# Effects of Non-absorbable Gases in the Absorption of Water Vapor by Aqueous LiBr Solution Film on Horizontal Tube Banks

Kyseok Kwon* and Byongjoo Kim**

**Key words:** Absorption process, Horizontal tube bank, Heat and mass transfer, Non-absorbable gases, Sherwood number ratio

## Abstract

In the present study, the effects of film Reynolds number (60~200) and volumetric content of non-absorbable gases (0~10%) in water vapor on the absorption process of aqueous LiBr solution were investigated experimentally. The formation of solution film on the horizontal tubes of six rows was observed to be complete for Re>100. Transition film Reynolds number was found to exist above which the Nusselt number and Schmidt number diminishes with solution flow rate. As the concentration of non-absorbable gases increased, mass transfer rate decreased more seriously than heat transfer rate did. The degradation effects of non-absorbable gases seemed to be significant especially when small amount of non-absorbable gases was introduced to the pure water vapor.

## Nomenclature

$A$ : Area [m$^2$]
$C$ : Mass concentration of LiBr [%]
$c_p$ : Specific heat [J/kgK]
$D$ : Mass diffusion coefficient [m$^2$/s]
$d$ : Diameter [m]
$g$ : Gravitational acceleration [m/s$^2$]
$h$ : Heat transfer coefficient [W/m$^2$K]
$k$ : Thermal conductivity [W/mK]
$L$ : Characteristic length [m]
$l$ : Tube length [m]
$\dot{m}$ : Mass flow rate [kg/s]
Nu : Nusselt number, $hL/k$
$p$ : Pressure [mmHg]
Pr : Prandtl number, $\mu c/k$
$Q$ : Heat transfer rate [W]
Re : Reynolds number, $4\Gamma/\mu$
Sh : Sherwood number, $\beta L/D$
$T$ : Temperature [℃]
$U$ : Overall heat transfer coefficient [W/m$^2$K]
$y_a$ : Volumetric concentration of air [%]

* Graduate School, Hongik University, Seoul 121-791, Korea
** Department of Mechanical and System Design Engineering, Hongik University, Seoul 121-791, Korea

## Greek symbols

$\beta$ : Mass transfer coefficient [m/s]
$\Gamma$ : Mass flow rate per unit width [kg/ms]
$\mu$ : Viscosity [Ns/m$^2$]
$\rho$ : Density [kg/m$^3$]

## Subscript

$a$ : Absorption or air
$c$ : Cooling water
$exp$ : Experiment
$f$ : Falling film
$i$ : Solution/vapor interface
$in$ : Inlet
$lm$ : Logarithmic mean
$out$ : Outlet
$pre$ : Predicted
$o$ : Without non-absorbable gases

## 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. Among the four primary heat/mass exchange units composing an absorption system, the absorber, where the refrigerant vapor is absorbed into the liquid solution, is the one least understood.

Among the numerous factors which affect the absorption process of absorbate (refrigerant vapor) into absorbent (liquid solution) in falling film absorber, non-absorbable gases seriously degrade its performance. Since the closed-type LiBr absorption system is maintained at vacuum, external ambient air may leak into the system any time. Besides, the corrosion caused by the absorbent solution on the steel structure can generate non-absorbable gases such as hydrogen. Since the interface is impermeable to the non-absorbable gases while the absorbate is absorbed at, non-absorbable gases accumulate at the interface and the concentration of non-absorbable gases 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. Burdukov et al.[1] investigated the effect of non-absorbable gases on the absorption of water vapor by aqueous LiBr solution flowing down a bundle of horizontal tubes. Their results indicated that as little as 0.5% volumetric concentration of non-absorbable gases resulted in the 50% reduction in mass transfer. The degrading effects of non-absorbable gases contents on the absorption process were also studied by Vliet and Cosenza[2] and Cosenza and Vliet[3] for the case of horizontal tube banks. They reported that if the volumetric air concentration is maintained below approximately 0.1%, its effect is less than 2% on absorption heat and mass flux. They found the diminishing effect of air content at higher film Reynolds number. Ameel and Wood[4] conducted an experiment consisting of a vertical tube over which an aqueous lithium chloride absorbent flowed in a thin film. They correlated the heat and mass transfer coefficients using the film Reynolds number, Prandtl number, Schmidt number, and air concentration. Yang and Wood[5] investigated the effects of non-absorbable gases on absorption for the vertical-tube $LiCl-H_2O$ system experimentally. Their results showed the transfer rates decreased significantly with increasing air content. The decreasing rate was much more prominent in lower solution flow rates. Heat transfer rate was also decreased. Yang and Jou[6] investigated numerically the effects of non-absorbable gases on the absorption process by the wavy falling film. Kim and Lee[7] studied the absorption of water vapor by the LiBr solution film on the inside of vertical tube experimentally. The degradation effects of the non-absorbable gases were very significant especially in the lower volumetric concentration of non-absorbable gases.

