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Heat and mass transfer characteristics of a helical absorber using LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions

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Abstract

An experimental study has been performed to investigate the heat and mass transfer performance in a falling film absorber of a small-sized absorption chiller/heater. The components of the chiller/heater were concentrically arranged in a cylindrical form with a low temperature generator, an absorber and an evaporator from the center. The arrangement of such a helical-type heat exchanger makes the system more compact compared to a conventional one. As a working fluid, LiBr + LiI + $LiNO_3$ + LiCl solution is used to get improved heat transfer effect. The heat and mass transfer coefficients of the helical absorber provide similar values compared with the data obtained for horizontal absorbers at similar solution flow rates. The heat and mass transfer coefficients of LiBr + LiI + $LiNO_3$ + LiCl solution increase as the solution flow rate per unit length increases. However, if the solution flow rate is larger than 0.03 kg/m s, the heat and mass transfer increase is minimal. Thus, 0.03 kg/m s is recommended as an optimal solution flow rate. The heat and mass flux performance of LiBr + LiI + $LiNO_3$ + LiCl solution shows the tendency of 2–5% increase compared with that of LiBr solution.

Keywords: Helical absorber; Heat/mass transfer; New solution; Absorption chiller/heater

1. Introduction

Absorption cooling systems have been widely used for the cooling of large buildings since they can reduce electric peak load during the summer, and do not use CFC, which is the main causer of ozone depletion of the stratosphere. Among various types of absorption cooling systems, an absorption chiller/heater using LiBr solution is the most popular one for commercial-sized equipment. However, LiBr solution leads to pitting corrosion and risk of crystallization in high concentration. Many researchers have focused on the investigation of a new

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working fluid that could replace LiBr solution. This study proposes the composition portion of the optimistic five component systems from the research result about three component systems and four component systems for developing of driving media of five component systems consisted of LiBr + LiI + $LiNO_3$ + LiCl/H_2O having a low vapor pressure and a high dissolving degree which is the property demanded importantly as the driving media based on H_2O commercialized water-cooled type [1,2]. The new fluid is LiBr + LiI + $LiNO_3$ + LiCl solution (mole ratio 5:1:1:2). It is composed of LiI as an anti-crystallization agent, $LiNO_3$ as an anti-corrosion agent, and LiCl as a vapor pressure suppression agent.

The vapor pressure and solubility curve of five-elements system solution and an H_2O/LiBr aqueous solution is shown by Figs. 1 and 2. The driving force of vapor absorption in the absorption solution comes from the difference of vapor pressure between vapor and solution. So, the absorption efficiency improves by maintaining the low vapor pressure of solution in an absorber. The vapor pressure difference, like Fig. 1, of H_2O/LiBr aqueous solution and five-elements system solution to 30–50 °C, range of a operating temperature in an absorber, have a little or identical value to the five-elements system solution, and the solubility, like Fig. 2, rise 4% at least because the crystallizable temperature of five-elements system solution to 60–62%, range of a operating concentration in an absorber, is lower than H_2O/LiBr aqueous solution.

Fig. 3 shows a Dühring diagram of LiBr + LiI + $LiNO_3$ + LiCl solution used in this study. From the diagram, it is found that LiBr + LiI + $LiNO_3$ + LiCl solution, as compared with LiBr solution, can be operated

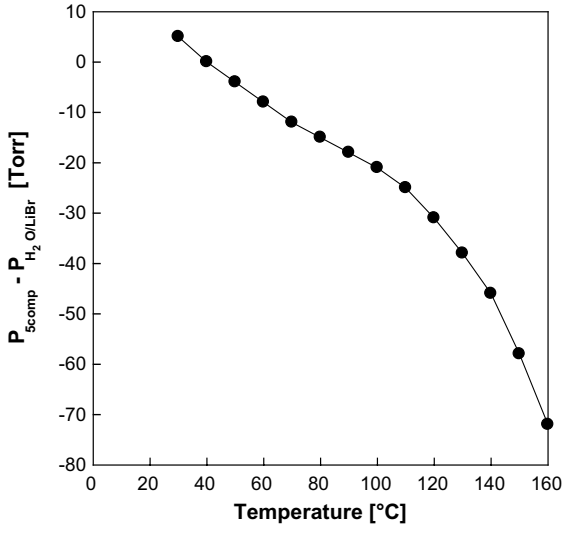

Fig. 1. Vapor pressure difference between H_2O/LiBr solution and five comp. solution at 60 wt%.

