Thermal and Absorbing Performance in a Vertical Absorber

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Key words : Absorber, LiBr-H_2O solution, Film Reynolds number, Absorption mass flux, Heat transfer coefficients

Abstract

The purpose of the present study is to investigate the absorbing characteristics in a vertical falling film type absorber using LiBr-H_2O solution as working fluids with the concentration of 60 wt%. The experimental apparatus consists of an absorber with the diameter of 17.2 mm and the length of 1150 mm, a generator, an evaporator (condenser), a weak solution tank and a sampling trap device and so on. The parameters were the solution temperatures of 45 and 50 ℃, coolant temperatures of 30 and 35 ℃, and the film Reynolds numbers from 50 to 150. The pressure drop in the absorber increased as the solution and coolant temperatures decreased. The pressure drop in the absorber increased up to the film Reynolds number of 90, however, decreased at the film Reynolds number above 90. The maximum absorption mass flux was observed at the film Reynolds number of 90. Absorption mass fluxes increased as the coolant temperature decreased. Accordingly, absorption mass fluxes and heat transfer coefficients under the subcooled condition increased more than those under the superheated condition. It is claimed that heat transfer coefficients are deeply affected by the solution temperature more than the coolant temperature within the experimental range.

Nomenclature

A : Surface area [m²]
C : LiBr-H_2O solution concentration [wt%]
C_S : Liquid-vapor interface concentration [wt%]
C_P : Constant-pressure specific heats [kJ/kg·K]
D : Diffusion coefficient [m²/s]
d : Diameter [m]
d_h : Hydraulic diameter [m], $d_a - d_0$
F : Fouling factor [m²℃/W]
f : Function of diameter ratio,

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$1 + 0.14\sqrt{d_a / d_0}$

G : Absorption mass flux [kg/m²·s]
h : Heat transfer coefficient [kW/m²·K]
k : Thermal conductivity [kW/m·K]
L : Length of absorber tube [m]
L_S : Characteristic length of liquid film [m] $(\nu^2 / g)^{1/3}$
$LMTD$: Log mean temperature difference [K]
M : Absorption rates [kg/s]
$\dot{m}$: Mass flow rate [kg/s]
Nu : Nusselt number,
Nu_∞ : Nusselt number in the infinite annulus, $3.66 + 1.2(d_0 / d_a)^{-0.8}$
Pr : Prandtl number
$\dot{Q}$: Heat flow rate [kW]
Re_f : Film Reynolds number, $4\Gamma_s / \mu_s$
r : Radius of absorber [m]
Sh : Sherwood number
T : Temperature [K]
U : Overall heat transfer coefficient [kW/m²·K]

Greek Symbols

β : Mass transfer coefficient [m/s]
Γ : Mass flow rate per circumferential length [kg/m·s]
ρ : Density [kg/m³]

Subscript

a : Inner tube of coolant channel
c : Coolant
i : Inner tube of absorber
lm : Arithmetic mean
o : Outer tube of absorber
s : Solution
ss : Stainless steel
w : Surface of absorber tube
1 : Inlet
2 : Outlet

1. Introduction

The residential absorption refrigeration system should be air-cooled, compact, and highly efficient to compete with the vapor compression system. Since the refrigerant vapor from the evaporator is absorbed by the absorbent in the absorber, absorbing performance is significantly considered for an optimal design of the absorption system. The study on the enhancement of the absorbent solubility by adding an additive, $CaCl_2$, to the LiBr-H_2O solution had been achieved by Cho et al.[1] The study of inserting a spring into a vertical tube and changing the shape of an absorber had been performed by Yoon et al.[2] In addition, the effect of the non-absorbable gas accumulated at the interface between absorbent solution and refrigerant vapor caused by corrosion or minute leakage in an inner tube had been investigated in the absorbing performance by Lee.[3] Morioka and Kiyota[4] and Morioka et al.[5] had proposed the optimal thickness of the vertical falling film for the maximum absorbing rate of refrigerant vapor. Ohm and Kashiwagi[6] stated that the film thickness to maximize total absorption rates was 0.3 ~ 0.4 mm in the vertical falling film absorber. Ohm et al.[7 8] measured heat and mass transfer coefficients in a vertical copper absorber with the inner diameter of 25mm and the length of 1000mm for the film Reynolds number from 35 to 130 and the concentration of 60wt%. Kim and Kang[9] experimentally investigated the effect of the system pressure and the solution temperature in the absorbing characteristics for the film Reynolds number from 30 to 200 in the vertical inner tube. They reported that the absorption rates were the maximum at a film Reynolds number of 130.