In the present work, the absorption process of water vapor into aqueous solution of lithium bromide flowing over the horizontal tubes was investigated experimentally in the presence of non-absorbable gases. The effects of non-absorbable gases on heat and mass transfer coefficients were investigated as a function of film Reynolds number. The aim is to understand the role of non-absorbable gases and quantify its degrading effects on the heat and mass transfer coefficients.

## 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 rows 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 by the temperature controller (PID control) for screw plug heaters and manually for the band heater.

The solution tank is a recovery tank of weak 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.

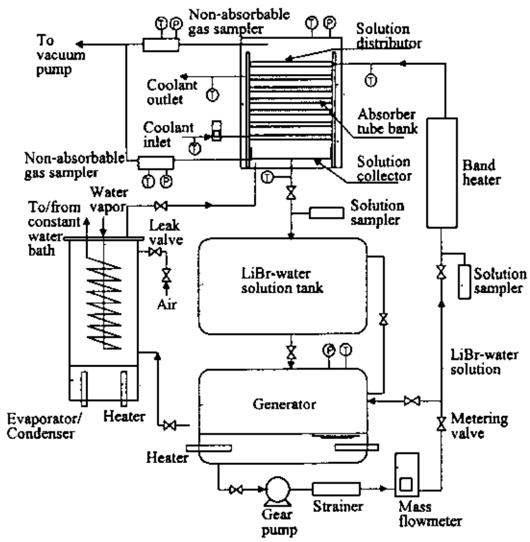


**Fig. 1** Experimental setup for the absorption process of water vapor into aqueous LiBr solution film.

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 and constant water bath to maintain the required absorber pressure. Evaporator also functions as a condenser by the cooling coil suspended inside of evaporator for the regeneration of solution. The cooling water required for the condensation of water vapor during the generation stage is supplied by the constant water bath.

Absorber tank is a cylindrical vessel which contains solution distributor, absorber tubes, and solution collector. Absorber tubes of 6 rows, which are made of smooth phosphorous bronze, have a 22.0 mm outer diameter with length of 100 mm. The absorption of water vapor takes place at the outer wetted surface of tubes. The heat of absorption is removed by the flow of cooling water inside the absorber tubes. At the top of the absorber tubes solution distributor are located to distribute the LiBr solution evenly on the absorber tube. The formation of falling film and film structure can be observed through the view port located at the front and rear of the absorber. The water vapor with non-absorbable gases, which is air for the present studies, for the absorption process is also supplied into the bottom of the absorber tank from the evaporator. The vapor flows upward, countercurrently with the LiBr solution, across the absorber tubes for a complete absorption. The diluted solution after absorption process is then collected at the solution collector located at the bottom of the absorber tubes.

## 2.2 Test procedure

At the start of absorption mode, the concentration and the temperature of solution in the generator were adjusted first and then the solution was fed into the absorber by a magnetic gear pump. The flow rate of solution into the absorber was controlled manually by the metering valve. Leak valve for air was installed at the outlet of evaporator to adjust its volumetric concentration. 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. In a constant vacuuming the flow rate out of the absorber was kept as small as possible to minimize the convection effects of gases flow on the heat and mass transfer of falling film, but large enough to prevent the accumulation of air near the top of the absorber tank. The coolant flow rate was measured by a rotameter with built-in flow-control valve, and the coolant temperature was controlled by an on-line coolant heater. When the remaining solution was insufficient to continue the experiment the system changes to a 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 functions as a condenser to condense the water vapor.

The flow rate of solution fed into the absorber was measured by a mass flowmeter. Solution at the inlet and outlet of the absorber tank was sampled by the pre-evacuated samplers for the measurement of concentration. The concentration of LiBr-water solution was measured by a pycnometer (25 ml) precisely at constant temperature of 30℃. The pressures of the evaporator and generator were measured by the convection-type vacuum gauge which gives the reading calibrated for air. They have been calibrated with direct readings of a capacitance type vacuum gauge installed at the top of the absorber. Type T thermocouples were located at the absorber inlet and outlet, at the cooling water inlet and outlet, at the evaporator, and at the generator.

