Integral Analysis of the Effects of Non-absorbable gases on the Heat Mass Transfer of Laminar Falling Film

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Key Words : Absorption process, Mass transfer resistance, LiBr/water system, Non-absorbable gas

Abstract

The absorption process of water vapor in a liquid film is an important process in LiBr-Water absorption system. The composition of the gas phase, in which a non-absorbable gas is combined with the absorbate, influences the transport characteristics. In the present work, the absorption processes of water vapor into aqueous solutions of lithium bromide in the presence of non-absorbable gas are investigated. The continuity, momentum, energy and diffusion equations for the solution film and gas are formulated in integral forms and solved numerically. It is found that the mass transfer resistance in gas phase increases with the concentration of non-absorbable gas. However the primary resistance to mass transfer is in the liquid phase. As the concentration of non-absorbable gas in the absorbate increases, the interfacial temperature and concentration of absorbate in solution decrease, which results in the reduction of absorption rate. The reduction of mass transfer rate is found to be significant for the addition of a small amount of non-absorbable gas to the pure vapor, especially at the outlet of tube where the non-absor-bable gas accumulates. At higher non-absorbable gas concentration, the decrease of absorption rate seems to be linear to the concentration of non-absorbable gas.

———————— Nomenclature ————————

A : Area, m^2
C : Mass concentration of water in solution
   film

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D : Mass diffusivity, m^2/s
e : Internal energy, kJ/kg
g : Gravitational acceleration, m/s^2
h : Distance from tube wall, m
i : Enthalpy, kJ/kg
K : Absorption ratio
k : Thermal conductivity, W/mK
L : Heat of absorption, kJ/kg

m : Mass flow rate, kg/s

p : Pressure, Pa

q : Heat transfer rate, W

q'' : Heat flux, W/m^2-

r : Radial coordinate

R : Tube radius, m, or Resistance, s/m

T : Temperature, ℃

t : Time, s

u : Axial velocity, m/s

v : Radial velocity, m/s

W : Mass concentration of water vapor in gas

x : coordinate in flow direction

y : Coordinate perpendicular to flow direction

δ : Solution film thickness, m

$\varDelta$: Concentation boundary layer thickness, m

μ : Viscosity, Ns/m^2

ρ : Density, kg/m^3

τ : Shear force, N

Subscript

a : Air

eq : Thermodynamic equilibrium

f : Solution film

g : Vapor-air mixture

o : Center-line in gas or inlet in solution film

s : Liquid-gas interface

v : Vapor

w : Absorber tube wall

1. Introduction

Absorption of gases and vapors into liquid films is encountered in numerous applications in chemical technology. Some broad areas of application include the formation of gas-liquid solutions in various reactors, the separation of gases from liquids in distillation processes, the removal of impurities from streams of gases, and the creation of heating and cooling effects in absorption heat pumps. For the film absorber it is possible to transfer heat into or out of the solutions during the process through the wetted solid surface supporting the film. Therefore falling film absorption involves simultaneous heat and mass transfer in the gas-liquid system.

There are several factors which affect the absorption process of absorbate (vapor) into absorbent (liquid solution) in a falling film absorber. The thermodynamic equilibrium properties of the participating substances, particularly their pressure-temperature-composition relations and the heat of absorption determine the relative influence of heat transfer on mass transfer. Transport properties of fluids such as thermal and mass diffusivities govern the heat and mass transfer at the gas-liquid interface. The flow regime-laminar, wavy, turbulent-affects the transfer rate toward and away from the interface. The overall process is a combined result of these factors and their relative importance varies depending on the conditions.

