and extraction systems. The mass transfer performance of a horizontal absorption cell [5,18,19] and a packed-distillation column [20–22] are affected by the spontaneous Marangoni effect; however, little research in the open literature has focused on the effects of a spontaneous Marangoni effect on the mass transfer performance of a packed-bed absorber. Mentioned above, an absorber packed with cylindrical packing was design to discuss the spontaneous Marangoni effect, and the difference in surface tension between absorbent solution and water vapor was used to induce the Marangoni effect in a packed-bed absorber. The concentrations of absorbent solution and air humidity were controlled to examine the mass transfer performance affected by the Marangoni effect.

Clearly, the Marangoni effect can be induced by sufficient difference in surface tension in the mass transfer devices with a continuous liquid phase. Since the absorption system can be used as an air cleaning equipments and for an absorption heat pump, enhancement of mass transfer performance is an important issue for an absorption system. The coverage of the packing can be increased and surface renewal can be promoted by the Marangoni effect. The falling-film and the packed-bed absorbers are two absorption system commonly used. Since the surface is wetted completely in the falling-film absorber, the Marangoni effect applied to the falling-film absorber is just to promote surface renewal. However, the channeling effect always causes inhomogeneous wetting in the packed-bed absorber. If the Marangoni effect is applied to raise the amount of packing that is wetted, the mass transfer performance will be increased. In addition, the liquid surface can also be renewed by interfacial disturbance. Therefore, the effect of a spontaneous Marangoni effect on the mass transfer behavior in the process of water vapor absorbed by TEG solution was discussed in this study.

Table 2
Type of difference of surface tension and the induced method.

Mass transfer devices	Type of difference	Induced method	Authors
Horizontal absorption cell	Solutal	Artificial	Wu and Chung [11]
			Yang et al. [12]
			Kim et al. [13]
			Lu et al. [14]
			Vazquez et al. [15]
Horizontal liquid layer	Thermal	Artificial	Kamotani and Masud [16]
			Kalitzova-Kurteva et al. [17]
Falling film absorber	Solutal	Artificial	Kashiwagi et al. [6]
Liquid–liquid system	Solutal	Artificial	Agble and Mendes-Tatsis [3]
Horizontal absorption cell	Solutal	Spontaneous	Sun et al. [5]
			Warmuzinski and Tanczyk [18]
			Chung et al. [19]
Packed-distillation column	Solutal	Spontaneous	Proctor et al. [20]
			Patberg et al. [21]
			Moens and Bos [22]
Packed rectification column	Solutal	Spontaneous	Martin and Perez [23]
Falling film absorber	Solutal	Spontaneous	Dijkstra and Drinkengburg [24]
			Imaishi et al. [25]
			Brian et al. [26]
			Maroudas and Sawistowski [27]
Liquid–liquid extraction	Solutal	Spontaneous	Bakker et al. [28]

2. Experimental section

Since the surface stress and the interfacial disturbance are induced by the gradient in surface tension, the surface tensions of desiccant solutions were measured by a surface tensionmeter (CBVP-A3). A Wilhelmy plate method was used to measure the surface tensions of desiccant solutions. The equilibrium state between the surface tension (platinic plate touching the surface of liquid solution) and the elastic force (drawing the platinic plate upward) was attained. The tensionmeter recorded the surface tension of the liquid solution at the equilibrium state. A platinic plate was used to measure the surface tension of absorbent solution due to its chemical inertness, in order to reduce the error in measuring surface tension to a minimum.