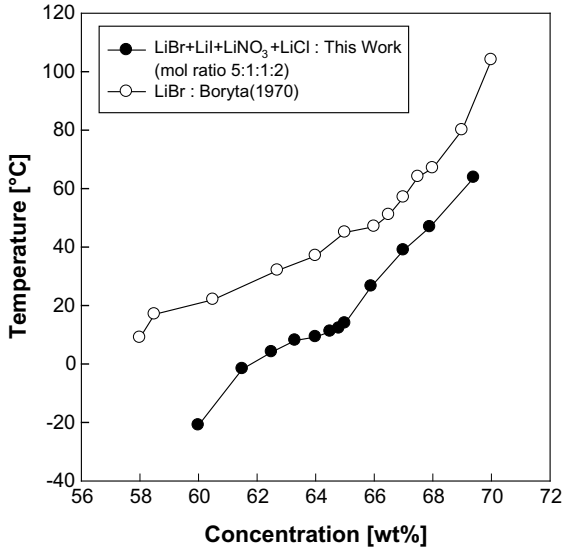

Fig. 2. Crystallization temperature of H_2O/LiBr solution and five comp. solution.

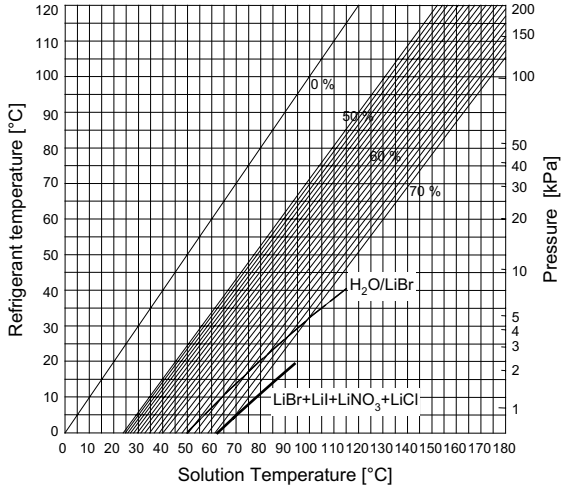

Fig. 3. Dühring diagram of LiBr + LiI + $LiNO_3$ + LiCl solution.

with a high temperature (>45 °C) and a low pressure allowing the appropriate concentration difference (4 wt%) without the danger of crystallization. This is an important factor for the construction of a water-cooled and an air-cooled absorption system. Absorption system consists of several heat exchangers such as an evaporator, an absorber, a generator, and a condenser. Among these, the absorber has a considerably large volume and gives a major effect on the entire efficiency indicating its great influence on the system performance. In many countries, extensive researches have been carried out on

high performance tubes [3–7] and surfactants [8–10] to improve the overall efficiency. Recently, Tsujimori et al. [11] experimentally investigated the heat transfer characteristics of LiBr + LiI solution for horizontal and vertical tubes. They reported that the heat transfer coefficient increased when the mass flow rate of the solution increased and the mass concentration of the solution decreased. The characteristics of LiBr + LiI solution were almost the same as those of LiBr solution.

In this study, experimental investigations of the heat and mass transfer with LiBr + LiI + $LiNO_3$ + LiCl solution and LiBr solution will also be presented. This comparative study will show how the solution affects the heat and mass transfer performance. And, I suggest the possibility of application about the design and manufacturing for compact, air-cooled and high efficiency of domestic and industrial absorption refrigerator a basis of numerous researches to the study and development of LiBr + LiI + $LiNO_3$ + LiCl/H_2O driving media based on H_2O/LiBr.

