Non-absorbable Gas Effects on Heat and Mass Transfer in Falling Film Absorption

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Film absorption involves simultaneous heat and mass transfer in the gas-liquid system. While the non-absorbable gas does not participate directly in the absorption process, its presence does affect the overall heat and mass transfer. An experimental study was performed to investigate the heat and mass transfer characteristics of LiBr-H_2O solution flowing over 6-row horizontal tubes with the water vapor absorption in the presence of non-absorbable gases. The volumetric concentration of non-absorbable gas, air, was varied from 0.17 to 10.0%. The combined effects of the solution flow rate and its concentration on the heat and mass transfer coefficients were also examined. The presence of 2% volumetric concentration of air resulted in a 25% reduction in the Nusselt number and 41% reduction in the Sherwood number. Optimum film Reynolds number was found to exist at which the heat and mass transfer reach their maximum value independent of air contents. Reduced Nusselt and Sherwood numbers, defined as the ratio of Nusselt and Sherwood numbers at given non-absorbable gas content to that with pure water vapor, were correlated to account for the reduction in the heat and mass transfer due to non-absorbable gases in a falling film absorption process.

Key Words : Falling Film Absorption, Aqueous LiBr Solution, Non-absorbable Gas, Optimum Reynolds Number, Reduced Nusselt Number, Reduced Sherwood Number

Nomenclature

A : Area (m^2)
C : Mass concentration of LiBr in solution (%)
c_p : Specific heat at constant pressure ($Jkg^{-1}K^{-1}$)
D : Mass diffusivity (m^2s^{-1})
g : Gravitational acceleration (ms^{-2})
h : Heat transfer coefficient ($Wm^{-2}K^{-1}$)
k : Thermal conductivity ($Wm^{-1}K^{-1}$)
L : Characteristic length (m)
l : Length (m)
Le : Lewis number, $=\rho D c_p/k$

Nu : Nusselt number, $=hL/k$
p : Pressure (mmHg)
Q : Heat transfer rate (W)
q : Heat flux (Wm^{-2})
Re : Reynolds number, $=4\Gamma/\mu$
Sh : Sherwood number, $=\beta L/D$
T : Temperature (°C)
U : Overall heat transfer coefficient ($Wm^{-2}K^{-1}$)
w : Mass flow rate (kgs^{-1})
y_a : Volumetric concentration of non-absorbable gas (%)

Greeks symbols

β : Mass transfer coefficient (ms^{-1})
Γ : Mass flow rate per tube length and tube side ($kgm^{-1}s^{-1}$)
μ : Viscosity (Nsm^{-2})
ρ : Density (kgm^{-3})

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Superscripts

*   : Equilibrium condition

Subscripts

0   : without non-absorbable gas
a : Absorption
c : Cooling water
f : Falling film
in : Inlet
lm : Logarithmic mean
s : Solution
out : Outlet
w : Water species in solution

1. Introduction

Absorption of gases and vapors into liquid film is encountered in numerous applications including the creation of heating and cooling effects in absorption heat pumps. Falling film absorption has been a problem of interest for a number of years due to its applicability to absorption systems. Among the parameters affecting the absorption process of absorbate (refrigerant vapor) into absorbent (liquid solution) in falling film absorber, non-absorbable gases seriously degrade its performance.

The composition of the gas phase, in which a non-absorbable gas is combined with the absorbate, influences the combined heat and mass transfer. The non-absorbable gas, in conjunction with the absorbate, is transported by convection and diffusion toward the liquid-gas interface. Since the interface is impermeable to the non-absorbable gas while the absorbate is absorbed at, non-absorbable gas accumulates at the interface and the concentration of the non-absorbable gas at the interface is significantly greater than that in the bulk of vapor. Then the partial pressure of the absorbate at the interface decreases and the absorbate mass transfer reduces significantly. The effects of non-absorbable gas on the absorption process share many similarities to the effects of non-condensable gas on the condensation processes. However the condensation problem requires only temperature-pressure equilibrium at the interface wheras the absorption problem re-

quires concentration-temperature-pressure equilibrium at the interface. The extra condition complicates the problem significantly.