While the non-absorbable gas does not participate directly in the absorption, its presence does affect the overall heat and mass transfer. Since the interface is impermeable to the non-absorbable gas in the absorption process, non-absorbable gas accumulates at the interface. Consequently the concentration of non-absorbable gas at the interface is grater than that in the bulk gas resulting in a decrease in the partial pressure of the absorbate at the interface and reduction in absorbate mass transfer. This problem is similar to the condensation problem with the presence of non-condensable gases which has received much attention by researchers both analytically[1~3] and experimentally.[4~6] However, the condensation problem requires only temperature-pressure equilibrium at the interface, whereas the ab-

sorption problem requires concentration-tem-perature-pressure equilibrium at the interface. The extra condition complicates the problem significantly.

Analytical and experimental studies to pre-dict the effects of non-absorbable gas in a falling film absorber are relatively rare in the literatures. Haselden and Maltay[7] conducted experiments on the absorption process of ammonia/water films and proposed that the presence of a 2% volumetric concentration of non-absorbable gases decrease the mass tran-sfer by 5%. Burdukov et al.[8] provided ex-perimental results in which the effect of non-absorbable gas on the absorption of water vapor by aqueous LiBr solution flowing down a bundle of horizontal tubes was investigated. Their results indicated that as little as 0.5% volumetric concentration of non-absorbable gas resulted in the 50% reduction in mass tran-sfer. The degrading effects of non-absorbable gas contents on the absorption process were also studied experimentally by Vliet and Co-senza[9] for the case of horizontal tube banks, and Yang and Wood[10] for the vertical-tube LiCl- H_2O system.

Boundary layer analysis with non-absor-bable gas was reported by Grossman.[11] He concluded that the reduction in mass transfer caused by the presence of non-absorbable gas was most critically influenced by the di-ffusion resistance in the gas phase. Habib et al.[12] investigated the effect of non-absorba-ble gas in the entrance region of a falling film absorber. They predicted about 50% re-duction in mass transfer when the non-ab-sorbable gas content was incre-ased from 0 to 2%. However all these studies were limited to the entrance region of tube where the analytical solution was possible.

In the present studies, the absorption pro-cesses of water vapor into aqueous solutions of lithium bromide flowing down inside of vertical tube in the presence of non-absor-bable gas are analyzed by the integral me-thod. The continuity, momentum, energy and diffusion equations(mass conservation of water species) are solved to estimate the effects of non-absorbable gas on the overall heat and mass transfer characteristics in the absorp-tion process.

2. Model and governing Equations

Figure 1 describes the schematic picture of a falling film and the coordinate system. A film of liquid solution flows down over a solid surface of given geometry. The solution is composed of two components-the absor-bent and the absorbate. Other substances not
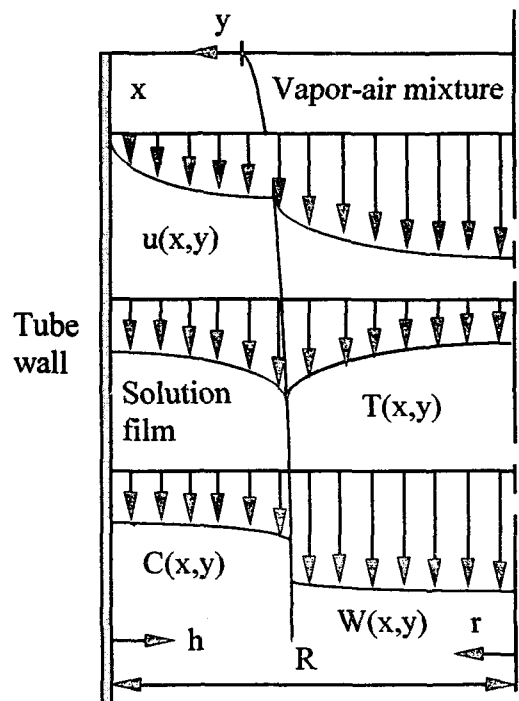

Fig.1   Schematic picture of falling film

participating in the absorption process may be contained in the liquid. The film is in contact with gases containing at least the absorbate component. The gases may contain other "inert" components not participating in the absorption process. For simplicity these non-participating components have been combined under the term of "non-absorbable gases", which is assumed to be air for the present analysis. For a subcooled solution at the inlet, absorbate vapor pressure in the solution is lower than that in the gas. This results in absorption taking place at the liquid-gas interface, with the absorbate diffusing through the gas phase and into the solution film. the heat generated in the absorption gives rise to temperature gradients which results in heat transfer. A falling film absorber makes it possible to remove the heat generated and keep the vapor pressure in the liquid low enough for the continuous absorption.

