Numerical Study on Simultaneous Heat and Mass Transfer in a Falling Film of Water-Cooled Vertical Plate Absorber

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Abstract : A model of simultaneous heat and mass transfer process in absorption of refrigerant vapor into a lithium bromide solution of water-cooled vertical plate absorber was developed. The model can predict temperature and concentration profiles as well as the absorption heat and mass fluxes, the total heat and mass transfer rates and the heat and mass transfer coefficients. Besides, the effect of operating condition on absorption mass flux has been investigated, with the result that the absorption mass flux is increased as the inlet cooling water temperature decreases, the system pressure increases and the inlet solution concentration increases. And among the effects of operating parameters on absorption mass flux, the effect of inlet solution concentration is dominant.

Key words: Numerical analysis, Absorption process, Vertical plate absorber, Water-cooled, Absorption chiller/heater

1. Introduction

Absorption cooling system have been used widely for the cooling of large building. Among major components of an absorption chiller/heater, the absorber, which has a direct effect on efficiency, size, manufacturing and operating costs of the system, is least understood. To achieve a compact and highly efficient absorber, plate type absorber is used to replace conventional shell and tube type.

Most of previous numerical studies on absorption process in plate absorber, such as the studies of G. Grossman et al. [1], Kawae et al. [2], Kim et al. [3], and so on, were performed on the assumption that either wall temperature was uniform or plate wall was cooled by air.

The purpose of the present study is to develop a model of simultaneous heat and mass transfer process in absorption of refrigerant vapor into a lithium bromide solution of vertical plate absorber, which was cooled by cooling water. The temperature and concentration profiles as well as the absorption heat and mass fluxes, the total heat and mass transfer rates and the heat and mass transfer coefficients were researched. Especially, the selected operating condition was expected to be present in an actual absorption chiller/heater system. Furthermore, the effect of operating parameters such as absorption film Reynolds number, inlet cooling water temperature, system pressure, inlet solution concentration and temperature on absorption mass flux have been investigated.

2. Analysis model of plate absorber

2.1 Analysis model

The numerical analysis for the absorption process in the present study is described schematically in figure 1. A film of LiBr

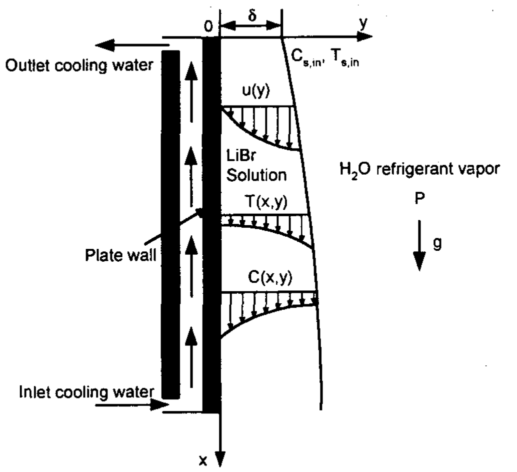

Fig. 1 Schematic diagram of absorption process in a water-cooled vertical plate absorber

solution composed of LiBr (absorbent) and H_2O (refrigerant) flows down over a vertical plate. The film is in contact with stagnant refrigerant vapor and cooled by cooling water flowed inside the plate.

The following assumption have been made:

(1) The flow of the liquid film is laminar, and fully developed throughout.

(2) The liquid is Newtonian and steady state.

(3) No shear forces are exerted on the liquid by the vapor at the interface.

(4) There is no heat transfer in the vapor phase.

(5) The system pressure is constant.

(6) Thermodynamic equilibrium exists at the interface.

(7) The thermal resistance of the plate wall has been neglected.

(8) The cooling water is flowed counter to the flow of LiBr solution and its temperature is changed linearly.