The role of non-absorbable gas in the falling film absorption has been studied by a limited number of investigators. Haselden and Maltay (1959), for the ammonia/water film on the outside of internally cooled vertical tube, reported that the presence of 2% volumetric concentration of non-absorbable gas decreased the mass transfer by 5%. While 35% reduction in mass transfer was resulted at 13% of non-absorbable gas. Burdukov et al. (1980) indicated that as little as 0.5% volumetric concentration of non-absorbable gas resulted in 50% reduction in mass transfer for an aqueous LiBr solution flowing down a bundle of horizontal tubes. For 2% of non-absorbable gas content mass transfer reduced up to 60%. However they had only 4 data points for this conclusion. Vliet and Cosenza (1992) found the diminishing effect of air content at high film Reynolds number for the case of horizontal tube banks. The lithium chloride-water absorption system with vertical tube absorber was studied by Ameel and Wood (1992), Yang and Wood (1993), and Ameel et al. (1997) very systematically. They correlated the heat and mass transfer coefficients using the film Reynolds number, Prandtl number, Schmidt number, and air concentration. They found that the degradation effect of non-absorbable gas is most prominent at low solution flow rates. Kim and Lee (1998), for an aqueous LiBr solution film in a vertical tube, reported 59% reduction in mass transfer at 6% of non-absorbable gas. However the results, particularly the amount of reduction in heat and mass transfer rate due to non-absorbable gases, are inconsistent among the researchers.

In the present work, experimental study was performed to investigate the heat and mass transfer characteristics of lithium bromide-water solution flowing over 6-row horizontal smooth tubes in the presence of non-absorbable gas. The effects of non-absorbable gas were analyzed with the variation of solution flow rate and its concentration. The aim is to understand the role of non-absorbable gas and to develop the correlations

quantifying its degrading effects on the heat and mass transfer.

2. Experimental Investigations

2.1 Experimental apparatus

The working fluid for the absorption experiment is LiBr-water solution. Lithium bromide is an absorbent and water is an absorbate. Aqueous solution of lithium bromide flows over the horizontal tubes of 6-row as wavy laminar film where water vapor is absorbed. Fig. 1 schematically shows the experimental apparatus, which consists of the absorber, the absorbent solution generator, the solution tank, the evaporator, and the cooling system. The experimental equipment is designed for a batch-mode operation.

The generator is a strong solution tank whose volume is 145 liters and is well sealed so it can be deaerated by a vacuum pump. Four screw plug heaters are installed near the bottom of the tank to heat the solution for regeneration. The temperature of solution is controlled through the use of four screw plug heaters embedded in the tank and the band heater that is wound around the stainless steel tubing containing the solution.

The solution tank is a recovery tank of weak

Fig. 1 Schematics of the experimental apparatus

solution, which can hold 145 liters. The solution tank simply collects the diluted solution during the absorption experiments and is located at the downstream of the absorber.

In order to supply water vapor into the absorber, cylindrical vessel (diameter 100 mm, height 500 mm) equipped with four immersion heaters is used as an evaporator. Distilled water that is used as the absorbate can be deaerated during the initial evacuation by a vacuum pump before each experiment. The evaporation rate is controlled by a power supply unit to maintain the required absorber pressure. Leak valve of non-absorbable gas, which is air for the present study, is installed near the top of evaporator to mix and adjust its volumetric concentration in the water vapor. The amount of non-absorbable gas introduced into the absorber is controlled by regulating the opening of leak valve. The cooling water required is supplied by the constant water bath.

Absorber tank is a cylindrical vessel containing a solution distributor, tube bank, and a solution collector. The tube bank consists of 6 horizontal tubes, arranged in a row vertically. The tubes are made of phosphorous bronze and are 22.0 mm in outer diameter with the length of 100 mm, respectively. Inside the tubes the cooling water was flowing in cross-countercurrent. Coiled wires are placed inside the absorber tubes to induce a turbulent flow of the cooling water for promotion of heat transfer. At the top of the tube bank a solution distributor is located to distribute the LiBr solution evenly over the absorber tubes. Formation of falling film and film structure were observed through the view port. Mixture of water vapor and air was supplied through the bottom inlet of the absorber tank. The vapor flows upward, countercurrently to the LiBr-solution flow, crossing the tube bank for complete absorption. The diluted solution after the absorption process flowed into the solution collector located under the absorber tubes.