In order to analyze the surface stress and to observe the disturbance between water droplets and absorbent solutions, a water droplet was dropped on the surface of the absorbent solution, as shown in Fig. 1. The model SZ4045 TRCTV microscope was used to observe interfacial disturbances resulted from water droplet dropping on the surface of absorbent solution, and the magnification was 20×. The images for the dropping process could be obtained and saved by the software Optical 6.5. In order to quantify the interfacial phenomena, the surface stress resulting from the difference in surface tension was calculated to analyze the relationship between mass transfer performance and surface tension. Since the Marangoni effect can be induced in a mass transfer device with a continuous liquid phase, a packed-bed absorber was designed to facilitate a spontaneous Marangoni effect in the process of water vapor being absorbed by absorbent solutions. As shown in Fig. 2, the design of an U-shaped air tunnel with an eliminator in the absorber allowed for concurrent contact between the air and the solution, which reduced carryover of the solution. The interlaced wire was used as eliminator and mounted in left hand side of the absorption tower and right hand side of the stripping tower. The regenerated solutions in the bottom of stripping tower were pumped by solution motor to flow through heat exchanger to attaining the liquid distributor in the absorption tower. The outlet of the liquid distributor was as close as possible to the cylindrical packing to avoid interference with the Marangoni effect, and 20 tubes made up of 1.5 inch polyvinyl chloride were packed in the absorber. The size for both side of the U-shaped absorption tower was 20 cm, 20 cm, and 40 cm in length, width, and height. The design of stripping tower was the same as absorption tower. Since this study was focused on the absorption performance affected by the Marangoni effect, the data for stripping tower were not reported in detail. The heater temperature must be controlled to keep the concentration of the working solution. The line for absorbent solution flowing to the absorber was immersed in water bath to control the temperature of absorbent solution. The flow rate of absorbent solution was controlled by rotameter. The peristaltic pump with rotameter was used to drive ambient air to flow into absorption tower to contact absorbent solution in the concurrent. The absorbent solutions, included TEG and LiBr solutions, were used to absorb water vapor in the packed-bed absorber. The concentrations of TEG solutions were controlled from 85 to 97.5 wt.%, and the concentrations of LiBr solutions were controlled from 45 to 60 wt.% The liquid flow rates were in the range from 0.14 to 0.26 kg/s, and the air velocity was 2.5 m/s. The liquid solution flowed slowly into the packed-bed to avoid rupturing of the liquid film. The concentrations of absorbent solutions were measured by a refractometer. A testo-400 hygrometer with two humidity probes was used to measure the absolute and relative humidity and the temperature of the air. After the humidity and the concentration of absorbent solution were obtained, the mass transfer coefficients of water vapor being absorbed by absorbent solution could be calculated and used to discuss the effects of surface stress on mass transfer performance.

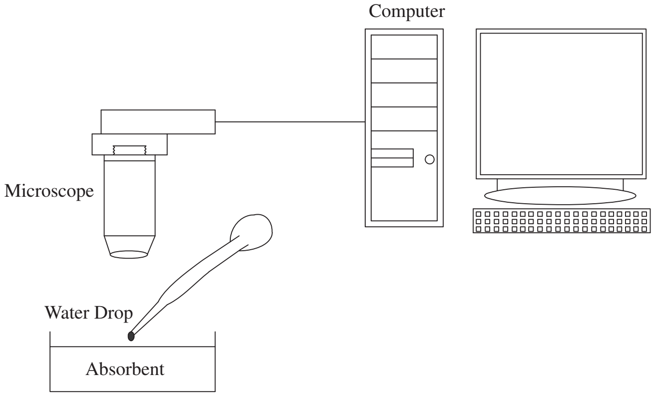


Fig. 1. Observing system of water droplet instilling on liquid surface.

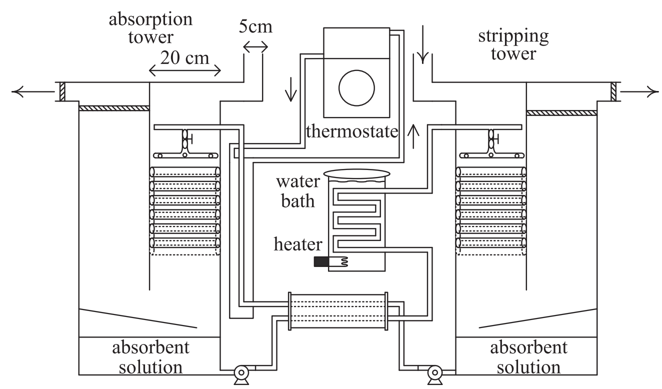


Fig. 2. The absorption system packed with closely cylindrical packing.

