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Absorption of Water Vapor into Wavy-Laminar Falling Film of Aqueous Lithium-Bromide

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Absorption processes of water vapor into lithium bromide-water solution film inside a vertical tube were studied experimentally. The heat and mass transfer coefficients were measured as a function of film Reynolds number in the range of 30~200. The variables considered were system pressure, coolant and solution temperatures whose differences were kept constant. Optimum film Reynolds number was found to exist for a maximun heat and mass transfer.

Key Words: Absorption Process, LiBr-Water Solution, Wavy-Laminar Falling Film, Heat and Mass Transfer

Nomenclature

A : Heat transfer area (m^2)
C_p : Specific heat at constant pressure (J/kgK)
c : Mass concentration of LiBr in solution (%)
D : Mass diffusion coefficients (m^2/s)
g : Gravitational acceleration (m/s^2)
Ga : Galileo number $=(z/L)^3$
h : Convective heat transfer coefficient (W/m^2K)
k : Thermal conductivity (W/mK)
L : Characteristic length (m) $=(\mu^2/\rho^2 g)^{1/3}$
$\dot{m}$: Mass flowrate (kg/s)
Nu : Nusselt number $=hL/k$
Q : Heat transfer rate (W)
$\dot{q}$: Heat flux (W/m^2)
Re : Film Reynolds Number $=4\Gamma/\mu$
Sc : Schmidt number $=\nu/D$
Sh : Sherwood number $=\beta L/D$
T : Temperature (K)
ΔT : Temperature difference (K)
U : Overall heat transfer coefficient (W/m^2K)
z : Absorber length (m)
β : Average mass transfer coefficient (m/s)
Γ : Mass flux (kg/ms)
δ : Film thickness (m) $=(3\mu\Gamma/\rho^2 g)^{1/3}$
μ : Viscosity (Pa s)
ν : Kinematic viscosity (m^2/s)
ρ : Density (kg/m^3)
σ : Surface tension (N/m)
ξ : Mass concentration of water in solution (kg/m^3)

Subscript

a : Absorption
c : Coolant
i : Interface
in : Incoming
lm : Logarithmic mean
out : Outgoing
s : LiBr-Water solution
w : Absorber tube wall

1. Introduction

Absorption of gases and vapors into liquid films is encountered in numerous applications including the creation of heating and cooling effects in absorption heat pumps. An absorption cycle is a thermodynamic engine, driven by thermal energy. This cycle forms an alternative ways of refrigeration to a motor-driven vapor compression cycle.

Among the four primary heat/mass exchange

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units composing an absorption system, the absorber, where the refrigerant vapor is absorbed into the liquid solution, is the one least understood. From the viewpoint of refrigeration cycles, a large concentration change in an absorber and a large absorption rate are regarded as important factors for achieving a higher coefficient of performance. It is therefore essential to acquire a fundamental and quantitative understanding of the combined heat and mass transfer process taking place in an absorption process.

Among the different types of gas-liquid solution contactors, liquid solution film absorbers are of particular interest. In contrast with sprays of packed towers, the film absorber makes it possible to transfer heat into or out of the solutions during the absorption process through the wetted solid surface supporting the film. Although falling-film type absorption is in the heart of an absorption system that has been used for several years, fundamental data and correlations for design purposes are seldom found in the open literature.

Morioka et al.(1991) performed experimental study on the absorption of water vapor into a lithium bromide-water solution film falling outside a vertical tube and analysed the effects of system pressure and coolant temperature. They proposed the optimum thickness of solution film for a maximum mass transfer rate. For the application to an air-cooled absorption systems, Ohm and Kashiwagi(1993) conducted experiments for the falling film inside a vertical tube and explained the effects of temperature and flowrates of solution and coolant, respectively.

The degrading effects of non-absorbale gas contents during an absorption process were studied by Yang and Wood(1988) for the films flowing outside the vertical tube and by Vliet and Cosenza(1992) for the case of horizontal tube banks. The decreasing rate of absorption with air concentration was found to be much more prominent in lower solution flow rates.