2.2 Test procedure

At the start of the absorption mode, concentration and temperature of the solution in the generator were adjusted first and then the solution was
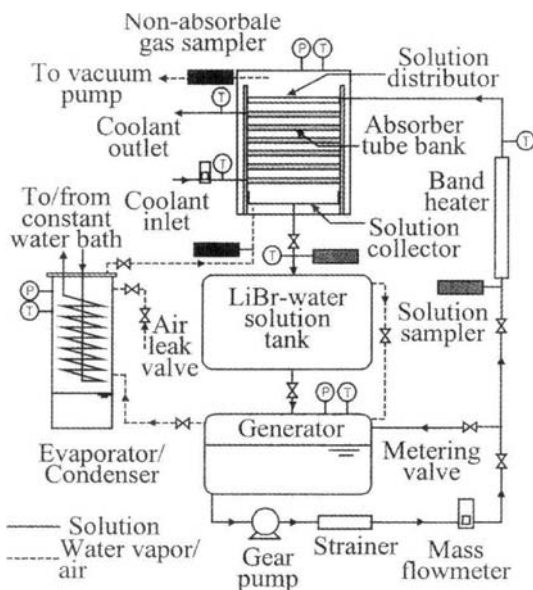
fed into the absorber by a magnetic gear pump. The water vapor generated at the evaporator was then mixed with air and supplied to the absorber. To keep the volumetric concentration of air constant during the absorption process, the absorber was operated in a constant vacuuming mode. When the remaining amount of the solution was insufficient to continue the experiment, the system switched to the regeneration mode. The diluted solution collected in the solution tank was fed to the generator, and regenerated by the heaters. In this mode, the evaporator functioned as the condenser to condense the regenerated water vapor.

The flow rate of solution fed into the absorber was measured by a mass flowmeter. Solution was sampled by the pre-evacuated sampler for the concentration measurement at the inlet and outlet of the absorber. Concentration of LiBr-water solution was measured by a pycnometer (25 ml) precisely under the constant temperature of 30℃. The pressures of the generator and the evaporator were measured by the convection-type vacuum gauge. Type T thermocouples were installed at the absorber inlet and outlet, at the cooling water inlet and outlet, at the evaporator, and at the generator.

The volumetric concentrations of air at the inlet and the outlet of the absorber tank were measured with the freezing method proposed by Ameel and Wood (1992). A stainless-steel bottle of sampler containing the sampled mixture was immersed into the dry ice bath. The mixture was cooled down to −60℃, at which the partial pressure of the water vapor should be small enough to be neglected compared to the total pressure. From the temperatures and pressures of the water vapor-air mixture before and after freezing, T_1, p_1 and T_2, p_2, respectively, the volumetric concentration of air can be evaluated assuming the ideal gas behavior.

$$y_a = \frac{p_2 T_1}{p_1 T_2} \qquad (1)$$

The experimental conditions including the absorber pressure, the temperature and the flow rate of the solution and the cooling water are summarized in Table 1.

Table 1   Range of parameters

Parameters	Ranges
LiBr-H_2O flow rate (kg/s)	0.008−0.03
LiBr-H_2O concentration (wt%)	58−61.5
LiBr-H_2O temperature (℃)	40−48
LiBr-H_2O inlet subcooling (℃)	2.7
Cooling water inlet temperature (℃)	30
Absorber pressure (mmHg)	8
Concentration of air (vol%)	0.17−10

2.3 Heat and mass transfer in falling film

The heat of absorption gives rise to temperature gradient in a falling film leading to the transfer of heat while the temperature affects the vapor pressure-composition equilibrium at the interface, which governs the mass transfer. The heat transfer rate to the coolant in the absorption process can be estimated by

$$Q = w_c c_{p,c}(T_{c,out} - T_{c,in}) = UAF\Delta T_{lm} \qquad (2)$$

where w is the coolant flow rate and $c_{p,c}$ is the specific heat of coolant at constant pressure. U, A, and F are the overall heat transfer coefficient between the solution and the cooling water, heat transfer area, and correction factor, respectively. Subscripts c, in, and out denote the coolant, the inlet, and the outlet of absorber respectively. The logarithmic mean temperature difference is defined as

$$\Delta T_{lm} = \frac{(T_{s,in} - T_{c,out}) - (T_{s,out} - T_{c,in})}{\ln\left(\dfrac{T_{s,in} - T_{c,out}}{T_{s,out} - T_{c,in}}\right)} \qquad (3)$$

where subscript s denotes the Libr-solution. The heat transfer coefficient of the falling film can be evaluated by

$$\frac{1}{h_f A_f} = \left(\frac{1}{UA} - \frac{\ln(r_f/r_c)}{2\pi kl} - \frac{1}{h_c A_c}\right) \qquad (4)$$

where k is the thermal conductivity of tube, l is the length of the absorber tube, and r_f and r_c are the outer and inner radius of absorber tube. The heat transfer coefficient of the cooling water, 2340 ± 50 W/m²K, was found from another set of experiment at the same geometrical and physical conditions as the absorber tubes.