2. Experiment

2.1. Experimental apparatus

Fig. 4 shows a schematic diagram of an experimental apparatus, which has an absorber, an evaporator/condenser, a generator with an electric heater, a weak solution tank, a refrigeration tank piping and measuring instrument. In this apparatus, the evaporator works as an evaporator itself in absorption process, and it serves as a condenser in generation process. The absorber consists of a set of tube coils, and upper and lower flanges are made of stainless steel 304. The tube coils are bolted to the upper and lower flanges with an inserted o-ring and enclosed with a transparent cylinder to observe absorption phenomena. In the absorber, the solution flows down from the topside through a distribution tray. The distribution tray has a diameter of 238 mm and 38 nozzles. Table 1 shows experimental conditions for LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions. For normal conditions, LiBr concentration at the absorber inlet is 60 wt% and the solution temperature is 45 °C. For LiBr + LiI + $LiNO_3$ + LiCl solution, the inlet concentration is 64 wt% and the inlet temperature is 54 °C.

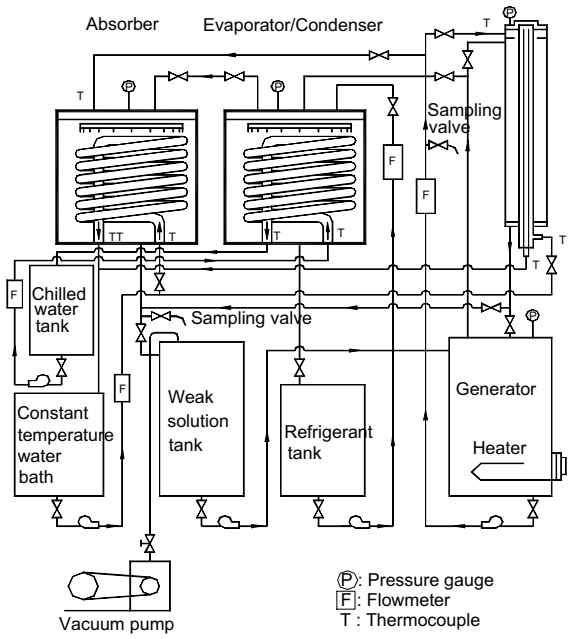

Fig. 4. Schematic diagram of the experimental apparatus.

Table 1
Experimental conditions

Investigated conditions	LiBr	LiBr + LiI + $LiNO_3$ + LiCl
Pressure of absorber (mmHg)	80.5	80.5
Inlet solution concentration (wt%)	57, 60	58, 61, 64
n-Octanol (ppm)	0, 500	0, 500
Inlet solution temperature (°C)	40–50	45–59
Solution flow rate (kg/m s)	0.01–0.04	0.01–0.04
Inlet cooling water temperature (°C)	30, 35	30, 35
Cooling water velocity (m/s)	1.43	1.43

The outer diameter and thickness of tubes in the helical absorber are 15.88 mm and 1.0 mm, respectively. Tube coils have the diameter of 236 mm and length of 7420 mm. A digital pressure gauge is installed on the upper flange. The absorber of one column and ten rows is selected in considerations of an optimum pitch among columns and height of a low temperature generator. The evaporator is also fabricated in the same form as the absorber, but it has one column and seven rows. Refrigerant flows down on the evaporator tube through a distribution tray. The evaporator tube has a diameter of 238 mm and 30 nozzles.

The generator has a volume of 32 l and is made of stainless steel 304. This is equipped with an electric heater of 2 kW for the concentration control, a thermostat for the solution temperature control, a level gauge for the solution flow rate verification and a pressure gauge ranging from 0 to 760 mmHg. The weak solution flows into the solution tank through the absorber and then is sent to the generator by a solution pump. The solution tank has a volume of 32 l and transparent glass.

The refrigerant that is not vaporized in the evaporator is sent to the refrigerant tank through a pipeline, which is located at the bottom of the evaporator. Then, it is circulated by a refrigerant pump into the evaporator again.

2.2. Experimental method

The experiment is conducted in two processes: a generation process and an absorption process. In the generation process, first of all, the cooling water to lower the solution saturation temperature reduces the condenser pressure. The refrigerant vapor obtained by heating the solution in the generator flows into the condenser and is condensed there by the heat exchange with the cooling water circulating inside the tube. The liquid refrigerant is finally sent to the refrigerant tank. The temperature and specific gravity of the generator solution are measured using a hydrometer and a refractometer (ATAGO R5000). When the concentration reaches the desired experimental condition, the heating process is stopped and then the solution will be cooled down to the assigned temperature.