The following assumptions have been made in formulating the model : (1) The physical properties of the liquid solution and the vapor-air mixtures are constant; (2) Thermodynamic equilibrium prevails at the liquid-gas interface; (3) Both the solution film and the gas are laminar flow; (4) The vapor-air mixture has fully developed velocity, temperature and concentration profiles; (5) The solution film is fully developed hydrodynamically and thermally but the concentration boundary layer is developing; (6) There is no slip between phases; (7) Thermal diffusion is negligible; (8) Axial diffusion is negligible.

Under these assumptions, the combined heat and mass transfer process in the absorption system is governed by the continuity, momentum, energy and diffusion equations of solution and gas. The integral forms of these equations for the solution film are

$$\frac{\partial}{\partial t} \int \rho_f dA_f + \frac{\partial}{\partial x} \int \rho_f u_f dA_f = \dot{m}' \tag{1}$$

$$\frac{\partial}{\partial t} \int \rho_f u_f dA_f - u_s \frac{\partial}{\partial t} \int \rho_f dA_f$$
$$+ \frac{\partial}{\partial x} \int \rho_f u_f^2 dA_f - u_s \frac{\partial}{\partial x} \int \rho_f u_f dA_f$$
$$= -\left(\frac{\partial p}{\partial x} - \rho_f g\right) \int dA_f + \tau_w' - \tau_s' \tag{2}$$

$$\frac{\partial}{\partial t} \int \rho_f e_f dA_f - e_{fs} \frac{\partial}{\partial t} \int \rho_f dA_f$$
$$+ \frac{\partial}{\partial x} \int \rho_f u_f i_f dA_f - i_{fs} \frac{\partial}{\partial x} \int \rho_f u_f dA_f$$
$$= -q_w' + q_{fs}' \tag{3}$$

$$\frac{\partial}{\partial t} \int \rho_f C dA_f + \frac{\partial}{\partial x} \int \rho_f u_f C dA_f = \dot{m}' \tag{4}$$

where equation (4) is the continuity equation of water species in a falling film. $\dot{m}$ is the absorption rate, q the heat transfer rate, τ the shear force, e the internal energy, and i is the enthalpy. C is the water concentration in the solution film. subscripts f, g, s and w denote the film, gas, liquid-gas interface and the wall.

For the gas flow they become

$$\frac{\partial}{\partial t} \int \rho_g dA_g + \frac{\partial}{\partial x} \int \rho_g u_g dA_g = -\dot{m}' \tag{5}$$

$$\frac{\partial}{\partial t} \int \rho_g u_g dA_g - u_s \frac{\partial}{\partial t} \int \rho_g dA_g$$
$$+ \frac{\partial}{\partial x} \int \rho_g u_g^2 dA_g - u_s \frac{\partial}{\partial x} \int \rho_g u_g dA_g$$
$$= -\left(\frac{\partial p}{\partial x} - \rho_g g\right) \int dA_g + \tau_s' \tag{6}$$

$$\frac{\partial}{\partial t} \int \rho_g e_g dA_g - e_{gs} \frac{\partial}{\partial t} \int \rho_g dA_g$$
$$+ \frac{\partial}{\partial x} \int \rho_g u_g i_g dA_g - i_{gs} \frac{\partial}{\partial x} \int \rho_g u_g dA_g$$
$$= -q_{gs}' \tag{7}$$

$$\frac{\partial}{\partial t} \int \rho_g W dA_g + \frac{\partial}{\partial x} \int \rho_g u_g W dA_g = -\dot{m}' \tag{8}$$

where W is the water vapor concentration in the gas phase. Once the profiles of velocity, temperature and concentration are given, the above equations could be solved to evaluate the momentum, energy, and mass transfer rate.