3. Results and discussion

3.1. Surface tensions of desiccant solutions

Fig. 3 shows that the surface tensions of TEG and LiBr solutions decreased as the temperature increased. The surface tensions of TEG solutions decreased as the concentration increased; however, the surface tensions of LiBr solutions increased as the concentration increased. The surface tension of liquid water is 72 mN/m at 25 °C. The surface tensions of LiBr solutions were in the range from 83 to 94 mN/m, greater than that of water. The surface tension of LiBr solution will be decreased while water vapor was absorbed by LiBr solution, which may result in the coverage of LiBr solution on the packing to be contracted. The surface tensions of TEG solutions were in the range from 44 to 47 mN/m, less than that of water. The surface tension of TEG solution will be increased while water vapor was absorbed by TEG solution, which may result in the coverage of TEG solution on the packing to be expanded. The temperature lower than 20 °C is quite energy consuming and the absorption performance is poor for the temperature greater than 30 °C. Therefore, the temperature was usually controlled from 20 to 30 °C to remove moisture from air. The Maraggoni effect or interfacial phenomena could be induced in the interface between absorbent solution and water vapor due to the adequate difference

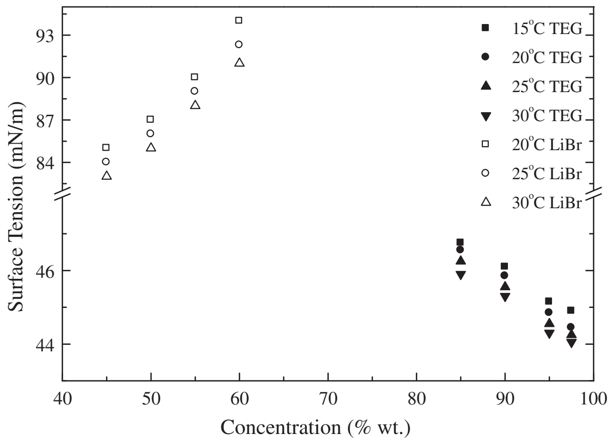


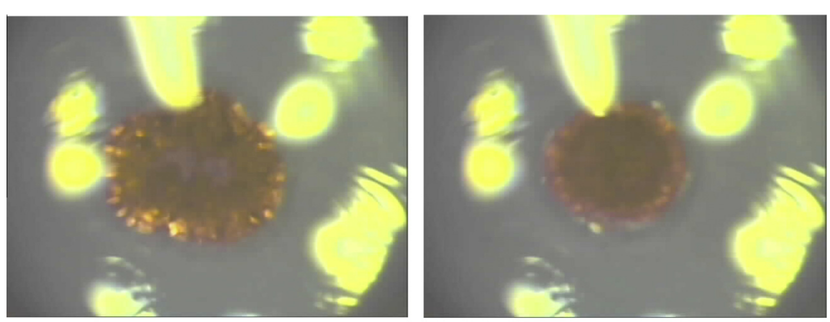
Fig. 3. Effects of concentration and temperature on surface tension of TEG and LiBr solutions.

in surface tension, but the change was not significant within the range of operating temperature.

3.2. Phenomena of interfacial disturbance

As mentioned in Section 2, the interfacial disturbances were observed by microscope and the observation system is shown in Fig. 1. In order to analyze the effects of concentration on interfacial disturbance, the images of water droplets on the surfaces of 90 wt.% and 97.5 wt.% TEG solutions are shown in Figs. 4 and 5. The liquid droplet would form thin liquid film immediately as it contacted with surface of TEG solution. The time between Fig. 4(a) and (b) is 1/12 second, and the contractive behavior of liquid film was observed during this period. After the contractive process, the liquid film expanded gradually due to diffusion in the absorbent solution. In addition, the continuous interfacial disturbance was found in the peripheral region of the liquid film. Both the contraction and interfacial disturbance were induced by the gradient in surface tension. Although the contractive behavior in Fig. 5 was more insignificant than in Fig. 4, the interfacial disturbance was also found in the interface between liquid film and TEG solution. In order to analyze the interfacial phenomena affected by TEG concentration, a reasonable index, such as surface stress, to represent the level of contractive behavior was defined and calculated.