2.2 Governing equations and boundary conditions

Because of constant film thickness, the cross-stream velocity is neglected ($v=0$). The downstream velocity u profile is parabolic as a function of y [1]

$$u(y)=u_{mean}\left[2\left(\frac{y}{\delta}\right)-\left(\frac{y}{\delta}\right)^2\right] \tag{1a}$$

where

$$u_{mean}=\frac{\Gamma}{\rho\delta} \qquad \delta=\left(\frac{3\Gamma\mu}{\rho^2 g}\right)^{1/3} \qquad Re_f=\frac{4\Gamma}{\mu} \tag{1b}$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(u\frac{\partial^2 T}{\partial x^2}+v\frac{\partial^2 T}{\partial y^2}\right)$$

$$+\left(\frac{\partial^2 C}{\partial y^2}T+\frac{\partial C}{\partial y}\cdot\frac{\partial T}{\partial y}\right)\frac{D(c_{p,LiBr}-c_{p,H_2O})}{c_p} \tag{2}$$

Mass diffusion equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(u\frac{\partial^2 C}{\partial x^2}+v\frac{\partial^2 C}{\partial y^2}\right) \tag{3}$$

Boundary conditions

At $x=0$ $T=T_{s,in}$ $C=C_{s,in}$ (4)

At $x=L$ $\frac{\partial T}{\partial x}=0$ $\frac{\partial C}{\partial x}=0$ (5)

At $y=0$ $T=T_{wall}$ $\frac{\partial C}{\partial y}=0$ (6)

At $y=\delta$ $C_{surf}=C_{surf}(T_{surf},P)$ (7a)

The refrigerant mass flux absorbed to the liquid film at the interface is determined as follows

$$\dot{m}_{surf}=-\rho D\left(\frac{\partial C}{\partial y}\right)_{y=\delta} \tag{7b}$$

The absorption heat flux generated at the interface is determined as follows

$$\dot{q}_{surf}=k\left(\frac{\partial T}{\partial y}\right)_{y=\delta}-(c_{p,H_2O}-c_{p,LiBr})T\rho D\left(\frac{\partial C}{\partial y}\right)_{y=\delta}=H_{abs}\cdot\dot{m}_{surf} \tag{7c}$$

where H_{abs} is the heat of absorption and determined as follows

$$H_{abs}=H_{latent}+H_{dilution} \tag{7d}$$

2.3 Method of numerical analysis

The integral forms of conservation equations were solved by the finite volume method proposed by Patankar [5]. The power-law scheme was used to treat the convection-diffusion term and get the discretization equations. The TDMA method was applied line by line to solve the system of discretization equations.

Table 1 Nominal condition of plate absorber

Parameters	Values
Plate height L	1m
System pressure P	1kPa
Inlet solution temperature $T_{s,in}$	46℃
Inlet solution concentration $C_{s,in}$	60.2wt%
Inlet cooling water temperature $T_{c,in}$	32℃
Outlet cooling water temperature $T_{c,out}$	36℃
Film thickness δ	0.2197mm
Film Reynolds number Re_f	14
Film mass flow rate Γ	0.0187 kg/m · s

3. Numerical results and discussions

The present study was performed under similar to an operating condition of actual absorption chiller/heater shown in table 1.

3.1 Validity of the model

In figure 2, the interface concentration profile along the plate wall of the present study was in good agreement with those of Kawae et al [2] and Kim et al. [3] under the same comparison condition.

3.2 Temperature and concentration profiles

Figure 3 show temperature profiles. In cross-stream direction, the temperature is highest at the interface and decreases to the lowest at the wall. In downstream direction, the interface temperature decreases rapidly at the inlet range but slowly as x increases.

Figure 4 shows the concentration profiles. In cross-stream direction, the concentration is lowest at the interface and increases to the highest at the wall. In downstream direction, the interface concentration is rapidly decreased at the inlet range but slowly as x increases.