Boundary conditions for the velocity, temperature and concentration profiles in the solution film are

$$u_f(x, 0) = u_s \tag{9.1}$$

$$u_f(x, \delta_f) = 0 \tag{9.2}$$

$$\mu_f \frac{\partial u_f(x, 0)}{\partial y} = \tau_s'' \tag{9.3}$$

$$T_f(x, 0) = T_s \tag{10.1}$$

$$T_f(x, \delta_f) = T_w \tag{10.2}$$

$$-k_f \frac{\partial T_f(x, 0)}{\partial y} = \dot{m}'' L + q_{gs}'' \tag{10.3}$$

$$C(x, 0) = C_s \tag{11.2}$$

$$C(x, \Delta_f) = C_o \tag{11.2}$$

$$\frac{\partial C(x, \Delta_f)}{\partial y} = 0 \tag{11.3}$$

where Δ_f is the thickness of the concentration boundary layer in the solution film and L is the absorption heat. Interfacial shear stress and heat flux can be calculated from the gas-side velocity and temperature profiles. Parabolic profiles satisfying the above boundary conditionss are

$$u_f(x, y) = u_s\left(1 - \frac{y^2}{\delta_f^2}\right) + \frac{\tau_s''}{\mu_f}\left(y - \frac{y^2}{\delta_f}\right) \tag{12}$$

$$T_f(x, y) = T_s + (T_w - T_s)\frac{y^2}{\delta_f^2}$$
$$+ \frac{\dot{m}'' L + q_s''}{k_f}\left(y - \frac{y^2}{\delta_f}\right) \tag{13}$$

$$C(x, y) = C_s\left(1 - \frac{2y}{\Delta_f} + \frac{y^2}{\Delta_f^2}\right)$$
$$+ C_o\left(\frac{2y}{\Delta_f} + \frac{y^2}{\Delta_f^2}\right) \tag{14}$$

where subscript o represents the value at absorber inlet for the solution film and the centerline value for the gas phase.

For the gas flow, boundary conditions for velocity, temperature and concentration profiles are all derived from the same concepts as those used for the solution film.

$$u_g(x, 0) = u_s \tag{15.1}$$

$$u_g(x, \delta_f - R) = u_{go} \tag{15.2}$$

$$\frac{\partial u_g(x, \delta_f - R)}{\partial y} = 0 \tag{15.3}$$

$$T_g(x, 0) = T_s \tag{16.1}$$

$$T_g(x, \delta_f - R) = T_{go} \tag{16.2}$$

$$\frac{\partial T_g(x, \delta_f - R)}{\partial y} = 0 \tag{16.3}$$

$$W(x, 0) = W_s \tag{17.1}$$

$$W(x, \delta_f - R) = W_o \tag{17.2}$$

$$\frac{\partial W(x, \delta_f - R)}{\partial y} = 0 \tag{17.3}$$

Velocity, temperature and concentration profiles in gas phase them become

$$u_g(x, y) = u_s + (u_s - u_{go})\left[\frac{2y}{(R - \delta_f)}\right.$$
$$\left. + \frac{y^2}{(R - \delta_f)^2}\right] \tag{18}$$

$$T_g(x, y) = T_s + (T_s - T_{go})\left[\frac{2y}{(R - \delta_f)}\right.$$
$$\left. + \frac{y^2}{(R - \delta_f)^2}\right] \tag{19}$$

$$W(x, y) = W_s + (W_s - W_o)\left[\frac{2y}{(R - \delta_f)}\right. $$

$$\left. + \frac{y^2}{(R - \delta_f)^2}\right] \quad (20)$$

From assumption (2), the concentration of solution at the liquid-gas interface should satisfy the thermodynamic equilibrium condition.