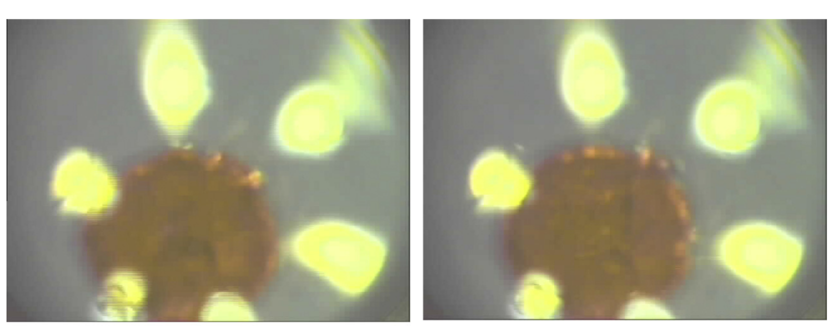
Mentioned above, the interfacial phenomena should be quantified to present the Marangoni effect affected by the concentration of absorbent solution. It is difficult to find a suitable scientific instrument to present or quantify interfacial phenomena resulted from the gradient in surface tension, even for the surface tensionmeter and the contact angle meter. The contractive phenomena of the liquid droplet became an indicator to quantify such phenomena resulted from the difference in surface tension. Therefore, the surface stress or contractive force was defined and calculated for contraction of the liquid film. The liquid droplet would form thin liquid film immediate as it contacted with surface of absorbent solution. Since the thickness of thin liquid film was smaller than its radius, the thickness of liquid film was regarded as a constant in deriving the surface stress. Assuming the droplet formed a homogeneous liquid film and the process of contraction was a plug flow, as shown in Fig. 6, to calculate the surface stress. The original



(a) Water drop instilled on the surface of 97.5wt% TEG solution.

(b) Contraction of the water drop by the surface tension gradient.

Fig. 4. Configuration in front (a) and back (b) of the surface stress acting on the system of water droplet –97.5 wt.% TEG solution.



(a) Water drop instilled on the surface of 90.0wt% TEG solution.

(b) Contraction of the water drop by the surface tension gradient.

Fig. 5. Configuration in front (a) and back (b) of the surface stress acting on the system of water drop –90 wt.% TEG solution.

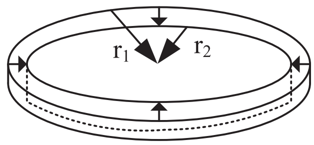


Fig. 6. Representation for the contraction of water droplet.

radius and the radius affected by surface stress were expressed as r_1 and r_2. The shape of the liquid film is nearly circle. The radiuses of eight directions were measured, and then the average radius was calculated to reduce error. The surface stress induced between liquid film and TEG solution can be derived as follows, where F is surface stress, m is mass, a is acceleration, ρ is liquid density, and V is liquid volume.

$$dF = dma \tag{1}$$

$$dF = d\rho Va \tag{2}$$

Since the contractive time, the time between Fig. 4(a) and (b), is just 1/12 second, the acceleration is assumed to keep at a constant momentarily. Therefore, the acceleration a and the density ρ were removed in front of the differential, as shown in Eq. (3). Eq. (4) shows the differential for volume change under assuming a constant thickness of the liquid film.

$$dF = a \times \rho \times dV \tag{3}$$

$$dV = \omega \times 2\pi r dr \tag{4}$$

The differential for volume change in Eq. (3) is replaced by Eq. (4) to obtain Eq. (5), and the integral range is from r_1 to r_2, where r_1 is the original radius and r_2 is the radius affected by surface stress. Finally, the surface stress resulting from the contraction of liquid film was calculated by Eq. (5).

$$\begin{aligned} F &= a \times \rho\omega \times 2\pi \int_{r1}^{r2} r dr \\ &= a \times \rho\omega \times 2\pi \frac{r^2}{2} = a \times \rho\omega \times \pi \times r^2 \Big|_{r1}^{r2} \end{aligned} \tag{5}$$