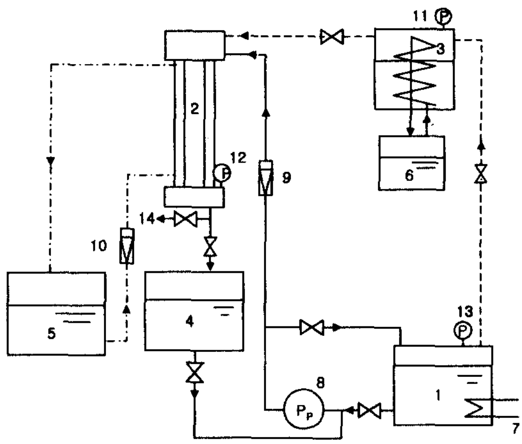
In the case of air-cooling type, the pressure drop in the vertical absorber tube is larger than that in the horizontal tube and causes the increase of the pressure and the temperature of refrigerant vapor in the evaporator and consequently influences the performance of the evaporator and the absorber. The experiments with the experimental parameters of a flow rate, a solution temperature, a pressure, a concentration, and the diameter of tube were performed respectively for estimating heat and mass transfer characteristics in a vertical absorber tube. The trends of the results which were obtained from the similar experimental conditions were neither consistent nor systematic depending on the researchers. The purpose of this study is to investigate the absorbing characteristics in a vertical falling film type absorber under the subcooled and superheated conditions, respectively.

2. Experimental apparatus

Figure 1 shows a schematic diagram of the present experimental system, which consists of an absorber, a generator, a solution tank, an evaporator/condenser, a constant temperature bath, a mass flowmeter and a sampling device. The absorber consisted of the upper header, the absorbing tube and the lower header. The 1150 mm-long-absorber stainless steel tube with the inner diameter of 17.2mm was used.

The coolant was circulated around the absorber tube in counter flow direction to make the experiment simple and to enhance the cooling efficiency. The LiBr-H_2O solution moved downward in parallel to the gravity from the upper header to the absorbing tube. Then, the weak solution resulted from absorption process ,and moved to the lower header of the absorber and then to the solution tank.

Thermocouples were installed at the upper and lower headers to measure the temperatures of both strong and weak solutions. The solution concentrations after absorbing were measured by using the sampling trap device located below the lower header. The vacuum pressure gauges were installed to measure the pressure drop in the absorber during absorption process. The coolant temperatures were also measured at the inlet and outlet of the coolant, respectively. T-type thermocouples used for the temperature measurement had outer diameter of 0.0762mm, and calibrated within ±0.10℃ by using the standard RTD sensor within the experimental temperature range. The specific gravity and solution temperature were measured for the strong solution in the generator and weak solution at the outlet of the absorber extracted by using the sampling trap, and then the solution concentrations were determined from the specific gravity temperature-concentration diagram for LiBr-H_2O solution. The weight of glass (25mℓ) contained the sampled



1. Generator 2. Absorber 3. Evaporator/Condenser
4. Weak solution tank 5~6. Constant temp.bath
7. Heater 8. Solution pump 9~10. Rotameter
11~12. Vaccum Pressure gage
13. Bourdon tube pressure gage 14. Sampling trap

Fig. 1 Schematic diagram of experimental apparatus.

solution was calculated an electronic balance with the accuracy of 0.1mg. The magnetic solution pump with the pumping capacity of 2 ℓ/min was used to circulate the solution into the absorber. The rotameter with accuracy of 0.01 ℓ/min was used to measure the flow rates of inlet strong solution, and cooling water. The pressures at the inlet and outlet of the absorber were measured by the absolute pressure gauge with the range of 260mmHg, and the accuracy of ±0.1% of the full scale. The pressure in the generator was measured by the bourdon tube pressure gauge with the accuracy of ±5%. The evaporator was made of SUS 304, and its inner volume was 4 ℓ.