The promotion of absorption by enhanced surfaces was investigated by Hijikata et al.(1992) for externally finned tube and tube with the ridged fins. Even though the increase of heat transfer was remarkable, the mass transfer did not seem to be much affected.

For improving performance, generation of interfacial turbulence by adding surface active agents to the solution is effective. Absorption characteristics of LiBr-water solution with 2-ethyl-1-hexanol as an additive were studied for the falling film on a flat plate(Kashiwagi et al., 1991), for films flowing over horizontal tubes (Cosenza and Vliet, 1990), and for the films ouside the vertical tube(Kim et al., 1994).

Even though many experimental works were performed, the results and physical interpretation of the phenomena are not fully consistent and partly contradictory. The understanding of the mechanism about the heat and mass transfer in a falling film type absorber does not seem to be well established yet. There is a strong need to establish better correlations for heat and mass transfer for the variety of conditions and geometries of interests.

In the present research, processes of heat and mass transfer are experimentally investigated for the water vapor absorption into aqueous solutions of lithium bromide flowing inside the vertical tube. The aim is to understand the effect of flow conditions represented by Reynolds numbers and to clarify the validity of available correlations on the heat and mass transfer during an absorption process.

2. Experimental Investigations

2.1 Experimental apparatus and test method

The working fluid for the absorption experiment is lithium bromide and water solution. Lithium bromide is an absorbent and water is an absorbate. Aqueous solutions of lithium bromide flow inside a vertical tube which absorbs water vapor. Figure 1 schematically shows the experimental setup, which consists of an absorber, an absorbent solution generator, a solution tank, an evaporator, and a cooling system. The experimental equipment is designed for a batch mode operation.

Generator The generator is a strong solution tank whose volume is 65 liters and is well sealed

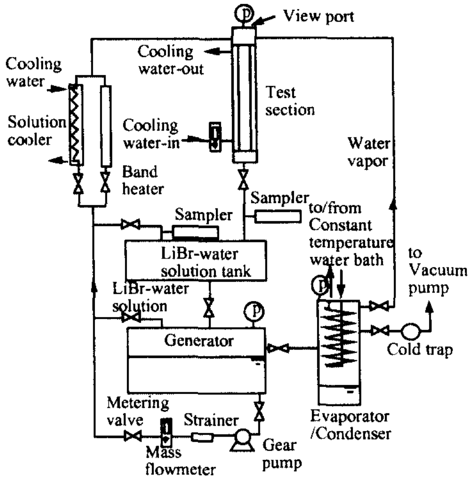

Fig. 1 Schematic diagram of experimental setup

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 the inlet solution is controlled by the temperature controller (PID control) and screw plug heaters, and a heat exchanger where the heating element is wrapped around the tubes. The solution can also be cooled by tap water with a single pass shell-and-tube type heat exchanger.

Solution tank The solution tank is a recovery tank of weak solution, which can hold 40 liters. The solution tank simply collects the diluted solution during the absorption experiments and is located at the downstream position of the absorber.

Evaporator In order to supply water vapor into the absorber, cylindrical vessel (diameter 100 mm, height 300 mm) equipped with four immersion heaters is used as an evaporator. The evaporator temperature is controlled by a power supply unit and constant water bath to maintain the required absorber pressure. Distilled water that is used as the absorbate can be deaerated during the initial evacuation by a vacuum pump before each experiment. 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 Absorber consists of an upper header, an absorber tube, and a lower header. Absorber tube, which is made of smooth stainless steel, has a 13.3 mm inner diameter with thickness and length of 1.3 mm and 800 mm, respectively. The absorption of water vapor takes place at the inner wetted surface of tube. The heat of absorption is removed by the upward flow of cooling water outside the absorber tube. The outer acrylic tube, inner diameter of 25 mm and length of 740 mm, serves to form the annular flow passage for cooling water. As the solution flows into the absorber, it first stays in the upper header. Then the solution overflows inside of the absorber tube and forms the falling film along the tube. The formation of falling film and the film structure can be observed through the view port located at the top of the upper header. The water vapor for the absorption process is also supplied into the upper header from the evaporator. The vapor flows downward inside the absorber tube for a complete absorption. The diluted solution after absorption process is then collected at the lower header. The temperatures of tube wall are measured by the 6 embedded T-type thermocouples.