$$C_s = C_{eq}(T_s, p_{vs}) \quad (21)$$

where p_{vs} is vapor pressure in the gas at the liquid-gas interface, which can be estimated as the product of total pressure and the mole fraction of water vapor in gas phase at the interface. The mole fraction of water vapor in the gas is determined as a function of vapor molar concentration in the gas and the molecular weight of the species. The continuity of heat flux and mass flux at the liquid-gas interface are given as

$$-k_f \frac{\partial T_f(x, 0)}{\partial y} = \dot{m}''L - k_g \frac{\partial T_g(x, 0)}{\partial y} \quad (22)$$

$$\rho_{fv} v_{s,f} - \rho_f D_f \frac{\partial C(x, 0)}{\partial y}$$

$$= \rho_{gv} v_{s,g} - \rho_g D_g \frac{\partial W(x, 0)}{\partial y} \quad (23)$$

where ρ_{vs} is the density of water vapor in the vapor-air mixture, v_s is the radial velocity of each phase near the interface, and D is the mass diffusivity. Since the liquid-gas interface is impermeable to the non-absorbable gas the radial velocity of the gas at the liquid-gas interface is given as

$$v_{s,g} = -D_g \frac{\partial W(x, 0)}{\partial y} \bigg/ (1 - W_s) \quad (24)$$

3. Solution Methods

Due to nonlinear nature of the conservation equations and property relations, it is difficult

to get steady-state solutions by solving them simultaneously. Therefore model is formulated with transient equations and solved until the rate of change of any variables with respect to time is very small, at which time steady state is reached.

Equation (1)-(8), (21), (23), and (24) form 11 simultaneous equations for the unknowns of δ_f, Δ_f, u_s, u_{go}, T_s, T_{go}, C_s, $\dot{m}$, W_s, W_o, and p for the case of constant wall temperature. They are solved by the explicit finite difference method. Discretization of equations using the first-order forward-time and backward-space scheme results in the difference equations. The temperature and concentration of LiBr are strongly coupled by the thermodynamic equilibrium conditions at the liquid-gas interface. The mass flux of water vapor absorbed into the solution film should satisfy equation (23) and (24), and at the same time the temperature and concentration at the interface should meet the requirement of thermodynamic equilibrium given in equation (21). Thus an iterative technique is used to find the interfacial temperature and resultant mass flux using the Newton method.

At each time step, calculation proceeds from the inlet to the outlet. At each node, the solution film thickness is first calculated from equation (1), and then interfacial velocity, gas core velocity and pressure are calculated by equation (2), (5) and (6). The temperature and concentration of the solution film and gas are calculated from the energy and diffusion equations for both fluids simultaneously with the interfacial conditions given in equation (22) and (23). When the rate of change of each variable with respect to time is less than the specified value, it is assumed that steady state is reached.

4. Results and discussion

The working fluid for the absorption analysis is a lithium bromide and water solution. Lithium bromide is an absorbent and water is an absorbate. Aqueous solutions of lithium bromide flow down inside a vertical tube as a falling film. The non-absorbable gas considered in the present analysis is air. Thus the mixture of water-vapor and air flows co-currently with the solution film in the core of tube. Table 1 shows the dimension of the vertical tube absorber and operating conditions used in the analysis of absorption process.

For the operating conditions considered in the present studies, the Reynolds number for the gas flow is 1,000 and for the falling films 130 at the inlet of the absorber. Since the system is maintained in a vacuum, the velocity of the vapor-air mixture at the inlet of absorber is relatively high. The interfacial shear stress is found to be approximately 5% of the wall shear stress, which could be bigger at a higher gas flow rate. The solution film seems to become thicker as it flows down the tube not only by the absorption of

water vapor but also by the reduced interfacial shear stress due to the lower gas velocity especially, near the outlet of the tube. For the co-current flow between the solution film and gas the higher gas flow rate would cause the bigger interfacial stress, the thinner solution film, and thus the lower heat transfer resistance in the solution film. These phenomena could be the reverse in the case of the counter-current flow.