The surface stress resulting from the contraction of the droplet was calculated by Eq. (5). Fig. 7 shows the effect of concentration of TEG solution on surface stress. The surface tension of TEG solution decreases as the concentration of TEG solution increases. Therefore, the difference in surface tension between TEG solution and water droplet increased as the concentration of TEG solution increased, which led to the increments of surface stress in Fig. 7. Fig. 7 also indicates that the surface stress increased significantly as the concentration of TEG solution exceeded 92 wt.% The contraction of the water droplet was insignificant at concentrations of TEG solution below 92 wt.% Nevertheless, the images show that the interfacial disturbance in the interface between the droplet and TEG solution still occurred at concentrations of TEG solution below 92 wt.%.

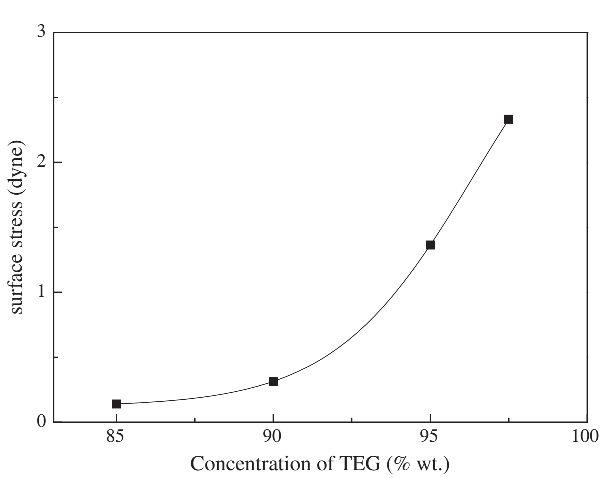


Fig. 7. Effect of concentration of TEG solution on surface stress.

The surface tension of LiBr solution is greater than that of liquid water, and the droplet dispersed immediately. The images obtained from the software almost cannot distinguish the changes in the front and back of the droplet on the surface of LiBr solution. Because the droplet dispersed rapidly, the images are not shown here. Similarly, the surface stress cannot be defined or calculated for a droplet on the surface of LiBr solution.

3.3. Effect of surface stress and interfacial disturbance on mass transfer performance

As mentioned above, the surface stress and the interfacial disturbance result from the gradient in surface tension, and the convection or disturbance near the interface between the water droplet and TEG solution can be called Marangoni convection or Marangoni instability. The contact probability in the gas–liquid or vapor–liquid systems will be increased due to the larger area or surface renewal. The interfacial disturbance will prompt the surface to renew and increase the contact probability in a vapor–liquid system. On the basis of the interfacial disturbance, some scholars have discussed the performance of distillation columns. Zuiderweg and Harmens [29], Moens [30] and Patberg et al. [21] used wetted-wall, plate and packed distillation columns to elucidate how mass transfer performance is affected by the spontaneous Marangoni effect. As long as surface tension differs sufficiently between phases, the Marangoni effect will be triggered in mass transfer devices with a continuous liquid phase. In order to comply with the condition of a continuous liquid phase, an absorber packed with closely cylindrical packing was designed for this study. The outlet of the liquid distributor was as close as possible to the cylindrical packing, and the packing cylinders were close together so that liquid desiccant solution would form a continuous liquid phase on the packed bed. Therefore, in this study, an absorber packed with close cylindrical packing was used to analyze the effects of the spontaneous Marangoni effect on mass transfer performance. The mass transfer coefficient for the gas phase was calculated according to Wu et al. [31]. In addition, the flow patterns of absorbent solution in the packed bed were captured by digital camera to analyze the effects of operating variables on the coverage of absorbent solution on the packing and to discuss the relationship between mass transfer performance and interfacial phenomena.