Nusselt number for the falling film absorption process is defined as

$$\mathrm{Nu} = \frac{h_f L_f}{k_s} \qquad (5)$$

where the characteristic length is given as a function of solution viscosity, density, and gravity.

$$L_f = \left[\frac{\mu_s^2}{\rho_s^2 g} \right]^{1/3} \qquad (6)$$

Generally Nusselt number is correlated as a function of film Reynolds number, which is defined by

$$\mathrm{Re} = \frac{4\Gamma}{\mu_s} \qquad (7)$$

where Γ is the mass flowrate per absorber tube length and tube side and μ is the kinematic viscosity.

Absorption rate of water vapor during the absorption process can be derived from the mass conservation of the solution.

$$w_a = w_s \left[\frac{C_{in}}{C_{out}} - 1 \right] \qquad (8)$$

where C is the weight concentration of LiBr.

The vapor/liquid interface of falling film is in a thermodynamic equilibrium at a given pressure and temperature of the solution during absorption process. The logarithmic density difference of water species in solution between the vapor/liquid interface and the bulk in a falling film can be defined as

$$\Delta \rho_{lm} = \frac{(\rho_{w,in}^* - \rho_{w,in}) - (\rho_{w,out}^* - \rho_{w,out})}{\ln \left(\frac{\rho_{w,in}^* - \rho_{w,in}}{\rho_{w,out}^* - \rho_{w,out}} \right)} \qquad (9)$$

where ρ_w is the density of water species per unit volume of solution. Superscript $*$ denotes the thermodynamic equilibrium condition, which could be calculated by the solution temperature and the absorber pressure.

Mass transfer coefficient of falling film could be expressed as

$$\beta = \frac{w_a}{\Delta \rho_{lm} A} \qquad (10)$$

Then the Sherwood number is defined by

$$\mathrm{Sh} = \frac{\beta L_f}{D_s} \qquad (11)$$

where D_s is the mass diffusivity of solution.

2.4 Uncertainties

An uncertainty analysis was conducted to determine the maximum error for the heat transferred and the mass absorbed (Kline (1985)). Since the true value of a given measurement is not directly known, it is more accurate to speak of experimental uncertainty than of experimental error. The uncertainty in the cooling load measured on the coolant side was $\pm 8.5\%$. As expected, the major error in the load was due to the temperature gain of the coolant. The average uncertainty in the mass absorbed for all the reported experimental data was $\pm 26.4\%$, which was unavoidable since the mass absorbed was pretty small. The major error was due to the concentration change of the solution. The uncertainty in the volumetric concentration of air was estimated to be $\pm 3.5\%$.

3. Results and Discussion

Since the major purpose of the present study was to identify the effects of non-absorbable gases on the heat and mass transfer in the absorption process, all the factors except liquid solution flow rate, its concentration, and the volumetric concentration of air were kept constant. The volumetric concentration of air was varied in the range of 0 to 10%. However the minimum air concentration achievable during all tests was 0.17%.

Solution flow rates were varied in the range of 30 to 100 of film Reynolds number. In this range falling film can be characterized as "wavy laminar". However, below the film Reynolds number of 70, the formation of solution film on the outer surface of entire 6 tubes was not complete.

Figure 2 shows the effects of air concentration on heat and mass transfer rates for $\mathrm{Re}_f = 60$. The mass transfer rate appears to steadily decrease for an increase in ya, especially at low concentration of air. The accumulation of non-absorbable gas at the interface increases the mass transfer resistance in the gas side and reduces the mass transfer. The decrease in the heat transfer is a direct result of the decrease in the mass transfer. As the mass transfer rate decreases, less heat of absorption is released in the solution leading to a reduction in
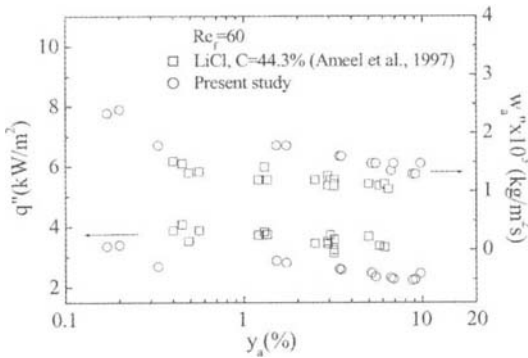
Fig. 2 Effects of non-absorbable gas concentration on heat and mass transfer rate