Temperature profiles in the solution film and gas at various locations along the tube are shown in Fig.2, where air concentration is 1%. Due to the absorption of water vapor by the solution film and the release of absorption heat, the liquid-gas interface temperature is the highest. The gas temperature seems to rise very quickly from the inlet conditions as a result of heat transfer from the solution. However, the fraction of heat transferred to the gas is less than 1% of heat transferred to the wall. The sharp temperature gradient in the solution film leads to a large quantity of heat transferred to the wall.

As the absorption process proceeds, the concentration profiles in the solution film and gas vary as shown in Fig.3 and 4. Since the

Table 1 Conditions for the analysis of absorption process

| Parameter	Values
Absorption tube diameter(mm)	13.3
Absorption tube length(mm)	1,000
System pressure(mmHg)	8.0
Wall temperature($°C$)	35.0
Solution water concentration(%)	42.0
Solution temperature($°C$)	40.0
Solution flow rate(kg/min)	0.4
Gas flow rate(kg/min)	0.005
Gas temperature($°C$)	8.0
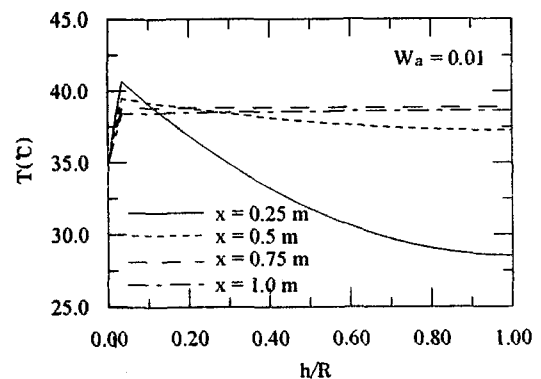
Fig.2 Temperature profiles of solution film and gas at various locations along the tube

development of the concentration boundary layer in the solution film is limited due to its small mass diffusivity, an abrupt increase of solution concentration can be noticed near the liquid-gas interface. The concentration of water vapor in the gas decreases relatively slowly near the interface. It can be noticed that the growth of the concentration boundary layer thickness in the solution film reaches about 40% of the film thickness at the outlet of the tube.

As the solution and gas are introduced into the absorption process, the absorptional mass flux increases abruptly due to its high vapor pressure difference. Since the solution temperature rises as a result of absorption heat, the driving force for the mass transfer decreases. Thus the absorption rate reaches its maximum and then decreases slowly depending upon the cooling capacity of the process as shown in Fig.5. For a very thin solution film, since the heat transfer resistance in the film would be very small, it might be possible that the absorption rate increases throughout the whole absorber. For both phases absorption occurs by diffusion and convection (bulk motion of fluid). Figure 5 shows most