Fig. 8 shows that the mass transfer coefficient increased as the concentrations of TEG and LiBr solutions increased. For TEG solution, the mass transfer coefficient increased significantly when TEG solution had a concentration greater than 92 wt.% under the condition of a lower flow rate. As a result of the greater difference in surface tension, the coverage of the higher concentration of TEG solution on the packing surface was wider than that of a lower concentration of TEG solution. As shown in Fig. 9, the area of the surface of the packing material covered by TEG solution with the higher concentration is greater than that with the lower concentrations. The sheet flow in the bottom of Fig. 9(a) also showed that the area of the surface of the packing material covered by TEG solution was wider, and the channeling effect was improved by the Marang-

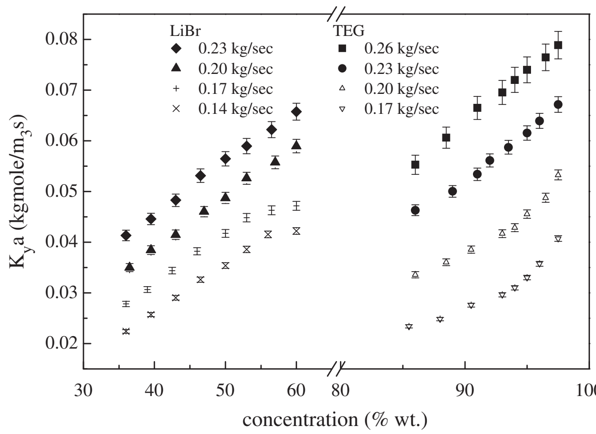


Fig. 8. Effects of solution concentration and liquid flow rate on the mass transfer coefficient.

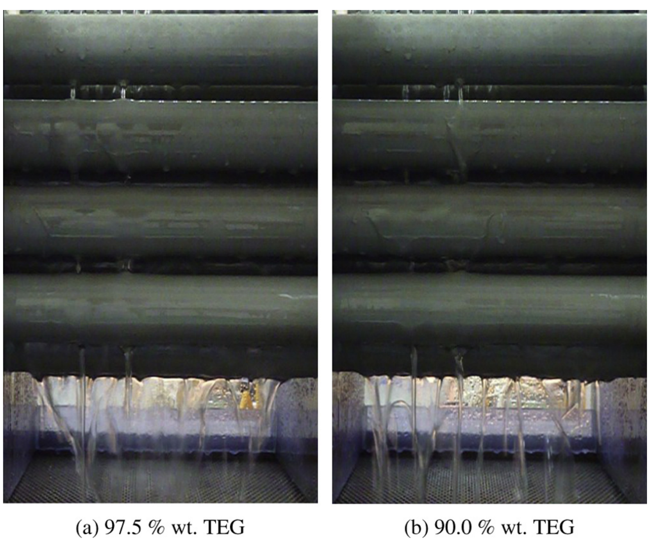


Fig. 9. Images for the surface of packing material under 97.5 and 90 wt.% TEG solution.

oni; The strip flow in the bottom of Fig. 9(b) showed that the area of the surface of the packing material covered by TEG solution was narrower, and the improvement of channeling effect was limited. However, the turbulent state resulting from the larger flow rate of TEG solution weakened the interfacial phenomena caused by the Marangoni effect. Therefore, the increment of mass transfer coefficient at the larger flow rate can be attributed to the increment of TEG concentration, and the trend seemed to be linear. Although the mass transfer coefficient also increased with the increment of LiBr concentration, the increment of mass transfer coefficient was insignificant for a higher concentration of LiBr solution. The surface tension of LiBr solution is greater than that of water vapor. The surface tension of LiBr solution decreased as water vapor was absorbed in the packed-bed absorber. The coverage of LiBr solution on the packing surface contracted due to the decline in surface tension. Similar to the observation in Fig. 9, the coverage of the 60 wt.% LiBr solution was less than that of the 45 wt.% LiBr solution. Nevertheless, the mass transfer coefficients still increased due to the larger driving force in the higher concentration. The larger flow rate weakened the interfacial phenomena, and the contraction of surface coverage was almost absent for the greater flow rate. The difference between TEG solution and LiBr solution is that the turbulent state appears at the lower flow rate for LiBr because of the lower viscosity. As described by Zarzycki and Chacuk [10] for solute absorbed by liquid film, more solute is absorbed by thinner film than by thicker film, especially at the edge of a liquid film on a packing surface. If the surface tension of the solute is greater than that of the absorbent solution, the edge of the liquid film will be extended due to the increment in surface tension, increasing the area covered by the liquid film. This phenomenon can be called a positive Marangoni effect for the absorption system, as in the case of water vapor absorbed by TEG solution. If the surface tension of the solute is lower than that of the absorbent solution, the edge of the liquid film will contract due to the decline in surface tension, reducing the area covered by the liquid film. This phenomenon can be called a negative Marangoni effect for the absorption system, as in the case of water vapor absorbed by LiBr solution.