A heater (1kW) was placed inside the evaporator to generate the vapor. The key experimental parameters were solution temperatures of 45℃ and 50℃, coolant temperatures of 30℃ and 35℃, and film Reynolds numbers from 50 to 150(Table 1). The concentration of $LiBr-H_2O$ solution was set at 60wt%, the pressure in the absorber was set at 7.6 mmHg, and the flow rates of cooling water were 0.09 m³/h.

3. Data reduction

The heat transfer rate from solution to coolant is obtained by the equation (1).

$$\dot{Q} = \dot{m}_c C_p (T_{c2} - T_{c1}) = UA_i LMTD \quad (1)$$

The heat flux (q) is obtained to divide the heat transfer rate from the equation (1) by the heat transfer area. The overall heat transfer coefficient in the equation (1) is shown in the equation (2).

$$U = \frac{1}{\frac{A_i}{A_0}\frac{1}{h_c} + \frac{A_i ln\left(\frac{r_0}{r_i}\right)}{2\pi k_{ss} L} + \frac{1}{h_s} + F} \quad (2)$$

Table 1 Range of key experimental parameters.

Parameters	Range
Solution Temperature (℃)	45, 50
Coolant Temperature (℃)	30, 35
Film Reynolds number (Re_f)	50, 70, 90, 110, 130, 150

The fouling factor which can be applied for an absorption system is 0.00015 m² ℃/W, the convective heat transfer coefficient, h_c , can be determined by the following equation (3) suggested by Lee[10].

$$N_c = \left[N_\infty + f \frac{0.19\left(Re_c \Pr_c \frac{d_h}{L}\right)^{0.8}}{1 + 0.007\left(Re_c \Pr_c \frac{d_h}{L}\right)^{0.467}} \right] \times \left(\frac{\Pr_c}{\Pr_w}\right)^{0.11} = \frac{h_c d_h}{k_c} \quad (3)$$

The heat coefficient in an absorber can be obtained by using the equations (1)~(3). The absorption rate per unit time is shown in equation (4).

$$M = GA_i = \dot{m}_{s1}(C_{s1} / C_{s2} - 1) \quad (4)$$

The mass transfer at a falling film is occurred by the difference between the concentration at the liquid-vapor interface and average concentration of a falling film. Since the solution concentration at liquid-vapor interface cannot be measured, it can be replaced with the saturated concentration at the pressure in the absorber and the solution temperature. The absorption rate of refrigerant vapor is given in the equation (5).

$$M = \rho_s \beta A_i \Delta C_{lm} \quad (5)$$

In the equation (5), the density of solution is the arithmetic mean value at inlet and outlet of the absorber, and ΔC_{lm} is given in the equation (6).

$$\Delta C_{lm} = \frac{(C_{s1} - C_1^s) - (C_{s2} - C_2^s)}{ln[(C_{s1} - C_1^s)/(C_{s2} - C_2^s)]} \quad (6)$$

Mass transfer coefficient can be calculated from equations (4)~(6). Sherwood number can be obtained by the equation (7).

$$Sh = \frac{\beta L_s}{D_s} \quad (7)$$

4. Experimental result

4.1 The pressure drop in the absorber

Figure 2 describes the absorption model related with heat and mass transfer characteristics in the vertical falling film

absorber. The subcooled condition in the absorber was set as the inlet solution temperature of 45℃, the solution concentration of 60 wt% and the saturation pressure of 6.7 mmHg. Since the saturated pressure in the evaporator was 7.8 mmHg, the refrigerant vapor was absorbed in the pressure difference of 1.1 mmHg.

The superheated condition in the absorber was set at the inlet solution temperature of 50℃, the solution concentration of 60wt% and the saturation pressure of 8.5 mmHg. The refrigerant vapor was absorbed into the solution when the saturation pressure in the absorber decreased below 7.8 mmHg by the coolant just after the absorbent was evaporated at the inlet of the absorber at the beginning of the experiment since the pressure in the absorber was larger than that in the evaporator.