In the absorption process, the refrigerant temperature of the evaporator is cooled to a saturation temperature of 10 °C by a chiller. An absorber pressure is then reduced to 8 mmHg by a vacuum pump. In the evaporator, the liquid refrigerant evaporates while flowing downward and the vapor comes into the absorber. The solution of high concentration in the generator maintains at the assigned temperature and is pumped up to the top of the absorber. The solution of high concentration flows down on the tube coils and absorbs refrigerant vapor. The solution flow rate is manipulated by a needle valve. Inlet and outlet temperatures of the solution at the absorber are measured by using thermocouples, which are installed at the top and bottom sides. The solution concentration at the absorber outlet is obtained by extracting samples using a hydrometer and a refractometer. Absorber inlet cooling water is kept at the assigned temperature by a constant temperature water bath and circulates from the bottom to the top of the absorber in counter flow with the solution. The flow rate of the cooling water is measured by a flow meter, and the inlet and outlet temperatures are measured by a flow meter and thermocouples, respectively.

For the present experiment, the steady state is approximately 5 min for each parameter, and the data points are plotted on graphs with the maximum deviation of 0.8% for the temperature of the solution (Γ: 3.2%, P: 1.2%, C: 0.8%). The uncertainties of the overall heat transfer coefficients at ultimate cases for the maximum heat flux and minimum heat flux are 1.4% and 5.5%, respectively.

2.3. Data reduction

For the heat transfer coefficient, h_i of the cooling water flowing inside the tube, the following correlation proposed by Yang [12] is applied to coiled tubes.

$$h_i = 0.023\frac{\lambda_c}{d_i}Re_c^{0.8}Pr_c^{0.4}\left[1 + 82.4\left(\frac{d_i}{d_{coil}}\right)^3\right] \quad (1)$$

The heat transfer coefficient, h_o, of the solution flowing outside the tube can be obtained from Eq. (2). In this equation the thermal resistance of the tube wall is neglected.

$$h_o = \left[\frac{1}{U} - \frac{d_o}{d_i}\cdot\frac{1}{h_i}\right]^{-1} \quad (2)$$

The solution flow rate per unit length, Γ (kg/m s), flowing down on the outer surface of the tube is expressed as Eq. (3).

$$\Gamma = \dot{m}_s/2\pi d_{coil} \quad (3)$$

The mass flow rate of the vapor absorbed by the absorption process is given as Eq. (4).

$$\dot{m}_v = \dot{m}_{s,in}\left(\frac{C_{in}}{C_{out}} - 1\right) \quad (4)$$

The logarithmic mean concentration difference, ΔC_{lm}, is defined between equilibrium concentration C^* at the vapor/liquid interface and the concentration C at the falling film as Eq. (5)

$$\Delta C_{lm} = \frac{(C^*_{s,in} - C_{s,in}) - (C^*_{s,out} - C_{s,out})}{\ln(C^*_{s,in} - C_{s,in})/(C^*_{s,out} - C_{s,out})} \quad (5)$$

where C^*_{in} and C^*_{out} are the equilibrium concentrations of the vapor–liquid interface at the absorber inlet and outlet, respectively. These are obtained from the falling film temperature and absorber pressure. The concentrations C_{in} and C_{out} are measured by solution samplings using a refractometer. The measurement error is less than ±0.2%. The mass transfer coefficient, β, in absorption process is defined in Eq. (6).

$$\beta = \frac{\dot{m}_v}{\rho_m \cdot \Delta C_{lm} \cdot A} \quad (6)$$

The thermal properties of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions are quoted from the data of McNeely [13] and KOGAS [1], respectively.