3.3 Variation of absorption heat and mass transfer rates

Figure 5 shows the variation of local heat and

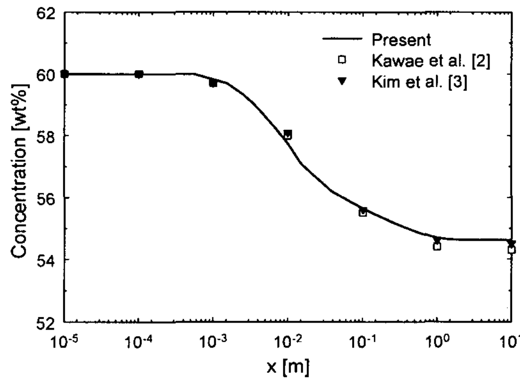

Fig. 2 Comparison of interface concentration with previous investigations

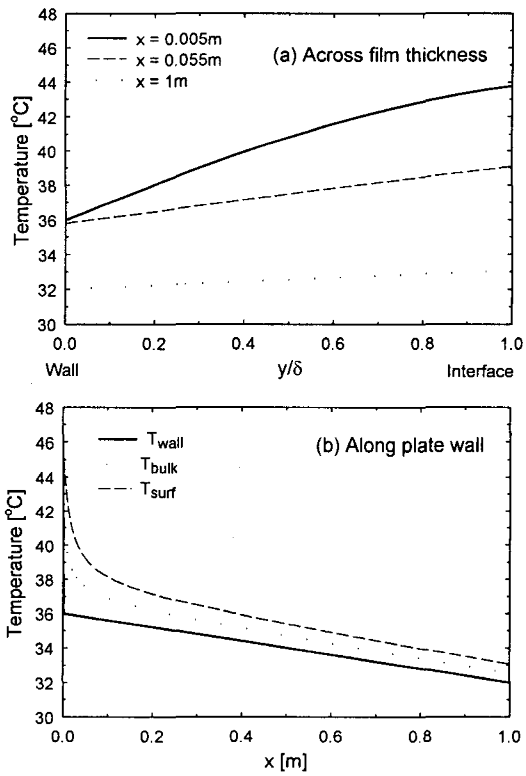

Fig. 3 Temperature profiles

mass fluxes. The local heat flux at plate wall is determined as follows

$$\dot{q}_{wall} = k\left(\frac{\partial T}{\partial y}\right)_{y=0} \quad (8)$$

The heat and mass fluxes increase rapidly at

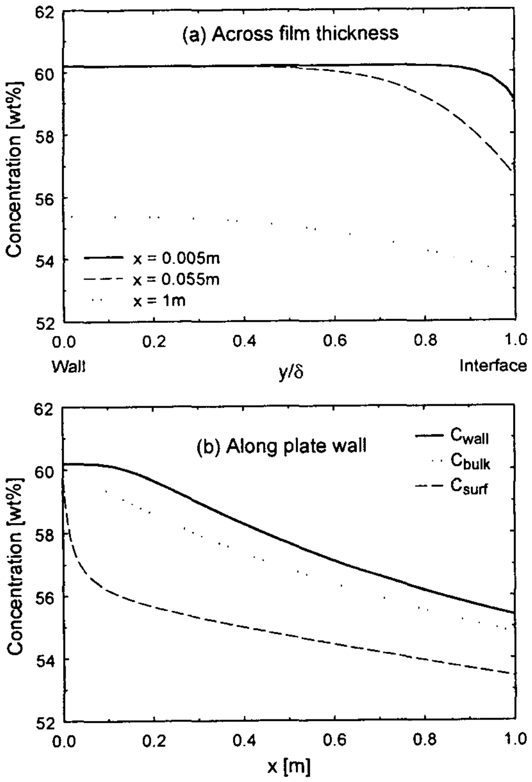

Fig. 4 Concentration profiles

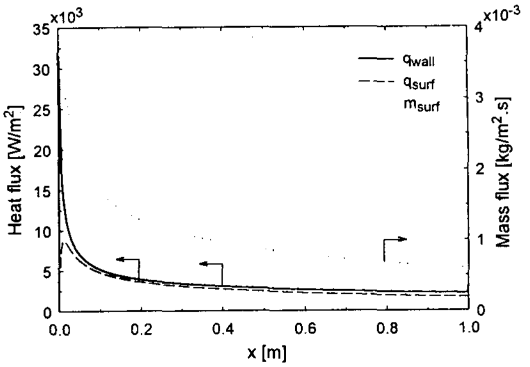

Fig. 5 Variation of local heat and mass fluxes along the wall

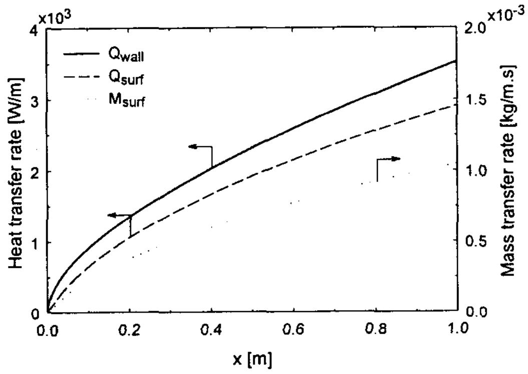

Fig. 6 Variation of total heat and mass transfer rates along the wall

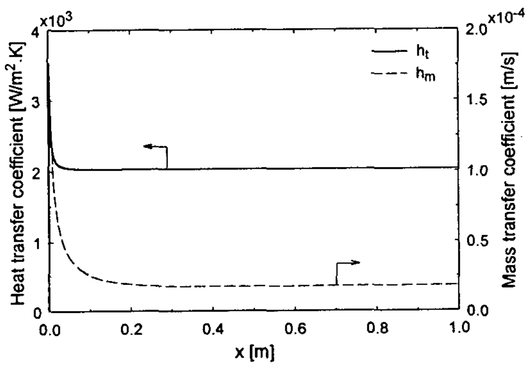

Fig. 7 Variation of local heat and mass transfer coefficients along the wall

the inlet range and reach their maximum values $\dot{q}_{surf,max} = 8.7336 \times 10^{3}\ W/m^2$ and $\dot{m}_{surf,max} = 3.1499 \times 10^{-3}\ kg/m^2 \cdot s$ respectively at $x = 11.7 \times 10^{-3} m$. Then they decrease rapidly at near their maximum values but slowly as x increases. The heat and mass fluxes are monotonically decreased toward zero as x increases.

Figure 6 presents the variation of total heat and mass transfer rates. The total heat and mass transfer rates are rapidly increased at the inlet range but slowly as x increases.

3.4 Variation of heat and mass transfer coefficients

Figure 7 shows the variation of local heat and mass transfer coefficients, which are determined as follows

$$h_t = \frac{k\left(\frac{\partial T}{\partial y}\right)_{y=0}}{T(\delta) - T(0)} = \frac{\dot{q}_{wall}}{T_{surf} - T_{wall}} \quad (9)$$