Fig. 3 Effects of non-absorbable gas concentration and film Reynolds number on Nusselt number and Sherwood number

the solution temperature gradient. As the volumetric air concentration increases from 0.17 to 5%, the mass transfer rate decreases nearly 37%, while the heat transfer rate decreases only 28%. The difference is due to the fact that the heat transfer is the combination of sensible heat from incoming LiBr-solution and absorption heat of water vapor. Knowing that the heat transfer rate is directly related to the mass transfer rate, the trends shown in Fig. 2 for the heat transfer rate are similar to those for the mass transfer rate. Even the working fluid and the operating conditions are different from the present study, the experimental results of Ameel et al. (1997), LiCl-water solution in vertical tube absorber, are also shown for the comparison of non-absorbable gas effects. Qualitatively, they show good agreement on the retardation of heat and mass transfer rate.

The effects of solution flow rate were evaluated for three flow rates equivalent to Re_f of approximately 50, 75, and 100, with the presence of non-absorbable gas. More data were available for Re_f in the ranges of 30 to 100. These data were not included since they do not add to the basic understanding that was gained from the included data. The effects of air contents with Re_f on the Nusselt and Sherwood numbers are given in Fig. 3. As easily expected the increase of air content reduces Sh regardless of Re_f. Consequently Nu also decreases. The diminishing effect of air content at high Re_f, proposed by Vliet and Cosenza (1992) and Ameel et al. (1997), were hardly noticeable. However the variation of Nu and Sh
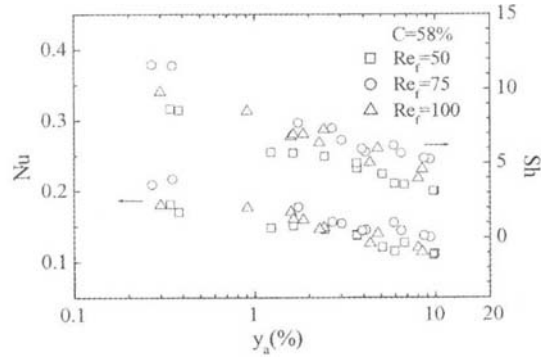
suggests that optimum Re_f, which is around 75 and is in good agreement with the result of Hikita et al. (1959), exists for the maximum heat and mass transfer. For $Re_f < 75$, the absorber tubes are not completely wet by the solution, which may cause the reduction in heat and mass transfer. As the solution flow rate increases, the wetting of absorber tubes improves. Meanwhile the increased solution flow rate results in the increase of film thickness, which increases the resistance to heat and mass transfer. These factors affect the transport process not by itself, but by an integrated manner. Therefore physical facts may vary depending upon the geometry, flow conditions, and materials. That might be the reason why the results reported by one investigator are contradictory to the other in some cases.

The combined effect of non-absorbable gas and the solution concentration is depicted in Fig. 4. At $Re_f = 75$, the absorber tubes are completely wetted by the solution film. As the concentration of solution increases at constant inlet subcooling, Nu and Sh tend to decrease. Even though the surface tension of solution remains almost constant, its viscosity increases as the solution concentration increases. As a result the falling film is probable to get thicker and the hydrodynamic characteristics may become weaker. Therefore the resistance to the heat and mass transfer increases leading to the decrease of Nu and Sh as mentioned by Hoffman et al. (1996). However, the decrease of Nu and Sh with the increase of the
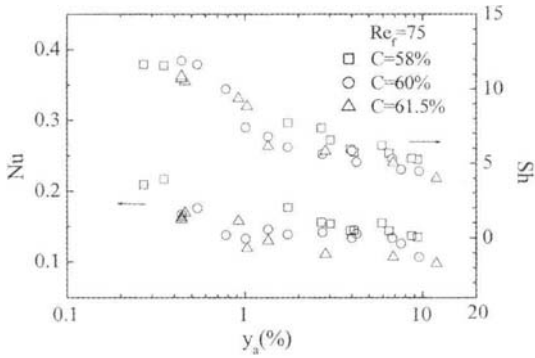
Fig. 4 Effects of non-absorbable gas concentration and solution concentration on Nusselt number and Sherwood number
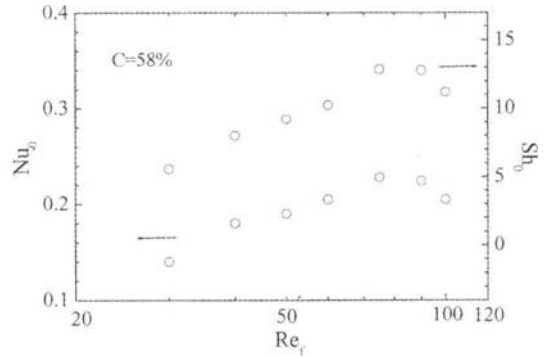