3. Results and discussion

The main purpose of this paper is to study the effects of the heat and mass transfer in a falling liquid film in an absorption heater/chiller. A helical type heat exchanger is selected to reduce the volume of an absorption heater/chiller. Also, the heat and mass transfer performance of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions is investigated to apply to a new compact absorption heater/chiller. The experimental parameters for the performance evaluation are the inlet solution temperature, the cooling water temperature, the inlet solution concentration, and the cooling water flow rate. Since no experimental study on a helical absorber is available in the literature, the data obtained by this experiment is

compared with those of horizontal absorbers, even though this comparison is not exact.

Fig. 5 shows the photographs of falling films of LiBr + LiI + $LiNO_3$ + LiCl solution when the solution flow rate per unit length (Γ) varies from 0.01 to 0.04 kg/m s. Fig. 5 shows good visual effect on the wetting of the helical tubes. When the solution flow rate is 0.01 kg/m s, the wetting of tubes is poor and the solution is separated by the unwetted regions. When the solution flow rate increases the solution shows the good wetted surface. From visual observation, it is known that the tubes are almost wetted when the solution flow rate is larger than 0.03 kg/m s.

Fig. 6(a) shows the heat transfer coefficient of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions with varying solution flow rate per unit length with $C_{s,i}$ = 60 wt%, $T_{s,i}$ = 45 °C, $T_{c,i}$ = 30 °C and m_c = 780 kg/h. The heat transfer coefficient of LiBr + LiI + $LiNO_3$ + LiCl solution is almost the same or a little bit higher than that of LiBr and LiBr + LiI solutions. For LiBr solution, the heat transfer coefficients for the solution flow rates starting from 0.01 kg/m s are 0.14, 0.08, 0.02 kW/m^2 K.

These data agree that when the solution flow rate increases from 0.01 kg/m s to 0.03 kg/m s, and the area of wetted surface increases. Thus, the heat transfer coefficient shows good enhancement until the solutions flow rate is 0.03 kg/m s. However, the increase ratio rapidly decreases with the increase of the solution flow rate after 0.03 kg/m s. Fig. 6(b) shows the mass transfer coefficient of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions with changing solution flow rate per unit length for the same condition. In both solutions, the mass transfer coefficient increases as the solution flow rate increases. The mass transfer coefficient of LiBr + LiI + $LiNO_3$ + LiCl solution increases a little bit comparing with that of LiBr solution. The enhancement of mass transfer coefficient between LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions is about 6% for the solution flow rate from 0.01 kg/m s to 0.04 kg/m s.

When the solution flow rate increases, the increase rate of the mass transfer coefficient is larger than that of the heat transfer coefficient.

LiBr + LiI + $LiNO_3$ + LiCl solutions with changing solution flow rate per unit length for the same condition. In both solutions, the mass transfer coefficient increases as the solution flow rate increases. The mass transfer coefficient of LiBr + LiI + $LiNO_3$ + LiCl solution increases a little bit comparing with that of LiBr solution. The enhancement of mass transfer coefficient between LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions is about 6% for the solution flow rate from 0.01 kg/m s to 0.04 kg/m s. When the solution flow rate increases, the increase rate of the mass transfer coefficient is larger than that of the heat transfer coefficient.