These findings are consistent with the experimental results from Zhang et al. [32] MDEA aqueous solution was used by Zhang et al. [32] to absorb carbon dioxide under a high partial pressure. The results indicated that the absorption rate at a high carbon dioxide partial pressure was greater than the calculated value because the Marangoni effect was strengthened by the elevated partial pressure. In addition, Wang et al. [33] also pointed out that the mass transfer was affected by the effective area, and the effective area could be affected by surface tension, capillary forces, and condensing effect. Therefore, an improved model for estimating the effective area of structured packing was proposed for application to elevated pressure distillation. As mentioned above, the Marangoni effect can be affected by high partial pressure. Since the concept of humidity in the air is similar to the partial pressure of water vapor in the air, the relationships between air humidity and mass transfer coefficient for TEG and LiBr solutions are discussed. The enhancement of the mass transfer coefficient of water vapor absorbed by TEG solution in high humidity can be found in Fig. 10. However, the enhancement of the mass transfer coefficient of water vapor absorbed by LiBr solution in high humidity was insignificant, as shown in Fig. 11. Similar observation as Fig. 9, the coverage of absorbent solution on packing for high and low air humidity indicated that the coverage of TEG solution on the packing in high humidity was wider than that in low humidity. The coverage of absorbent solution on the packing surface was extended due to the significant Marangoni effect in high humidity, and this phenomenon can be called a positive Marangoni system. On the contrary, the coverage in high humidity was narrower for

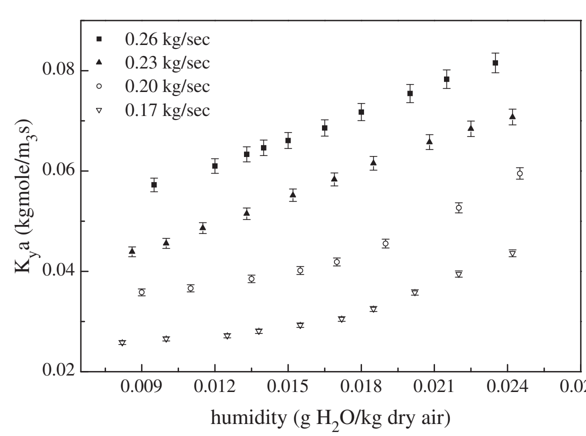


Fig. 10. Effect of humidity on mass transfer coefficient for TEG solution.

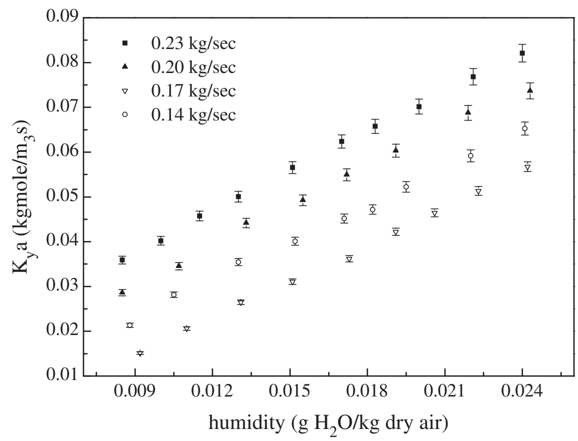


Fig. 11. Effect of humidity on mass transfer coefficient for LiBr solution.

LiBr solution. The coverage of absorbent solution on the packing surface was reduced, and this phenomenon can be called a negative Marangoni system. Similar to the results of concentration tests, turbulence resulting from the larger flow rate of TEG solution weakened the interfacial phenomena could also be found from Fig. 10.