Experimental method At the start of absorption mode, the concentration of lithium bromide and the temperature of the solution in the generator are adjusted to specified values, and the solution is fed to the absorber by a magnetic gear pump. The flowrate of solution into the absorber is controlled manually by the metering valve and is measured by the mass flowmeter. The water vapor is generated from the evaporator, which is heated by electric immersion heaters, and is entirely absorbed into the lithium bromide solution in the absorber. The coolant flowrate is measured by a rotameter with built-in flow-control valve, and the coolant temperature is controlled by an on-line coolant heater. When the remaining solution is insufficient to continue the experiment the system changes to a regeneration mode. The diluted solution collected in the solution tank is fed to the generator, and regenerated by the heaters. In this mode, the evaporator functions as a condenser for condensing the water vapor generated during the regeneration stage.

Measuring devices The flowrate of solution fed into the absorber is measured by a mass flowmeter. Solutions at the inlet and outlet of the absorber tube are sampled by the pre-evacuated samplers for the measurement of solution concentration. The concentration of LiBr-water solution is measured by a densimeter roughly and with pycnometer (25 ml) more precisely at constant temperature bath of 30℃. The pressures at the evaporator and generator are measured by the convection-type vacuum gauge which gives the reading calibrated for air. They have been calibrated with direct readings of a McLeod gauge and capacitance type vacuum gauge installed at the top of the absorber. Type T thermocouples are located at the absorber inlet and outlet, the cooling water inlet and outlet, the evaporator, the generator, and the absorber tube wall.

Experimental conditions Many conventional absorption systems use lithium-bromide concentration less than 60% to protect the absorption process from crystallization. The inlet concentraion was chosen to be 58% since solution has a relatively high driving potential for absorption and crystallization is not of concerns at this concentration.

The experimental conditions including the absorber pressure, temperature and flowrate of solution and coolant are summarized in Table 1. The subcooled solutions at 40℃ which are independent of the absorber pressure, and the superheated solutions at about 1℃ higher than the equilibrium temperature corresponding to absorber pressure were generated. However, the temperature difference between the solution and the coolant were kept constant at 10℃ in all the experiments.

Table 1 Range of experimental conditions

	Parameter	Range
Absorption tube	Inner Diameter (mm)	13.3
	Length (mm)	800
	Pressure (mmHg)	7.0, 8.0, 9.2
Coolant	Temperature (℃)	30∼36
	Flowrate (l/min)	0.8
LiBr-Water Solution	Temperature (℃)	40∼46
	Flowrate (kg/min)	0.1∼0.6 (Re=30∼200)
	Concentration (%)	58

2.2 Evaluation of heat and mass transfer coefficients

Film absorption normally involves simultaneous heat and mass transfer in the gas-liquid system. The heat of absorption gives rise to temperature gradients leading to the transfer of heat as shown in Fig. 2 and the temperature of the absorber influences the pressure-composition equilibrium between the two phases which affects the mass transfer.

The heat transfer rate to the coolant in the absorption process can be estimated with the coolant mass flowrate and temperature rise of coolant between the inlet and outlet of absorber as given in Eq. (1).