Figure 3 shows the pressure drop under both subcooled and superheated conditions. The pressure drop under the subcooled condition was barely changed as the film Reynolds number increased from 50 to 70 at the coolant temperature of 30℃, where as it rapidly increased by 20% as the film Reynolds number was set up to 90 and then it is almost constant when the film Reynolds number increased from 90 to 130. The pressure drop over the film Reynolds number of 130 was slightly decreased. The pressure drop at the coolant temperature of 35℃ increased by 15% below the film Reynolds number of 70, but decreased by 32% over the film Reynolds number of 90 compared with that at the coolant temperature of 30℃. The slight increase of the pressure drop for the film Reynolds number from 50 to 70 was due to the decrease of absorption rates caused by the forming of the unstable film resulted from the low flow rates. The rapid increase of the pressure drop at the film Reynolds number of 90 was due to the maximum absorbing area by forming the stable film.

The slight decrease of the pressure drop after little change over the film Reynolds number of 90 may be due to the increase of saturation pressure of solution caused by the decrease of

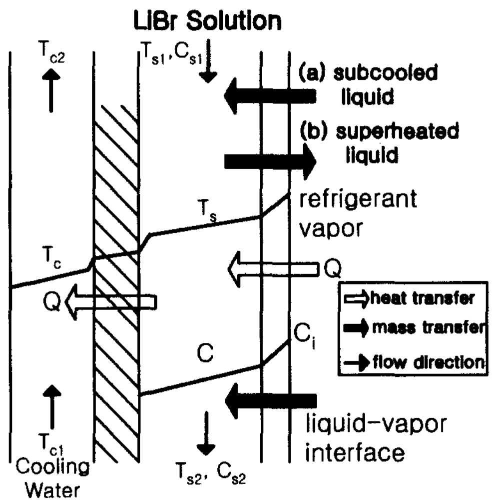


Fig. 2 Absorption model.

cooling effect resulted from the pressure drop under the superheated condition indicated the similar trend with that under the subooled condition. The pressure drop under the subcooled condition was larger than that under the superheated condition. That is due to the difference of the saturation pressure at the exit of the evaporator and the inlet of the absorber. As the coolant temperatures are decreased under the superheated and the subcooled conditions, the pressure drops increased between the inlet and the outlet of the absorber.

4.2 Mass transfer characteristics in the absorber

Figure 4 shows the absorption mass flux with respect to the film Reynolds number under both subcooled and superheated conditions. The absorption mass flux at the coolant temperature of 30℃ increased by 40% in the range of the film Reynolds number from 50 to 70 under the subcooled condition. The absorption rates rapidly increased 1.6% over the film Reynolds number of 90. The similar trend was observed at the coolant temperature of 35℃.

The absorption mass flux at the coolant temperature of 35℃ were similar to those at 30℃ within the film Reynolds number of 70 under the superheated condition. The absorption mass flux decreased by 26% than that at the coolant temperature of 30℃ over the film Reynolds number of 90. The data by Morioka et al.[5] showed the larger value than the present data at low film Reynolds number.

The reason is that the effective absorption

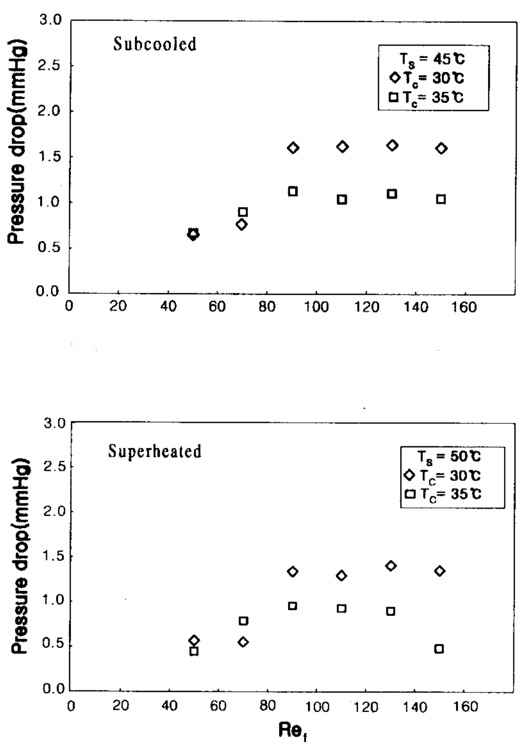


Fig. 3 Pressure drops in absorber.