of the absorption flux is induced by convection in the gas phase. In the solution film, the diffusional mass flux is slightly larger than the convectional flux. Convection and diffusion seem to contribute to the mass transfer with almost the same importance in the solution film.
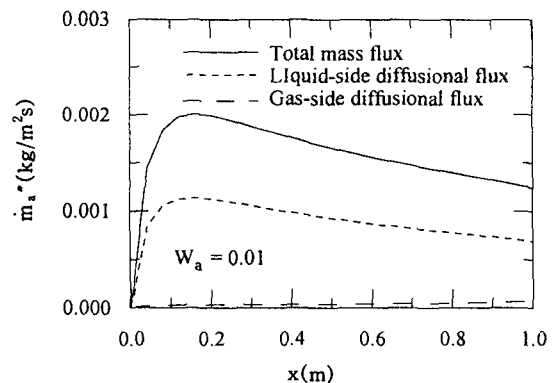
The variation of mass transfer resistance for both phases is given in Fig.6. Since the growth of the concentration boundary layer in the solution film is not affected very much by the air content, mass transfer resistance in
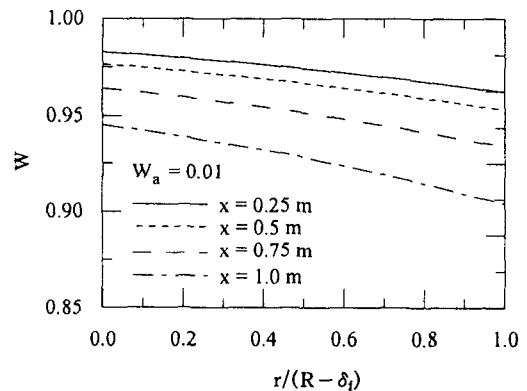
Fig.4 Concentration profiles of water vapor in gas at various locations along the tube
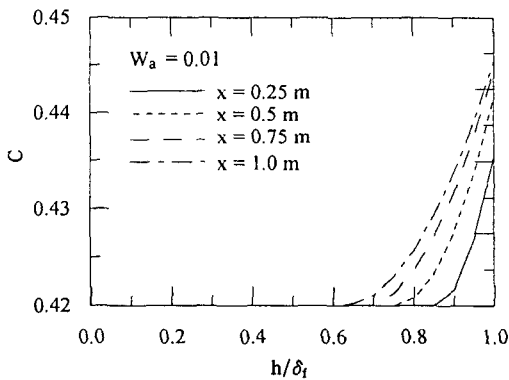
Fig.3 Concentration profiles of water in solution film at various locations along the tube

Fig.5 Variation of total and diffusional absorption mass fluxes along the tube

the solution remains the same regardless of the concentration of non-absorbable gas in the water vapor-air mixture. The mass transfer resistance in gas phase increases with the addition of the non-absorbable gas. Basically the primary resistance to mass transfer is in the liquid phase due to its low mass diffusivity. The mass transfer resistance in gas phase is very small when compared to that of the solution. However the driving force for the mass transfer, the difference between the bulk density and the interfacial density, is prevailed by the liquid phase. Therefore the mass transfer resistance in the gas phase should not be neglected.

The variation of the interfacial equilibrium concentration of the solution and the effects of air content are shown in Fig.7. The rise of interfacial concentration is reduced as the air content increases. Since the non-absorbed air accumulates as the gas flows down the tube the reduction of the interfacial concentration is remarkable, especially near the outlet of tube.

At the inlet of tube the absorption rate is assumed to be very small. As the film forms and flows down the tube, the absorption rate

rapidly increases due to the driving pressure difference. However, the increase of the absorption rate with tube length is limited to a certain point due to the increase in interfacial temperature and the accompanying reduction of the vapor pressure difference. This could be overcome by an increase of the cooling rate, the heat transfer to the wall. Once the absorption rate reaches its maximum, it decreases slowly depending on the concentration of air in gas. As a result of a decrease in the interfacial concentration in the solution and in the vapor pressure difference, the mass absorption rate decreases with the content of air as shown in Fig.8.

As mentioned in the analysis of the interfacial concentration in the solution, the reduction of the absorption rate is remarkable, especially near the outlet of the tube. The qualitative trends of absorption rate with tube length are invariant with the concentration of non-absorbable gas. The absorption ratio K is defined as the absorption rate in the presence of non-absorbable gas divided by the absorption rate in the absence of non-absorbable gas. K is depicted as a function of air contents in Fig.9. The absorption ratio de-
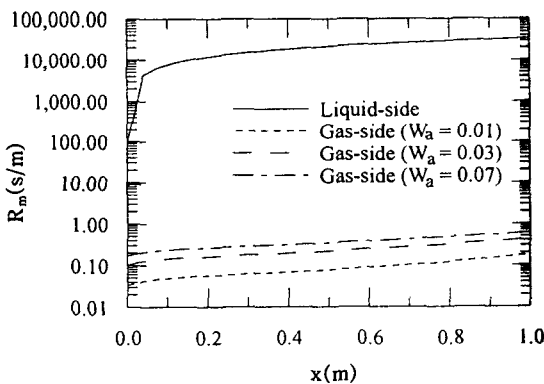