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

The logarithmic mean temperature difference is defined as

$$\Delta T_{lm} = \frac{(T_{s,in} - T_{c,out}) - (T_{s,out} - T_{c,in})}{ln\left(\frac{T_{s,in} - T_{c,out}}{T_{s,out} - T_{c,in}}\right)}. \qquad (2)$$

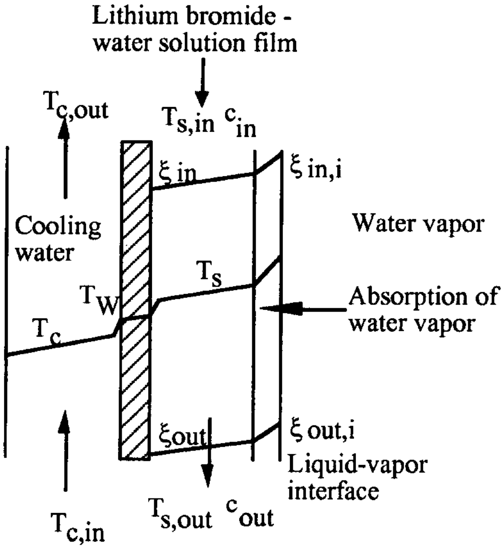

Fig. 2 Physical model of an absorption process

When the absorber wall temperature is known, convective heat transfer coefficient of the falling film can be evaluated by the following Eq. (3).

$$h_s=\frac{Q}{A(\bar{T}_s-\bar{T}_w)} \tag{3}$$

where $\bar{T}_s$ and $\bar{T}_w$ are the average temperature of solution and absorber wall respectively.

Nusselt number for the heat transfer during the absorption process is defined as

$$Nu=\frac{h_sL_s}{k_s} \tag{4}$$

where the characteristic length is given by

$$L_s=\left[\frac{\mu_s^2}{\rho_s^2g}\right]^{1/3}. \tag{5}$$

Generally Nusselt number is correlated as a function of film Reynolds number.

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

$$\dot{m}_a=\dot{m}_s\left[\frac{C_{in}}{C_{out}}-1\right]. \tag{6}$$

The vapor/liquid interface of the falling film is in a thermodynamic equilibrium at a given pressure and temperature of the solution in the absorber. The logarithmic mean mass concentration difference of water in solution between the vapor/liquid interface and the bulk in a falling film can be defined as

$$\Delta\xi=\frac{(\xi_{in,i}-\xi_{in})-(\xi_{out,i}-\xi_{out})}{ln\left(\frac{\xi_{in,i}-\xi_{in}}{\xi_{out,i}-\xi_{out}}\right)}. \tag{7}$$

The mass transfer coefficient in the absorption process is expressed by using the definition in Eq. (7) as

$$\beta=\frac{\dot{m}_a}{\Delta\xi A}. \tag{8}$$

The Sherwood number for the mass transfer coefficients is defined as in Eq. (9).

$$Sh=\frac{\beta L_s}{D_s}. \tag{9}$$

3. Results and Discussions

The heat and mass transfer in the falling liquid film depends on the flowrate and transport properties of the solution. Other parameters which influence the mass transfer are the inlet solution temperature, the cooling water temperature, the inlet solution concentration, the cooling water flowrate, the absorber pressure, and the non-absorbable gas contents. Among them the effects of absorber pressure and the solution flowrate on the heat and mass transfer for the falling film inside a vertical tube were studied.

The absorber pressure was varied by changing the temperature in the evaporator, which gave the similar effects as changing the inlet solution concentration and/or coolant temperature. Solution flowrates were varied in the range of 30 to 200 of liquid film Reynolds number. In this range the flow can be characterized as "laminar or wavy laminar"(Sherwood and Pigford, 1952). In the present studies, even at the low mass flowrate, the inception of the circumferential wave was found as the solution overflows into the vertical absorber tube. The wave amplitude seemed to increase with the solution mass flowrate, but was not directly proportional to it.

Figure 3 shows the variation of average heat flux removed from the absorber tube during the absorption process. Heat flux is shown as a function of film mass flux at different absorber pressure. As solution flowrate increases the heat flux increases slightly up to a certain film flowrate, beyond which heat flux is constant or even decreases.