Many conventional absorption systems use lithium-bromide concentration less than 60% to protect the absorption process from crystallization. The inlet concentration was chosen to be 58% since solution has a relatively high driving potential for absorption and crystalli-

**Table 1** Range of experimental conditions

| | Parameters | Range |
|---|---|---|
| Absorption tube | Outer diameter [mm] | 22 |
| | Length [mm] | 100 |
| | Pressure [mmHg] | 8.0 |
| Coolant | Temperature [℃] | 30 |
| | Flow rate [l/min] | 0.8 |
| LiBr-water solution | Temperature [℃] | 40 |
| | Flow rate [kg/min] | 0.4~1.5 (Re=60~200) |
| | Concentration (%) | 58 |
| Air | Volumetric Concentration (%) | 0~10 |

zation is not of concerns at this concentration. The experimental conditions including the absorber pressure, temperature and the flow rate of solution and coolant are summarized in Table 1.

## 2.3 Heat and mass transfer in falling film

The heat transfer rate to the coolant in the absorption process can be estimated by Eq. (1).

$$Q = \dot{m}_c c_{p,c}(T_{c,out} - T_{c,in}) = UA\Delta T_{lm} \quad (1)$$

where $\dot{m}_c$ is coolant flow rate and $c_{p,c}$ is the specific heat at constant pressure. $U$ and $A$ are overall heat transfer coefficient and heat transfer area. Subscripts $c$, $in$, and $out$ denote the coolant, the inlet, and outlet of absorber, respectively. The logarithmic mean temperature difference is defined as

$$\Delta T_{lm} = \frac{(T_{f,in} - T_{c,out}) - (T_{f,out} - T_{c,in})}{\ln \frac{T_{f,in} - T_{c,out}}{T_{f,out} - T_{c,in}}} \quad (2)$$

where subscript $f$ denotes the LiBr solution film. The heat transfer coefficient of the falling film can be evaluated by Eq. (3).

$$\frac{1}{h_f A_f} = \frac{1}{UA} - \frac{1}{h_c A_c} - \ln\left(\frac{r_f}{r_c}\right)/2\pi kl \quad (3)$$

where $k$ is the thermal conductivity of tube, $l$ is the length of absorber, and $r_f$ and $r_c$ are the outer and inner radius of absorber tube.

Nusselt number for the falling film during the absorption process is defined as

$$\mathrm{Nu} = \frac{h_f L_f}{k_f} \quad (4)$$

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

$$L_f = \left(\frac{\mu_f^2}{\rho_f^2 g}\right)^{1/3} \quad (5)$$

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

$$\mathrm{Re}_f = \frac{4\Gamma}{\mu_f} \quad (6)$$

where $\Gamma$ is the mass flow rate per perimeter of absorber and $\mu$ is the kinematic viscosity.

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

$$\dot{m}_a = \dot{m}_f\left(\frac{C_{in}}{C_{out}} - 1\right) \quad (7)$$

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 true mean mass concentration difference of water in solution between the vapor/liquid interface and the bulk in a falling film can be defined as the logarithmic density difference.

$$\Delta\rho_{lm} = \frac{(\rho_{i,in} - \rho_{in}) - (\rho_{i,out} - \rho_{out})}{\ln \frac{\rho_{i,in} - \rho_{in}}{\rho_{i,out} - \rho_{out}}} \quad (8)$$

Mass transfer coefficient of falling film could be expressed as Eq. (9).

$$\beta_f = \frac{\dot{m}_a}{\Delta\rho_{lm} A} \quad (9)$$

Then the Sherwood number is defined by

$$Sh = \frac{\beta_f L_f}{D_f} \tag{10}$$

where $D_f$ is the mass diffusivity of solution.

The volumetric concentrations of air at the inlet and the outlet of the absorber tank were measured by a "freezing method".[4] A stainless steel bottle of sampler containing water vapor-air mixtures taken during the steady state of absorption process was immersed into the dry ice bath. The mixtures were frozen down to −60℃, at which the partial pressure of water vapor should be small enough that the total pressure was that of air itself. For the temperature and pressure of $T_1$ and $p_1$ for the water vapor-air mixtures before freezing and $T_2$ and $p_2$ after freezing, the volumetric concentration of air was evaluated by assuming the ideal gases behavior.

$$y_a = \frac{p_2 T_1}{p_1 T_2} \tag{11}$$

## 3. Results and discussion

Since the major purpose of the present study was to identity the effects of non-absorbable gases on the heat and mass transfer in the absorption process, all the factors except liquid solution flow rate and the volumetric concentration of air were kept constant.