3.4. Analysis of mass transfer for TEG and LiBr solutions

Gandhidasan et al. [34] reported that water vapor transferred from gas phase to liquid phase to equilibrate vapor pressure in an absorption system. Since the vapor pressure of water is higher than that of desiccant solution in the absorption system, the difference in vapor pressure between water and TEG solution is regarded as the driving force in the absorption system. The effect of concentrations of TEG and LiBr solutions on driving force of water vapor absorbed by TE them is shown in Fig. 12. The driving force increases almost linearly as the concentrations of TEG and LiBr solutions increase. If there is no paratonic effect, the mass transfer performance of water vapor absorbed by TEG solution should increase linearly with the increment of concentration of TEG solution. However, the mass transfer coefficients increased significantly with higher concentration TEG solutions, as shown in Fig. 8. The results imply that the mass transfer performance was enhanced due to the larger contact area and due to the stronger interfacial disturbance caused by the more significant Marangoni effect in the higher concentration of TEG solution. Because the Marangoni effect is weaker at a lower concentration, the mass transfer performance is dependent only on the driving force. In addition, the paratonic effect, such as the larger flow rate of absorbent solution, weakened or destroyed the Marangoni effect, and then the mass transfer performance increased with the increment of driving force. Therefore, the TEG solution should be controlled around 92–97 wt.% to absorb water vapor in a dehumidification system, and higher humidity should be maintained in the absorber of the absorption heat pump.

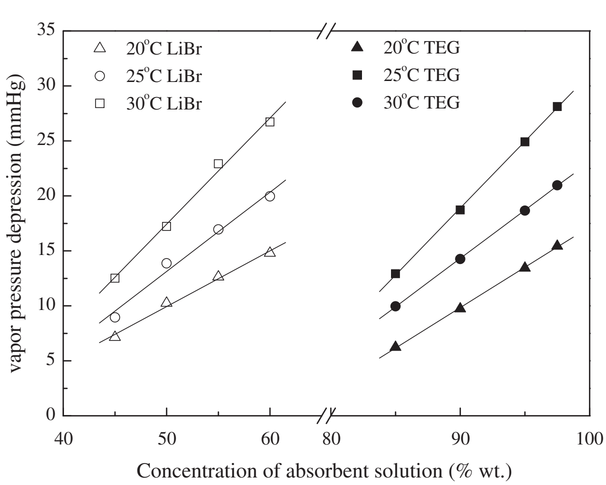


Fig. 12. Vapor pressure depression for LiBr and TEG solutions.

4. Conclusions

An absorber packed closely with cylindrical packing was designed to discuss the relationship between mass transfer and spontaneous Marangoni effect, and the variables of concentration of absorbent solution, air humidity, and liquid flow rate were controlled in this study. Since the coverage of the higher concentration of TEG solution on the packing surface is wider, the mass transfer coefficients for TEG solution were increased significantly under the condition of the concentration larger than 92 wt.% and the lower flow rate. As a result of the increment in surface tension by absorbing more water vapor, the coverage of TEG solution on the packing surface in high humidity was extended. The extended phenomenon can be called a positive Marangoni effect for the absorption system. Since the coverage of LiBr solution on the packing surface is contracted, the mass transfer coefficient is just increased linearly with a higher concentration of LiBr solution. As a result of decrement in surface tension by absorbing more water vapor, the coverage of LiBr solution on the packing surface in high humidity was contracted. The contracted phenomenon can be called a negative Marangoni effect for the absorption system. Mentioned above, the Marangoni effect resulted from absorption of water vapor by TEG solution can be used to enhance mass transfer performance for an air cleaning equipment and in an absorption heat pump in future. Calculations of surface stress and mass transfer experiments demonstrated that mass transfer performance increases significantly as the concentration of the TEG solution exceeds 92 wt.% Therefore, the concentration of TEG solution exceed 92 wt.% is suggested to use in a dehumidification system or in an absorption unit of absorption heap pump.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cej.2013.11.068.

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