The increase in the heat flux can be noticed as absorber pressure increases when the solution is subcooled at 40℃. Since the solution temperature

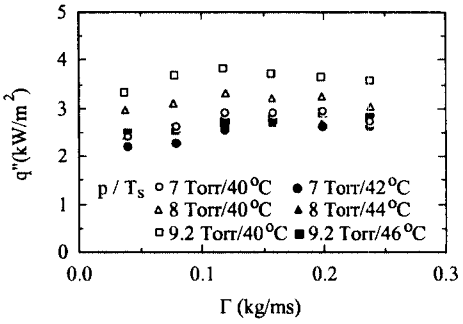

Fig. 3 Effects of solution mass flux on the heat flux at various absorber pressures

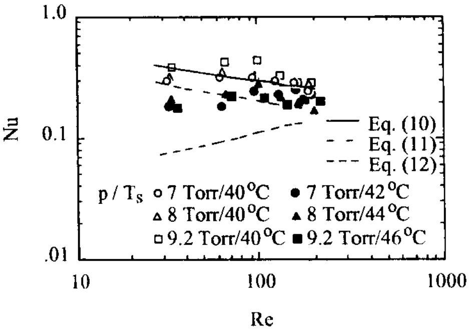

Fig. 4 Effects of film Reynolds number on the Nusselt number at various absorber pressures

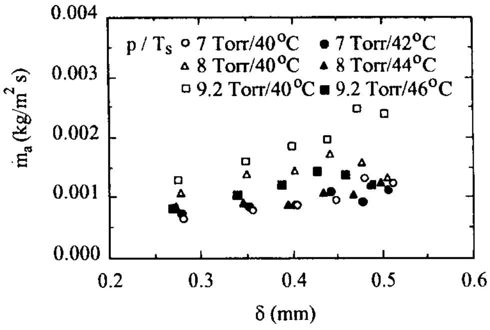

Fig. 5 Effects of solution film thickness on the absorption rate at various absorber pressures

were kept constant at 40℃, the degree of subcooling of the solution increases with absorber pressure and so does the driving potential for the absorption and the heat transfer. However, when the solution is superheated, the heat transfer rates were almost the same regardless of the absorber pressure. In the experiments the cooling capacity of the cooling water was relatively small compared to the actual absorption system the outlet solution temperature was found to be even greater than the inlet solution temperature when the absorber pressure was 9.2 mmHg.

Since the absorber wall temperature was measured, Nusselt number for the heat transfer of the solution film was calculated from Eqs. (3) and (4) directly and given in Fig. 4. As the film Reymolds number increases Nusselt number increases slightly in lower film Reynolds number, ($Re=30-100$), beyond which Nusselt number decreases regardless of the absorber pressure. The inflection of Nusselt number at a certain Reynolds number can be noticed whether the solution is subcooled or superheated.

The heat transfer characteristics of falling film as a function of film Reynolds number was presented by many investigators. Chun and Seban (1971) prpoposed

$$Nu=0.822Re^{-0.22} \tag{10}$$

Ohm and Kashiwagi(1993) correlated their experimental data as

$$Nu=0.934Re^{-0.25}\left(\frac{T_s}{T_c}\right)^{-1.3} \tag{11}$$

for the subcooled soliution, and

$$Nu=0.0176Re^{0.36}\left(\frac{T_s}{T_c}\right)^{0.6} \tag{12}$$

for the superheated solution. However, the existence of optimum film Reynolds number for heat transfer was not proposed in the open literature yet. Present works show higher Nusselt number than that presented by Ohm and Kashiwagi (1993) for the whole range of film Reynolds number considered. Chun and Seban's correlation (1971) shows higher Nusselt number than Ohm and Kashiwagi's, and is closer to the present works.

As easily noticed in Fig. 4, some experimental results are very contradictory to each other particularly at low film Reynolds number. This discrepancy could be understood as the effects of film sturcture, smooth or wavy. For the falling film of solution inside the vertical tube, the film flow pattern is hard to observe. The solution film structure should be governed by the absorber geometries and by the technique involved in the formation of solution film. For instance, smaller absorber diameter may cause inception of interfacial wave even at a low flowrate of solution and enhance the heat transfer characteristics even at low film Reynolds number.