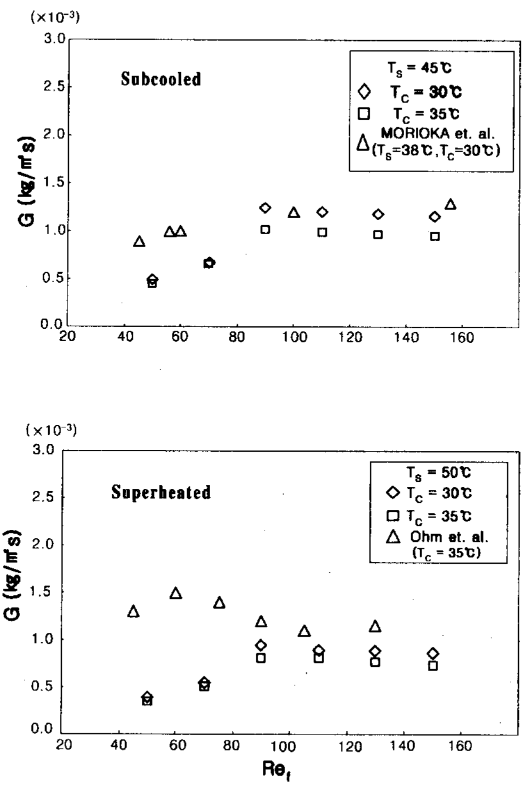


Fig. 4 Absorption mass flux.

area of the absorber was 90% larger than the present study, and the solution flows outside the absorber tube. The absorption mass flux decreased over the film Reynolds number of 90 because of the increase of thermal resistance caused by the increase of film flow rates. The absorption mass flux under the subcooled condition showed 30% higher than those under the superheated condition. The effects of coolant temperature on the absorption mass flux under the superheated condition were less by 16% than those under the subcooled condition, because of the less absorption under the superheated condition. The present data under the superheated condition were smaller than those by Ohm et al.[7 8]. The main reason is due to the difference of the size and material of the absorber tube.

Figure 5 shows the Sherwood numbers with respect to the film Reynolds number under both subcooled and superheated conditions. The Sherwood numbers at the coolant temperature of 30℃ increased by the maximum of 45% and 38%, compared with those at the coolant temperature of 30℃ under the subcooled and superheated conditions, respectively. Kim et al.[11] reported that the maximum Sherwood number occurred at the film Reynolds number of 70. That may be due to the outer flow for the study by Kim et al.[11]

In other words, the absorption mass flux for outer flow was accelerated by the wider surface area, compared with the inner flow inspite of the low flow rate. The differences from Ohm et al.'s[7-8] results under the superheated condition resulted from the increase of the mass transfer at the low film Reynolds number as explained in Fig. 4.

4.3 Heat transfer characteristics in the absorber

Figure 6 shows the heat fluxes with respect to the film Reynolds numbers under both subcooled and superheated conditions. Under the subcooled condition, the heat fluxes with respect to the change of coolant temperature increased by 20% for the film Reynolds numbers from 50 to 70, increased by 50~100% for the film Reynolds numbers from 70 to 90, and then were kept constant. Under the superheated condition, the heat fluxes with respect to the change of coolant temperature increased by 10% for the film Reynolds number from 70 to 90, and then slowly increased.

This is due to the rapid increase of the mass transfer at the film Reynolds number of 90. The reason for low increasing rate of heat flux over the film Reynolds number of 90 is due to the increase of sensible heat as the flow rate in-

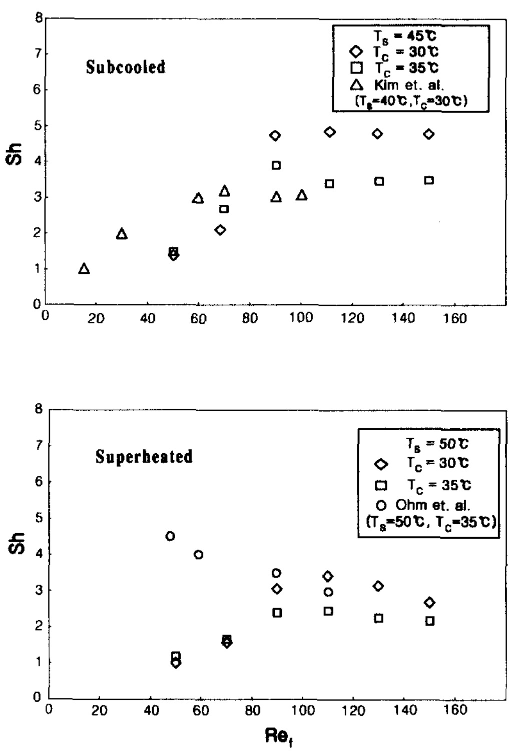


Fig. 5 Sherwood numbers.