Solution flow rate was varied in the range of 60 to 200 of film Reynolds number. In this range falling film can be characterized as "wavy laminar". In the present studies, even at the lowest mass flow rate, the inception of circumferential wave was found as the solution flowed over the horizontal absorber tubes. However, below the film Reynolds number of 120, the formation of the solution film on the outer surface of entire 6 tubes was not complete. Local surface area of $5^{th}$ and $6^{th}$ tubes near the both ends was wetted periodically by the solution film and the wetted area fraction was somewhat unpredictable.

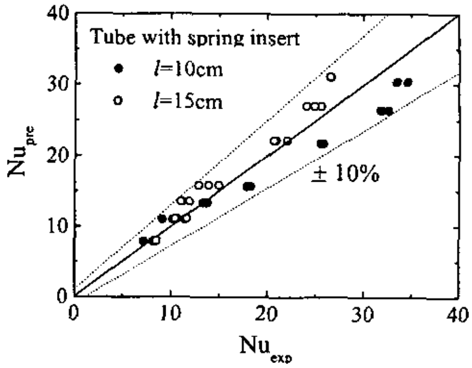


**Fig. 2** Comprison of experimental data with prediction for the heat transfer coefficient of coolant.

In order to estimate film heat transfer coefficient, the heat transfer coefficient of coolant in the absorber tube should be given. Heat transfer coefficient of coolant, water, was evaluated from another set of experiments which accounted for the effect of entrance region. By the regression of experimental data, the Nusselt number for the coolant flow in tube was correlated by Eq. (12).

$$Nu_c = 0.35 Re_c^{0.475} Pr_c^{0.33} (d/l)^{0.015} \tag{12}$$

where $d$ and $l$ are the diameter and length of absorber tube, respectively. The correlation showed mean deviation of 15% in the range of $300 < Re_c < 1500$ and $0.1\ m < l < 0.2\ m$.

Fig. 3 and Fig. 4 show the variation of average heat flux removed from absorber and the corresponding Nusselt number of solution film during absorption process. They are shown as a function of film Reynolds numbers at different volumetric concentration of air. The heat flux increases at lower Reynolds number but decreases at higher Reynolds number regardless of air content. Since the coolant heat transfer coefficient remains almost the same, Nusselt number shows similar trends as heat

