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Simulation of Heat and Mass Transfer Process in Falling Film Single Tube Absorption Generator

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Abstract- The objective of this paper is to introduce correlations for the Nusselt (heat transfer) and Sherwood (mass transfer) Numbers for a falling film of Li/Br solution over a single horizontal heated tube used in generator of absorption chillers. The analysis is based on laminar flow of Li/Br solution on a horizontal single tube having constant tube wall temperature. The effect of boiling has been ignored and free surface of falling film Li/Br solution is assumed to be saturated. The role of liquid impingement on the top of tube has been considered.

The correlations are derived from an extensive numerical code based on finite difference scheme. The Nusselt and Sherwood Number for Li/Br solution falling film over the heated tube are obtained as a function of Prandtl Number, Schmidt number and Tube geometry

The results showed that the Sherwood number is linearly proportion to Re number and is proportion to inverse of Dimensionless diameter of tube. Also the Nusselt Number is increase with increasing Re number and is independent of Schmidt number of Li/Br solution. A comparison of the correlations with existing experimental and analytical results is presented and verifies the validation of the present model.

Keywords- *Falling film, heat and mass transfer,Absorption chiller,generator*

I. INTRODUCTION

Falling film evaporation having thin films in contact with the heat transfer surfaces is one of the most efficient mechanisms of heat and mass transfer in power, petrochemical and refrigeration industries. Due to large heat transfer coefficient, low solution feed rate, small temperature difference and consequently usage of low-grade energy sources, falling film generators are more frequently used in absorption chillers. Their operation is based on heat addition through hot water or steam to the falling film Li/Br solution, causing evaporation of water from free surface of Li/Br solution; consequently there will be a Li/Br rich solution.

Majority of experimental and analytical studies on falling film evaporation are based on pure water. Little data are available for evaporation of Li/Br solution on horizontal single tube and tube bundle as well.

Chyu and Bergles [1] performed experimental and analytical research on falling film test rig focusing only on the heat transfer effects. They considered water in saturated state neglecting existence of boiling . Fletcher et al. [2] have made an extensive experimental study on the heat transfer phenomena for pure water and seawater in saturated state over horizontal tubes considering simultaneous single phase and two phase effects. They considered turbulent flow with a constant heat flux at wall. They observed increased heat transfer coefficient with increase in water flow rate, saturation temperature and heat flux. Lorent and Yang [3] compared the heat transfer coefficient for falling film of pure water on a single tube and tube bundle as well. They concluded that for Reynolds numbers greater than 300, the mean heat transfer coefficient of a tube bundle was the same as for a single tube and the tube arrangement did not affect the heat transfer coefficient.. Kim et al. [4] studied experimentally and numerically falling film Li/Br solution over a single tube. They measured heat transfer coefficient for different surface geometries of horizontal tube. Their numerical and experimental results are fairly in a good agreement. Jani et al. [5-7] modeled numerically heat and mass transfer of Li/ Br solution falling on a horizontal single tube and tube bundle. Based on their numerical results a correlation has been derived to predict average heat transfer coefficient and evaporation performance of a horizontal single tube.

Shi et.al [8-10] is conducted experimental and analytical investigation of heat and mass transfer performance of an vertical in tube Li/Br solution falling film generator. They showed the heat transfer coefficient is 4.37 times higher than that of flooded generator.

The objective of the present work is to introduce numerically-based dimensionless heat and mass transfer correlation of Li/ Br solution falling on a horizontal single heated tube. The thermal hydraulic analysis has been performed considering laminar flow and constant tube wall temperature. The effect of boiling has been ignored. The Nusselt and Sherwood number correlation are obtained as a function of film Reynolds Number, Schmidt Number and tube geometry. The parametric study has been performed and the effects of the parameters on each of the falling film heat and mass transfer phenomena have been shown in detailed and compared with existing analytical and experimental data.

II. NOMENCLATURE

cp	specific heat at constant pressure
D	tube diameter
D_m	diffusion coefficient
g	gravity constant
h	heat transfer coefficient
k	conductivity
K_m	mass transfer coefficient
$\dot{m}$	mass flow rate
Lc	characteristics length $(v^2/g)^{1/3}$
M	molecular weight
Nu	nusselt number(hLc/k)
P	Pressure
Pr	prandtl number
q	heat transfer
R	tube radius
Re	film Reynolds number ($4\Gamma/\mu$)
Sh	Sherwood number $(k_m L_c/\rho D_m)$
Sc	Schmidt number $(\mu/\rho D_m)$
T	temperature
u	peripheral velocity
v	normal velocity
w	Li/Br concentration (wt%)
x	peripheral distance
y	normal distance
Greek letter	
α	Thermal diffusion coefficient
δ	falling film thickness
Γ	Li/Br solution flow rate per unit length per one side of tube
μ	dynamic viscosity
θ	angular position
ρ	density
Subscript	
e	evaporation
f	fluid flow
i	Entrance
m	mass transfer
w	Wall
Superscript	
`	per unit length
``	per unite area
*	dimensionless parameter

III. HEAT AND MASS TRANSFER MODELING

A falling film impinging vertically on a horizontal smooth heated tube with constant wall temperature and moving symmetrically around the tube has been considered as a model for investigation as shown in Fig.1.