$$h_m = \frac{-D\left(\frac{\partial C}{\partial y}\right)_{y=\delta}}{C(0) - C(\delta)} = \frac{\dot{m}_{surf}}{\rho(C_{wall} - C_{surf})} \quad (10)$$

The heat and mass transfer coefficient are zero at the inlet ($x=0$) and get the highest value as x begins to increase from the inlet. Those are $h_{t,\max} = 3.5386 \times 10^3\ W/m^2 \cdot K$ and $h_{m,\max} = 1.7527 \times 10^{-4} m/s$ respectively at $x = 1.67 \times 10^{-3} m$. Then they are rapidly decreased at the inlet range but slowly and become steady as x increases.

3.5 Effect of operating condition on absorption mass flux

Figure 8 to 12 show effect of film Reynolds number, inlet cooling water temperature, system pressure, inlet solution concentration and temperature on absorption mass flux respectively.

A variable parameter is changes while another are fixed under nominal condition. System pressure, inlet solution temperature and concentration are changed so that the LiBr solution can get superheated, equilibrium and subcooled state at the inlet. In the figures, the positive of ordinate means a positive absorption mass transfer rate of refrigerant vapor into solution and the negative value of ordinate means an evaporation mass transfer rate of refrigerant liquid from solution into refrigerant vapor.

In the case of small film Reynolds number, the absorption mass flux gets higher at the inlet range but becomes lower as x increases as shown in figure 8.

The absorption mass flux is increased as the inlet cooling water temperature decreases, the system pressure increases and the inlet solution concentration increases as shown from figure 9 to 11 respectively.