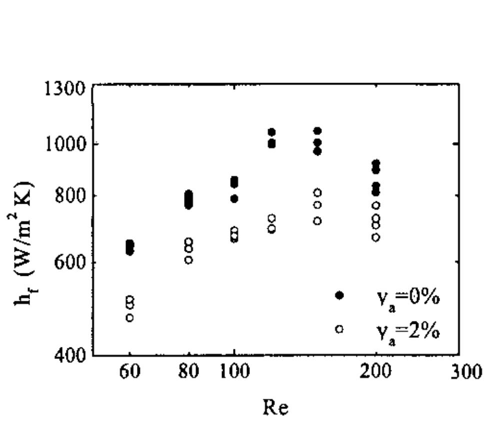


**Fig. 3** Effects of film Reynolds number on heat transfer coefficient.

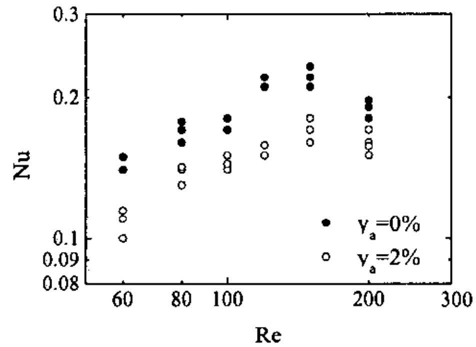


**Fig. 4** Effects of film Reynolds number on Nusselt number.

flux does. The variation of heat transfer characteristics of the solution film suggests that critical film Reynolds number,[8] which is around 150, exists for maximum heat transfer. At the film Reynolds number lower than 120, it is pretty possible that the surface of absorber tubes is not completely wet by the solution film, which may cause the reduced Nusselt number. As the solution flow rate increases, the improved wetting of the surface leads to higher heat transfer rate. Even the formation of wave on the film surface may enhance the heat transfer. The solution film structure should be governed by the absorber geometry and by the technique involved in the formation of solution film. For instance, smaller absorber diameter may cause higher wetted area fraction and lead to the inception of interfacial wave even at lower flow rate of solution and enhance the heat transfer. Meanwhile the increased solution flow rate results in the increase of film thickness, which acts as a 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 minimum value of the volumetric concentration of non-absorbable gases obtained in the present study was about 0.1% even the absorber was operated with a mechanical vacuum pump continuously removing the air accumulated in the absorber. The addition of air up to 2% to water vapor retarded heat flux and the Nusselt number seriously, as much as 25% at Re=150. As non-absorbable gases accumulate at the interface as a result of the absorption of water vapor, the concentration of non-absorbable gases at the interface becomes greater than that in the bulk of gases. Then the partial pressure of water vapor at the interface decreases and the driving pressure difference for mass transfer reduces. Once the non-absorbable gases inhibit the absorption of water vapor at the liquid-gases interface, the heat of absorption to be released would be very limited. Then the temperature gradient in the solution film could not develop, which results in the decreased heat transfer rate to the coolant.

The effect of film Reynolds number on the absorption mass flux and the Sherwood number are shown in Fig. 5 and Fig. 6 at different volumetric concentration of air. Fig. 6 shows the increase of Sherwood number with film Reynolds number at lower film Reynolds number up to 150, which seems to be the optimum film Reynolds number for the maximum mass transfer in the present studies. The analogies

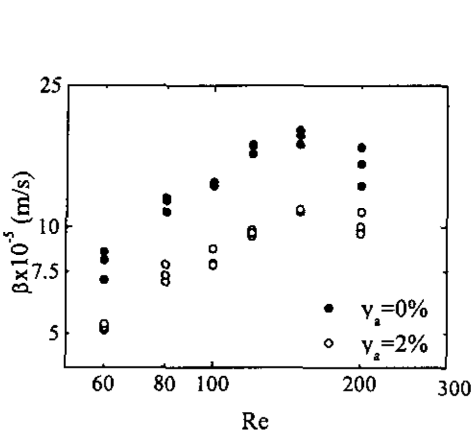


**Fig. 5** Effect of film Reynolds number on mass transfer coefficient.

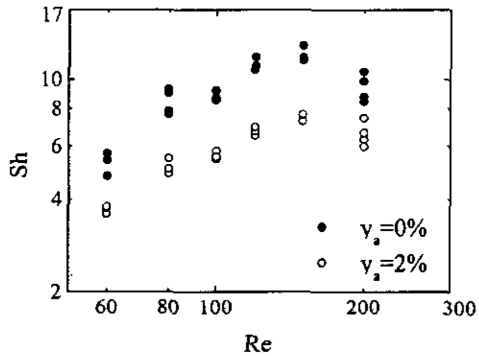


**Fig. 6** Effects of film Reynolds number on Sherwood number.

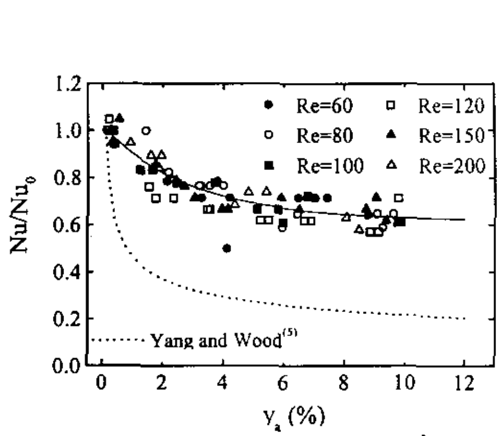


**Fig. 7** Effects of non-absorbable gases on the Nusselt number ratio.

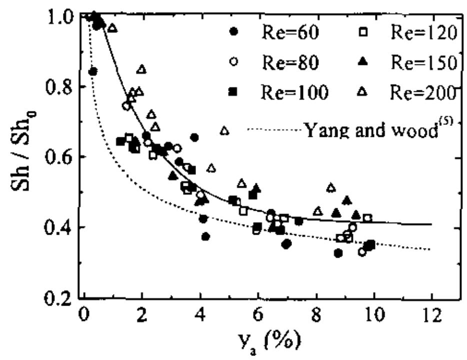


**Fig. 8** Effects of non-absorbable gases on the Sherwood number ratio.

between heat and mass transfer during the absorption process could be confirmed by comparing Fig. 4 to Fig. 6 qualitatively. The decrease of Sherwood number with the volumetric concentration of air seems to be significant when the air content is increased from 0.1% to 2.0%, where the Sherwood number decreases by 40% at Re=150.