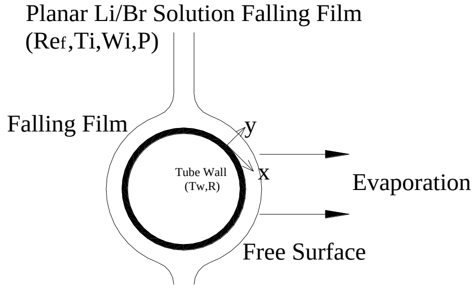

Fig. 1 Falling film thermal hydraulic parameters and geometry

Flow regime assumed to be laminar fully developed. The following assumptions have been made in order to formulate the problem:

1-The fluid flow on the tube is laminar and hydro dynamically fully developed.

2-No shear stress exists at the vapor liquid interface.

3-Thermodynamic equilibrium achieves at the vapor liquid interface.

4-The heat transfer in the vapor phase can be neglected.

5-Constant temperature on the tube wall.

6-The mass diffusion has little effect on the temperature profile.

From the assumptions 1-6 mentioned above the velocity profile can be expressed as follows [5]:

$$u = \frac{\rho g}{\mu}\sin(\theta)(2\delta y - y^2)$$
$$v = -\frac{g}{2\nu}y^2[\frac{d\delta}{dx}\sin(\theta) + \frac{1}{r}(\delta - \frac{y}{3})\cos(\theta)] \qquad (1)$$
$$\delta = [\frac{3\nu\Gamma}{\rho g Sin(\theta)}]^{\frac{1}{3}}$$

The energy equation, neglecting pressure gradients, viscous dissipation and energy transport by mass diffusion and heat of dilution can be simplified to the following form:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2} \tag{2}$$

Similarly the mass transfer equation in terms of Li/Br concentration is given by:

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}=\alpha\frac{\partial^2 w}{\partial y^2} \tag{3}$$

The partial differential equations (2),(3) is to be solved with the following boundary conditions:

$$\begin{aligned}
&T=T_i, w=w_i && x=x_i, \quad 0\le y\le\delta\\
&T=T_w, \frac{dw}{dy}=0 && x_i\le x\le x_o, \quad y=\delta\\
&T_s=f(p,w_s) && x_i\le x\le x_o, \quad y=\delta\\
&m''=\frac{\rho D_m}{w_s}\frac{dw}{dy} && x_i\le x\le x_o, \quad y=\delta\\
&q''_e=k\frac{dT}{dy}=m''\Delta H && x_i\le x\le x_o, \quad y=\delta
\end{aligned} \tag{4}$$

In the above boundary conditions, temperature T*i* is found from the saturation state at the entrance.

Velocity components u and v and the thickness of falling film are estimated from Eq.(1).We may realize that set of Eqs. (2) and (3) are of parabolic types. These set of equations have coupled boundary conditions and variable coefficients as well. In the absence of any clear analytical solution, numerical method is used to solve them. The Crank-Nicolson implicit method is used for solving conservation equations. Finite difference scheme having forward difference in ξ direction and averaged central difference in η direction are used. It is shown that the final round off error of discrete equations has the order of O (Δξ2, Δη2). Liquid film thickness ,Velocity, temperature and concentration distributions, local and average heat and mass transfer coefficient in the film of Li/Br solution falling on the horizontal tube with governing equations (2) to (4) have been revealed completely in detail by using the aforementioned numerical method [5].

IV. HEAT AND MASS TRANSFER CORRELATION

According to the dimensionless analysis the average Nusselt number and average Sherwood number for a single tube is affected by the film Reynolds Number, Solution Prandtl number, solution Schmidt Number and dimensionless tube diameter. The aforementioned independent parameter in falling film heat and mass transfer may define as follows:

$$\begin{aligned}
&\mathrm{Re}_f=4\Gamma/\mu\\
&\mathrm{Pr}=\mu c_p/k\\
&Sc=\mu/\rho D_m\\
&D^*=2R/L_C
\end{aligned} \tag{5}$$

where Lc is the characteristics length and is equal to .