The effects of absorber pressure on the absorption rate is depicted in Fig. 5 as a function film thickness. Solution film thickness was estimated by the following Eq. (13) (Bird et al., 1960).

$$\delta=\left[\frac{3\mu_s\Gamma}{\rho_s^2 g}\right]^{1/3}. \tag{13}$$

As the film thickness increases the absorption rate increases up to a certain point. In this range, absorber pressure affects the absorption rate remarkably, about twice higher absorption rate at 9.2 mmHg than at 7 mmHg when the solution is subcooled. This can be understood on the same basis as explained in the previous case of heat flux. Beyond the critical film thickness, the absorption rate decreases with film thickness. Thicker film with wave of relatively smaller amplitude could retard heat removal rate to the cooling water and result in a smaller mass transfer. The critical film thickness for the inflection point of absorption rate is about 0.45 mm. Superheated solution shows lower absorption rate due to smaller mass concentration differences.

Sherwood number for the mass transfer can be calculated from the mass transfer coefficient, Eq. (9). Figure 6 shows the effects of film Reynolds number on the Sherwood number for the subcooled solution only. Even though the data seems to be scattered, they shows the increase of Sherwood number with film Reynolds number at low solution flowrate. When the film Reynolds number is greater than 130, Sherwood number decreases with film Reynolds number. The analogies between heat and mass transfer during the absorption process could be confirmed by comparing Fig. 6 to Fig. 4 qualitatively.

Hikita et al.(1959) proposed the following correlation for the Sherwood number, which has inflective characteristics in the absorption rate.

$$Sh=\left(\frac{100}{C_{out}}\right)Sc\left(\frac{Re}{4}\right)L_s\left(\frac{1}{W}\right) \tag{14}$$

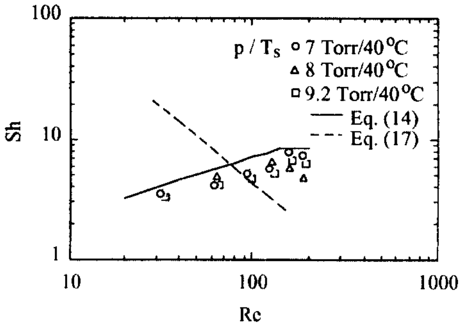

Fig. 6 Effects of film Reynolds number on the Sherwood number at various absorber pressures

where

$$W=22.8L_sRe^{0.5}Sc^{0.38}Ga^{0.44}\left(\frac{\sigma_s}{0.072}\right)^{0.15}$$

$$\text{for } Re<Re_c \tag{15}$$

$$W=2.36L_sRe^{1.0}Sc^{0.5}$$

$$\text{for } Re>Re_c \tag{16}$$

and critical Reynolds number is given as

$$Re_c=93.3Sc^{-0.24}Ga^{0.08}\left(\frac{\sigma_s}{0.072}\right)^{0.3}. \tag{17}$$

The critical film Reynolds number estimated by Eq. (17) was 135 for the present experiments. Ohm and Kashiwagi(1993) proposed

$$Sh=1655.4Re^{-1.29} \tag{18}$$

for the subcooled soliution.

Present works show quite contradictory trends of Sherwood number compared to the results of Ohm and Kashiwagi(1993). Here again the effects of film structure depending upon the tube diameter and solution flow conditions seem to play an important role in determining the transport characteristics qualitatively and quantitatively. Obviously more elaborate and accurate works about film structure and transport characteristics should be performed for better understanding of the phenomena.

4. Conclusions

In the present works, absorption processes of water vapor into lithium bromide-water solution film inside the vertical tube were studied experimentally. The heat and mass transfer coefficient were measured as a function of film Reynolds number in the range of 30～200. The variables considered were system pressure, solution and coolant temperatures whose difference were kept constant.

Some conclusions obtained from the present experiments are as follows :

(1) Optimum film Reynolds number exists for maximun heat and mass transfer

(2) The structure of vapor/liquid interface with the film thickness, that is, smooth or wavy, affects heat and mass transfer characteristics.

The effects of film structures on combined heat and mass transfer during the absorption process of water vapor into LiBr-water solution should be studied intensively in the future.

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