Fig. 5 Effect of film Reynolds number on Nusselt number and Sherwood number in the absence of non-absorbable gas

solution concentration is not very clear. Also the reduction rate of Sh is greater than that of Nu especially at low concentration of air.

To quantify the effects of non-absorbable gas on the absorption heat and mass transfer rates, it is necessary to evaluate the transfer rate in the absence of non-absorbable gas. However the minimum value of the volumetric concentration of air obtained in the present study was about 0.17% even the absorber was operated with a mechanical vacuum pump continuously removing the air that accumulated in the absorber. The values of Nu and Sh at given Re_f with pure water vapor were determined by the linear regression and are shown in Fig. 5 for the solution concentration of 58%. For $Re_f < 75$, Nu and Sh increase steadily and their increase rates are relatively high at low solution flow rate. However, for $Re_f > 75$, Nu and Sh decease due to the increase in film thickness.

The retardation of heat transfer with the presence of non-absorbable gas is expressed in terms of the reduced Nusselt number, Nu/Nu_0, which is the ratio of Nu at given non-absorbable gas content to that with pure water vapor. Reduced Sherwood number is also defined by the same manner. They are correlated as an explicit function of the non-absorbable gas content as

$$\frac{Nu}{Nu_0} = 0.825 y_a^{-0.134} \qquad (12)$$

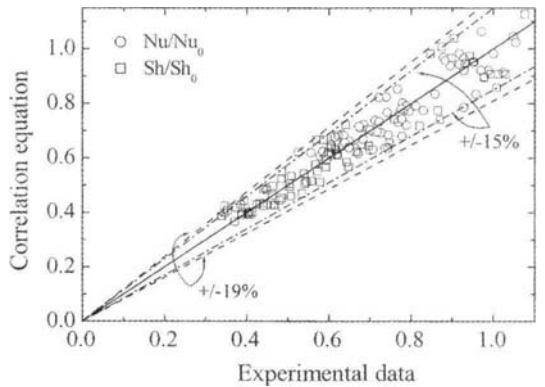$$\frac{Sh}{Sh_0} = 0.724 y_a^{-0.275} \qquad (13)$$

Fig. 6 Comparisons of correlation equations with experimental data

Comparisons of the correlation equations with experimental data for the reduced Nu and reduced Sh are depicted in Fig. 6. The overall deviation in the reduced Nusselt number is 15% for the fitted data. The correlation of reduced Sherwood number has an overall deviation of 19% for the fitted data. Even though great care was exercised in data acquisition, systematic errors and process control difficulties were the probable cause of the data scatter present in Fig. 6.

Figure 7 and 8 show the effect of non-absorbable gas on the reduced Nu and Sh numbers. As the volumetric concentration of air increases from 0 to 1%, Nu decreases nearly 18%, while Sh decreases about 28%. The decrease of Sh is more susceptible to the presence of non-absorbable gas
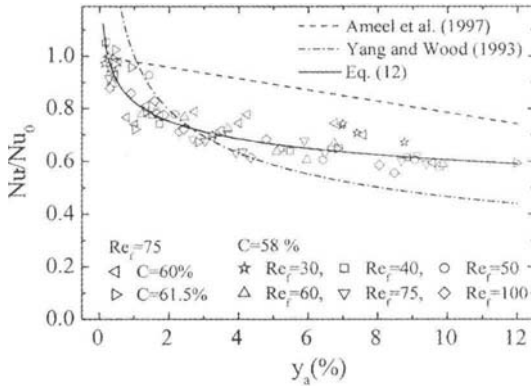
Fig. 7 Reduced Nusselt number as a function of non-absorbable gas concentration
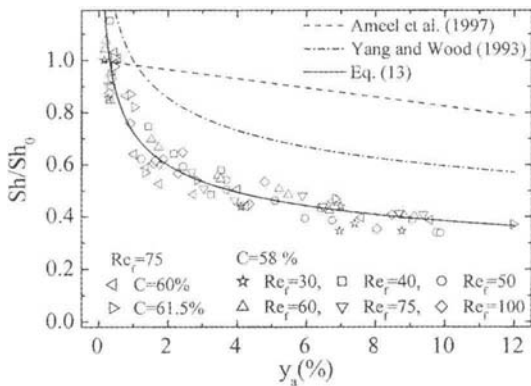