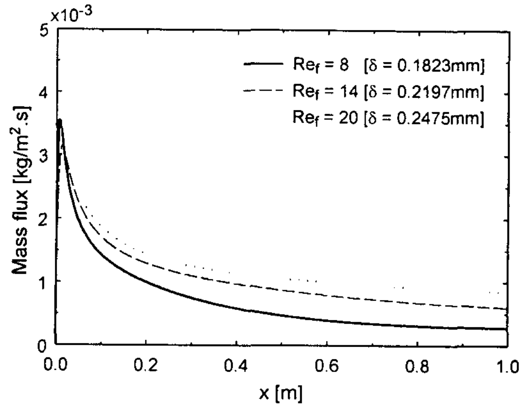

Fig. 8 Effect of film Reynolds number on local mass flux

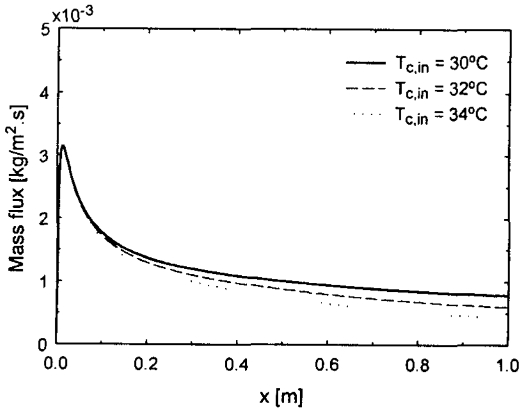

Fig. 9 Effect of inlet cooling water temperature on local mass flux

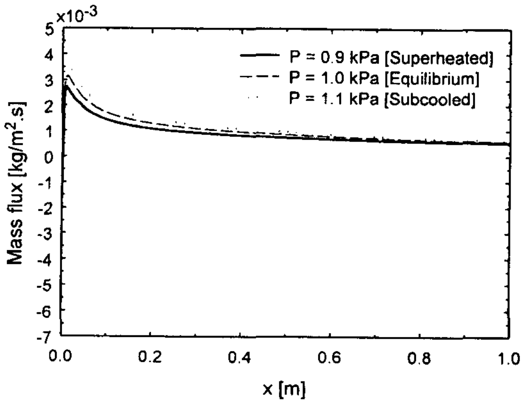

Fig. 10 Effect of system pressure on local mass flux

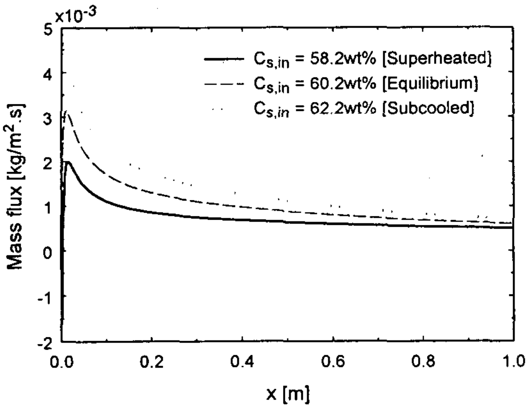

Fig. 11 Effect of inlet solution concentration on local mass flux

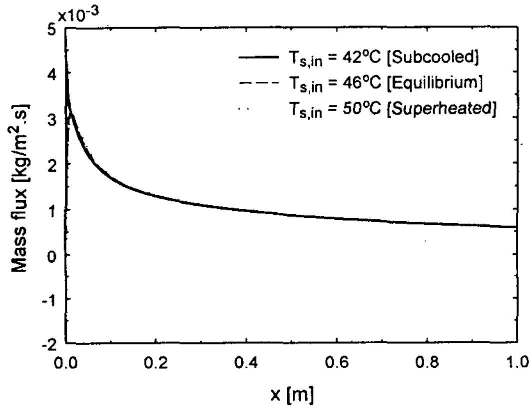

Fig. 12 Effect of inlet solution temperature on local mass flux

In figure 12, the absorption mass flux is increased at the inlet range as the inlet solution temperature decreases but from $x=0.2m$, the mass fluxes of the different inlet solution temperatures become to equal to each other.

4. Conclusions

The results obtained can be summarized as follows:

The interface temperature and concentration are rapidly decreased at the inlet range but slowly as x increases.

The absorption heat and mass fluxes, and the heat and mass transfer coefficients get high values at the inlet range but decrease at the outside of the inlet range.

The total heat and mass transfer rates are rapidly increased at the inlet range but slowly as x increases.

The effect of operating condition on absorption mass flux is as follows:

In the case of small film Reynolds number, the absorption mass flux gets higher at the inlet range but becomes lower as x increases.

The absorption mass flux is increased as the inlet cooling water temperature decreases, the system pressure increases and the inlet solution concentration increases.

The absorption mass flux is increased at the inlet range as the inlet solution temperature decreases but from $x=0.2m$, the mass fluxes of the different inlet solution temperatures become to equal to each other.

Among the effects of operating parameters on absorption mass flux, the effect of inlet solution concentration is dominant.

In the case of subcooled stated of solution at the inlet, the mass flux increases over a corresponding equilibrium state. And for the superheated state, the refrigerant in absorption solution evaporates into refrigerant vapor at the inlet.

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