creases. The heat fluxes under the superheated condition were larger by 5% than those under the subcooled condition. The reason is that the absorption heat influences the heat fluxes under the subcooled condition, whereas the absorption heat and the sensible heat influence the heat fluxes under the superheated condition.

Figure 7 shows the heat transfer coefficients with respect to film Reynolds number both under subcooled and superheated conditions. The heat transfer coefficients under the subcooled condition were larger than those under the superheated condition. The heat transfer coefficients were affected by the inlet solution temperature rather than by the coolant temperature. The reason is that the heat transfer coefficients increased by the heat transfer due to the mass transfer just after the solution flew into the absorber under the subcooled condition. The heat transfer coefficients were kept constant due to the increase of the thermal resistance. The heat transfer coefficients under the subcooled condition were higher than those under the superheated condition. The reason is that the absorption process was delayed due to the evaporating at the beginning of flowing into the absorber.

5. Conclusion

(1) The pressure drop in the absorber increased as the solution and coolant temperatures decreased. As the flow rates of solution increased, the pressure drop increased, then kept constant and then decreased within the experimental range.

(2) The maximum absorption mass flux was

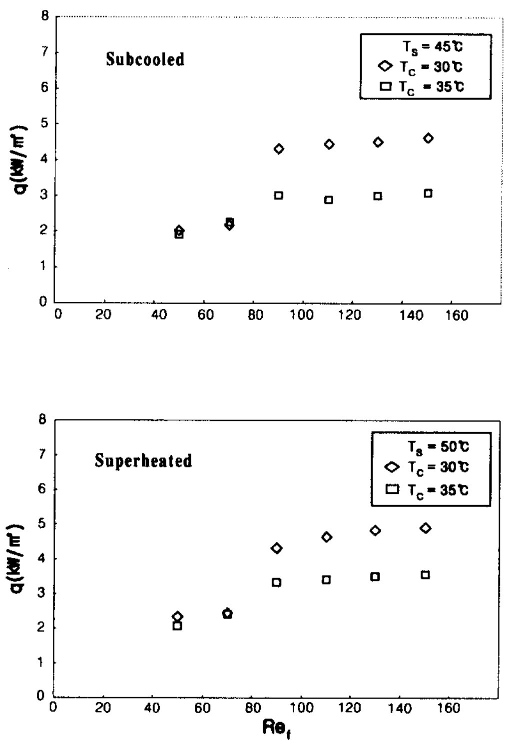


Fig. 6 Heat flux.

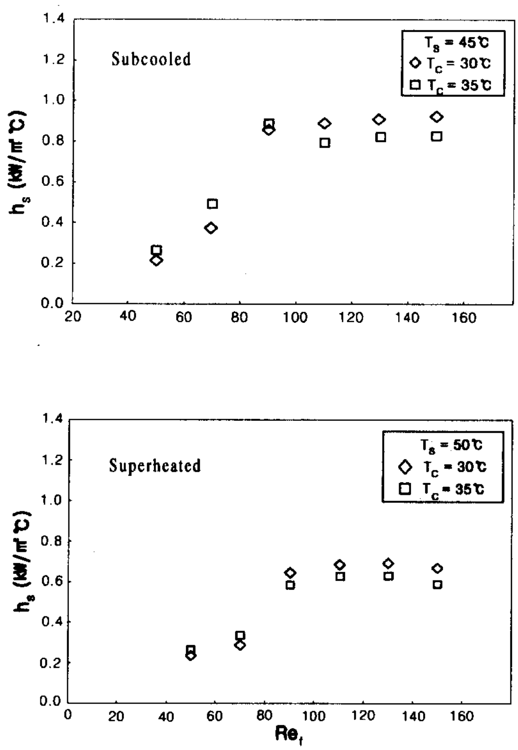


Fig. 7 Heat transfer coefficients.