Fig.6 Variation of mass transfer resistance in liquid and gas-side along the tube
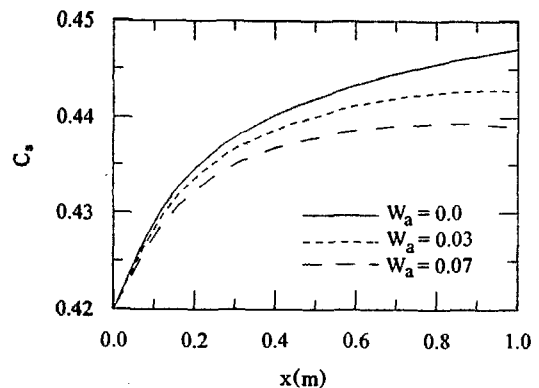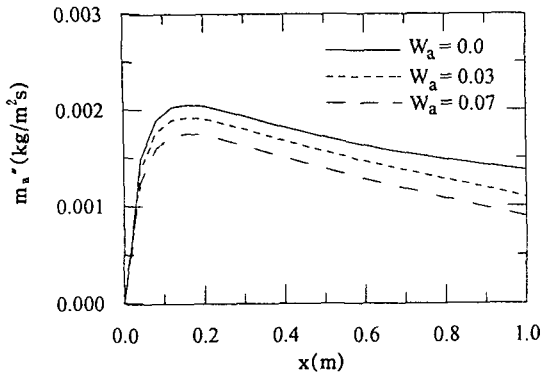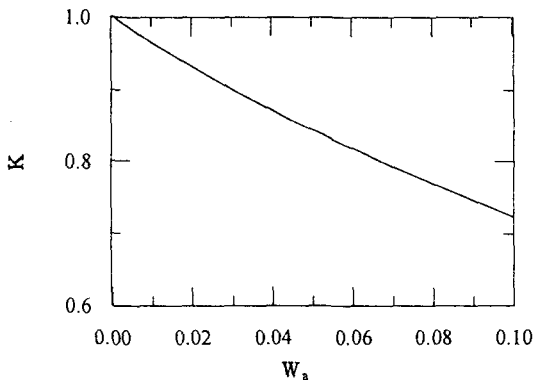

Fig.7 Effects of non-absorbable gas on the variation of interfacial equilibrium concentration of solution along the tube length

Fig.8 Effects of non-absorbable gas on the absorption rate of water vapor along the tube length

Fig.9 Effects of non-absorbable gas on the absorption ratio

creases relatively sharply as a small amount of air is introduced to the pure vapor. How-ever, with the addition of more air, the de-crease of absorption rate seems to be less dramatic. The reduction of absorption rate appears to be linear with the concentration of non-absorbable gas at higher air content in the vapor-air mixture. The overall reduction of absorption rate may reach 15% for the addition of 5% mass concentration of air to the pure water vapor in gas.

5. Conclusions

In the present work, the absorption process of water vapor into aqueous solutions of li-thium bromide in the presence of non-absor-bable gases were investigated. The continu-ity, momentum, energy and diffusion equa-tions for both the solution film and the gas phase were formulated in integral forms and solved numerically.

As the non-absorbable gas concentration in the absorbate increased, the interfacial tem-perature and concentration of absorbate in solution decreased, which resulted in the re-duction of absorption rate. The reduction of mass transfer rate was found to be relatively significant for the addition of small amount of non-absorbable gas to the pure vapor, es-pecially at the outlet of the tube where the non-absorbable gas accumulated. At higher non-absorbable gas concentration the decre-ase of absorption rate seemed to be linear with the concentration of non-absorbable gas.

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