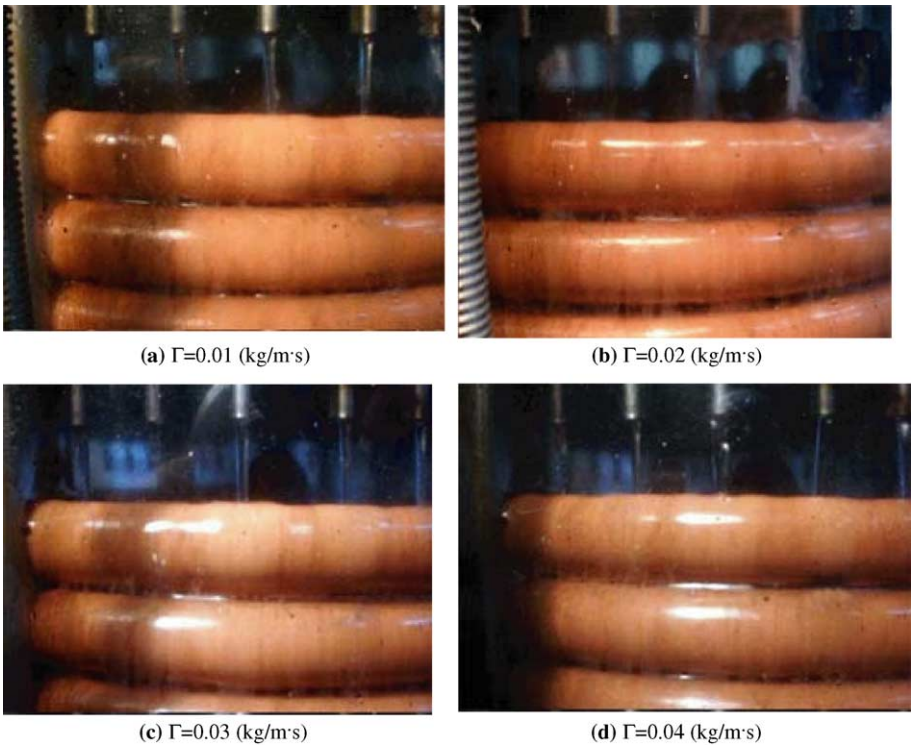

Fig. 5. Flow patterns with various flow rate of solution.

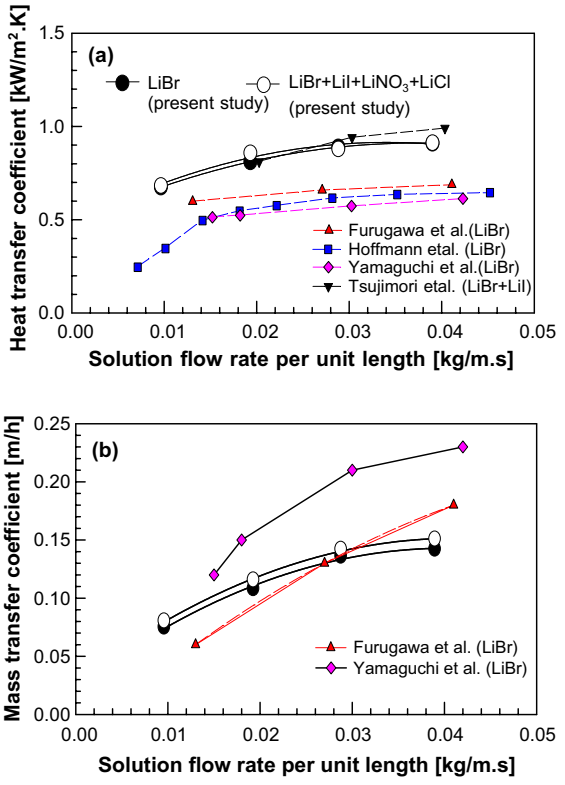

Fig. 6. Comparison of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions: (a) heat transfer coefficient, (b) mass transfer coefficient.

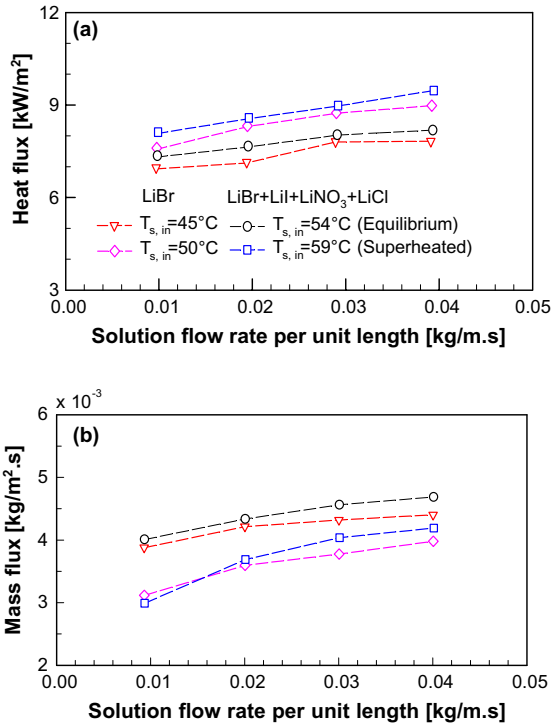

Fig. 7. Effect of cooling water temperatures on solution flow rate per unit length: (a) heat flux, (b) mass flux.