The effects of volumetric concentration of air on the Nusselt and Sherwood number are shown in Fig. 7 and Fig. 8. $Nu/Nu_0$, Nusselt number ratio, is the ratio between the Nusselt number in the absorption process with non-absorbable gases and that with pure vapor. As mentioned earlier the Nusselt number without non-absorbable gases was not obtainable in the present study. Therefore it was extrapolated from the experimental data for each case of film Reynolds number. As the volumetric concentration of air increases Nusselt number decreases drastically. The decrease of Nusselt number seems to be more significant especially when small amount of air is present to pure water vapor as Yang and Wood[5] reported. Meanwhile the decrease of Sherwood number is more serious than the Nusselt number. Nusselt number decreases by 13% as 1% of non-absorbable gases are added to pure water vapor. The reduction of Sherwood number is as much as 26% by the addition of 1% air and 47% at 3.0% air. In Fig. 8, It could be noticed more or less that the reduction of mass transfer with non-absorbable gases is retarded at higher solution flow rate.[4] As the solution flow rate increases the wave amplitude of falling film increases and the wave patterns become more irregular. The interaction between the vapor and the fluctuating liquid surface will perturb the vapor layer near the interface, resulting in convection transport away from the interface. The disturbance at the interface reduces the local air concentration, allowing more absorbate mass transfer to occur. However, since the uncertainties for the Sherwood number is 7.5%, it is very hard to verify the effects of the film Reynolds number on the mass transfer in conjunction with the content of non-absorbable gases.

## 4. Conclusions

In the present studies, absorption processes of water vapor into lithium bromide-water solution film on the horizontal tubes were studied experimentally. The effects of non-absorbable gases on heat and mass transfer coefficient were measured as a function of film Reynolds number in the range of 60～200. The volumetric concentration of air was varied from 0.1 to 10%

Some conclusions obtained from the present experiments are as follows.

(1) Non-absorbable gases reduce mass transfer rate significantly as much as 25% by the addition of 1% air to the pure water vapor.

(2) The retarding effect of non-absorbable gases on the heat transfer is not so serious as on the mass transfer.

(3) Optimum film Reynolds number, approximately 150 for the horizontal tubes, exists for maximum heat and mass transfer, regardless of the volumetric concentration of non-absorbable gases.

## References


1. Burdukov, A. P., Bufetov, N. S., Deriy, N. P., Dorokhov, A. R. and Kazakov, V. I., 1980, Experimental study of the absorption of water vapor by thin films of aqueous lithium bromide, Heat Transfer-Soviet Research, Vol. 12, pp. 118-123.
2. Vliet, G. C. and Cosenza, F. B., 1992, Absorption phenomena in water-lithium bromide films, Proc. Absorption Heat Pump Conf., pp. 53-61.
3. Cosenza, F. B. and Vliet, G. C., 1990, Absorption in falling water/LiBr films on horizontal tubes, ASHRAE Transactions, Vol. 96, Part I, pp. 693-701.
4. Ameel, T. A. and Wood, B. D., 1992, Non-absorbable gas effects on heat and mass transfer in wavy laminar falling film absorption, Solar Engineering, Vol. 1, ASME, pp. 219-228.
5. Yang, R. and Wood, B. D., 1993, Experimental study for heat and mass transfer in wavy film absorption with the presence of non-absorbable gases, Chem. Eng. Comm., Vol. 125, pp. 77-90.
6. Yang, R. and Jou, T., 1998, Non-absorbable gas effect on the wavy film absorption process, Int, Journal of Heat and Mass transfer, Vol. 41, pp. 3647-3668.
7. Kim, B. J. and Lee, C. W., 1998, Effects of non-absorbable gases on the absorption process of LiBr solution film in vertical tube: (1) Experimental study, J of KSME(B), Vol. 22, No. 4, pp. 489-498.
8. Hikita, H., Nakanishi, K. and Kataoka, T., 1959, Liquid phase mass transfer in wetted-wall columns, Chem. Eng., Tokyo, Vol. 23, No. 7, pp. 459-466.