Fig. 8 Reduced Sherwood number as a function of non-absorbable gas concentration

than Nu because of the reason explained in Fig. 2. The volumetric concentration of air of 5% resulted in a 34% reduction in Nu while a 54% decrease in Sh. As the air content increases the reduction rate of Nu and Sh retards. 40% and 62% of reductions in Nu and Sh are resulted at 10% of air content, respectively. The correlations proposed by Yang and Wood (1993) and Ameel et al. (1997) are also depicted in Fig. 7 and Fig. 8 for the comparisons. Yang and Wood (1993) proposed

$$\frac{Nu}{Nu_0} = y_a^{-0.2147} \qquad (14)$$

$$\frac{Sh}{Sh_0} = y_a^{-0.225} \qquad (15)$$

Yang and Wood (1993) also observed the significant decrease of heat and mass transfer with

increasing air contents, especially at low concentration of air. They predicted that the decrease of heat transfer is more serious than that of mass transfer, which is in contradictory to the present study. In their experiments, a solution of lithium chloride and water was used for the falling film absorbent, which flowed down the outer surface of vertical tube. Therefore the overall absorption characteristics could be different from that found in the present study. However the volumetric concentration of air ranged from 4 to 30% and it was unable to correlate the retardation effects of air especially in lower air contents. As a result their correlation predicts that the reduced Nu and Sh are even greater than 1.0 in low air contents. The correlations of Ameel et al. (1997) was given as

$$\frac{Nu}{Nu_0} = \frac{0.0203 - 3.225 \times 10^{-5} y_a - 5.365 \times 10^{-5} Le}{0.0203 - 5.365 \times 10^{-5} Le} \qquad (16)$$

$$\frac{Sh}{Sh_0} = \frac{0.0258 - 3.225 \times 10^{-4} y_a - 7.839 \times 10^{-5} Le}{0.0258 - 7.839 \times 10^{-5} Le} \qquad (17)$$

where Le is the Lewis number. Basically they assumed the factor that deals with the effect of non-absorbable gas is a linear function of its contents. The experimental conditions were almost the same as those of Yang and Wood (1993). However they had only 17 and 13 distinct measurements for the correlations of Nu and Sh in the range of 0 to 7% of non-absorbable gas contents. The number of data and the range of non-absorbable gas seemed to be insufficient for the development of accurate correlations.

Considering the experimental data of the present study and those published in the open literatures, correlation Eqs. (12) and (13) are practical and reasonable for the explanation of the experimental findings and the physical interpretation of the retardation effects of non-absorbable gas on the heat and mass transfer in the falling film absorption process.

4. Conclusions

In the present work, an experimental study was performed to investigate the heat and mass transfer characteristics of lithium bromide-water solu-

tion flowing over 6-row horizontal smooth tubes in the presence of non-absorbable gases. The effects of non-absorbable gas were analyzed with the variation of solution flow rate and its concentration.

The presence of a 1% volumetric concentration of non-absorbable gas resulted in a 28% reduction in the Sherwood number while a 5% concentration resulted in a 54% reduction. The Nusselt number was reduced by 18% for a 1% of volumetric concentration of non-absorbable gas, while 34% for a 5% concentration. The Sherwood number was more susceptible to the presence of non-absorbable gas.

Optimum film Reynolds number, approximately 75 for the horizontal tubes, existed for maximum heat and mass transfer, regardless of the volumetric concentration of non-absorbable gas. The heat and mass transfer coefficients decreased with then increase of viscosity.

Correlations for the reduced Nusselt and reduced Sherwood numbers were proposed, which account for the reduction in the heat and mass transfer due to non-absorbable gases in a falling film absorption process.

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