Fig. 7(a) shows the variation of heat flux with the solution flow rate per unit length for different inlet temperatures of cooling water. For example, when Γ is 0.03 kg/m s, the heat flux increases about 14% when the inlet temperature of cooling water changes from 35 °C to 30 °C for LiBr solution. It is observed that the heat flux in the absorber increases with the decrease of the inlet temperature of cooling over entire solution flow rates. For LiBr + LiI + $LiNO_3$ + LiCl solution, the effect of the inlet temperature of cooling water shows a similar increase. The heat flux of LiBr + LiI + $LiNO_3$ + LiCl solution shows about 2–5% increase compared with LiBr solution according to the cooling water temperature over entire solution flow rates. The result shows that LiBr + LiI + $LiNO_3$ + LiCl solution gives a good performance in a helical type heat exchanger. Fig. 7(b) shows the variation of mass flux with the solution flow rate per unit length. The figure shows that the mass flux in the absorber increases with the decrease of the inlet temperature of cooling water. For both solutions, the heat and mass flux increases rapidly with the increase of the solution flow rate up to 0.03 kg/m s. However, when Γ is over 0.03 kg/m s, the increase is minimal. From Fig. 5, it is evident the solution almost covers the surface of the helical tubes when Γ is above 0.03 kg/m s. It is true only for the first tube. When the solution flows down to the tubes from the distributor, the first tube has a good wetted surface. When the solution flows down to the next tube, the wetting of the lower tubes becomes poor. This is why still there is a minimal increase when Γ is over 0.03 kg/m s. The heat and mass flux in the helical type heat exchanger shows a good performance.

Fig. 8(a) shows the heat flux with the solution flow rate per unit length with varying inlet temperatures of solution. The heat flux increases when the flow rate of solution increases. In this figure the heat flux for the superheated solution is approximately 8.5% higher than that for an equilibrium state at the solution flow rate 0.01 kg/m s and 14% higher at 0.04 kg/m s for LiBr solution, and 9.9% and 15.2% higher for LiBr + LiI + $LiNO_3$ + LiCl solution, respectively. When the solution is superheated, the heat amount is removed by using cooling water is larger than that in an equilibrium state. Thus, the heat flux increases in the superheated state. The heat flux of LiBr + LiI + $LiNO_3$ + LiCl solution increases 5–7% more than that of LiBr solution for $T_{c,n}$ = 30, m_c = 780 kg/h. Fig. 8(b) shows the variation of mass flux with the solution flow rate per unit length for two different inlet solution temperatures for each solution. The mass flux of an equilibrium state for both

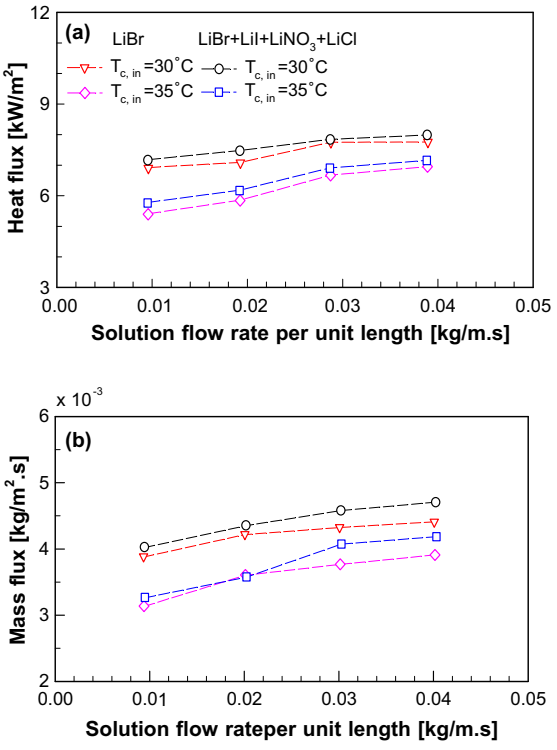

Fig. 8. Effect of solution temperatue on solution flow rate per unit length: (a) heat flux, (b) mass flux.

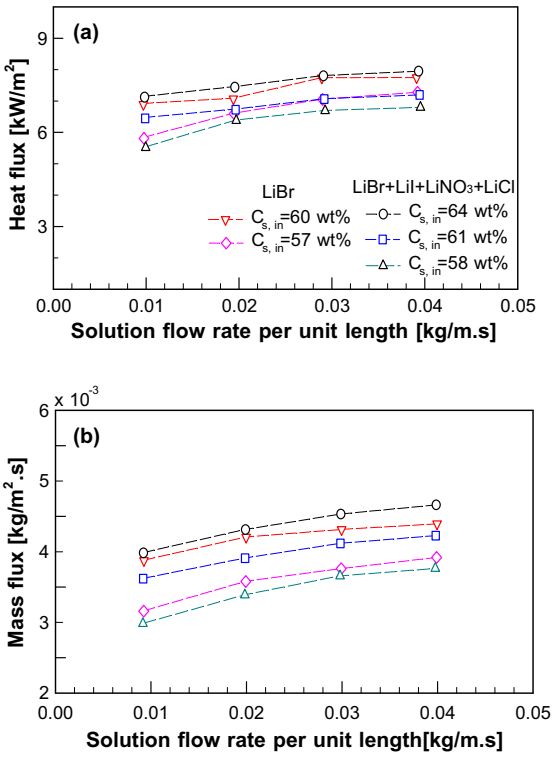

Fig. 9. Effect of solution temperatures on solution flow rate per unit length: (a) heat flux, (b) mass flux.

solutions increases more than that of a superheated state of the solutions. It is because in an equilibrium state the absorption time of solution is shorter than that in a superheated state of solution.

Fig. 9(a) shows the heat flux with the solution flow rate per unit length when inlet concentration of solution varies. The heat flux increases when the flow rate and inlet solution concentration of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions increase. When the inlet concentration of solution increases, the saturation temperature of solution increases and the saturation vapor pressure increases. It makes the temperature difference between solution and cooling water large. The heat flux increases because the difference of the saturation vapor pressure and the absorption heat quantity of refrigerant increases. The heat flux of LiBr + LiI + $LiNO_3$ + LiCl solution increases about 5% larger than that of LiBr solution over the whole range of solution flow rate. This is proved that LiBr + LiI + $LiNO_3$ + LiCl solution shows very good solubility and does not occur crystallization of solution in high concentration. This means that LiBr + LiI + $LiNO_3$ + LiCl solution can be applied to improve the overall efficiency of an absorption heater/chiller. Especially, the solution can be applicable to a small-sized absorption heater/chiller. Fig. 9(b) shows the mass flux of refrigerant vapor for the solution flow rate per unit length with changing inlet solution concentration of solution. The mass flux of LiBr and LiBr + LiI + $LiNO_3$ + LiCl solutions is large when solution concentration is high. Absorption quantity increases when the pressure difference between the refrigerant vapor pressure and solution saturation pressure increases.

4. Conclusions

A fundamental study on the heat and mass transfer of a helical absorber is studied to develop a small-sized absorption chiller/heater. The results of this experiment are as follows.

The heat and mass transfer coefficients of a helical absorber provide similar values compared with the data obtained for horizontal absorbers at similar solution flow rates. This shows that a helical absorber can be applied to reduce the volume of an absorber without any loss of performance. The heat and mass transfer coefficients increase as the solution flow rates per unit length increase over whole solution flow rates. However, if the solution flow rate is larger than 0.03 kg/m s, the heat and mass transfer increase is minimal. Thus, 0.03 kg/m s is recommended as an optimal value of solution rate. The heat and mass flux performance of LiBr + LiI +

$LiNO_3$ + LiCl solution shows the tendency of 2–5% increase than that of LiBr solution. LiBr + LiI + $LiNO_3$ + LiCl solution shows very good solubility and does not occur crystallization of solution in high concentration. Thus LiBr + LiI + $LiNO_3$ + LiCl solution can be applied to improve the overall efficiency of an absorption heater/chiller.

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