$(v^2/g)^{1/3}$

The Nusselt and Sherwood numbers can be expressed in the simple form as:

$$\begin{aligned}
&Nu=\frac{hL_c}{k}=f(\mathrm{Re}_f,\mathrm{Pr},Sc,D^*)=a_1\mathrm{Re}_f^{a_2}\mathrm{Pr}^{a_3}Sc^{a_4}D^{*a_5}\\
&Sh=\frac{k_mL_c}{\rho D}=f(\mathrm{Re}_f,\mathrm{Pr},Sc,D^*)=b_1\mathrm{Re}_f^{b_2}\mathrm{Pr}^{b_3}Sc^{b_4}D^{*b_5}
\end{aligned} \tag{6}$$

Where h is the average heat transfer coefficient which in the case of constant wall temperature is defined as:

$$h=\frac{q''}{(T_w-T_i)} \tag{7}$$

Also km is the average mass transfer coefficient defined as:

$$k_m=\frac{\dot m''_e}{(w_o-w_i)}=\frac{2\Gamma_i-\dot m'_e}{2\pi R w_i} \tag{8}$$

Based on the numerical results [5] and by using multiple logarithmic regression method we will come up with the following general dimensionless correlations of heat and mass transfer for the falling film of Li/Br solution over a single horizontal tube:

$$\begin{aligned}
&Nu=0.7893\,\mathrm{Re}_f^{0.16587}\mathrm{Pr}^{0.37275}Sc^{-0.041769}D^{*-0.40335}\\
&Sh=0.0020\,\mathrm{Re}_f^{1.0023}\mathrm{Pr}^{-0.74049}Sc^{1.3455}D^{*-1.0006}
\end{aligned} \tag{9}$$

It should be noted that the thermodynamic properties are calculated at the mean of saturated temperature of Li/Br solution and wall temperature. The domain of applicability of correlations (10) is specified as below:

$$\begin{aligned}
&7\le \mathrm{Pr}\le 10\\
&100\le \mathrm{Re}\le 500\\
&5kpa\le P\le 10kpa\\
&50\%\le w\le 60\%
\end{aligned} \tag{10}$$

Deviation of heat and mass transfer coefficient in Eqs. (9) from the numerical results are about 1.33 and 0.55 percent, respectively.

V. RESULTS

The correlations (9) shown that Nusselt number increases with Reynolds number by power of 0.1658 while the Sherwood number is linearly proportional to the Reynolds number. Also its can be deduced, the Nusselt number is independent of Schmidt number and the Sherwood number is increases with Schmidt number as a power of 1.345. Nusselt number increases with increasing of the prandtel number while the Sherwood number decreases. By increasing the tube diameter the Nusselt and Sherwood number decrease.

The effect of Reynolds Number on heat and mass transfer:

Figure 2 shows heat and mass transfer coefficient as a function of Reynolds number. It can be deduced that heat and mass transfer coefficient increase with increasing film Re. In comparison with the existing data in the case of intube-vertical laminar falling film generator [10] the heat transfer coefficient decrease with increasing Re but the variation of mass transfer coefficient is the same as present study.

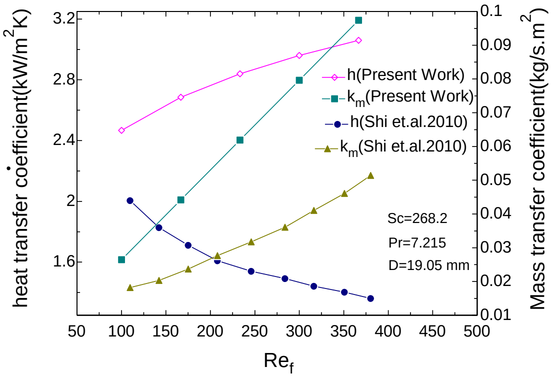

Fig. 2 Heat and mass transfer coefficient vs. Reynolds number

Average sensible heat flux is defined as the difference between average wall heat flux and free surface heat flux. The ratio of the average sensible heat flux to the average total wall heat flux as a function of the Reynolds number of falling film is given in the following Eq.11 and is shown in Fig. 3.

$$\frac{q_s''}{q_{tot}''} = 1 - \frac{q_e''}{q_{tot}''} = 1 - \frac{Sh}{Nu}\frac{Pr}{Sc}\frac{h_{fg}(w_o - w_i)}{c_p(T_w - T_i)} \qquad (11)$$

At low Reynolds number, the predicted values are in good agreement with the existing experimental data of Kim [4]. However, at high Reynolds numbers due to the wavy effects at free surface, the numerical results diverge from the experimental data. As the film flow rate increased, the fraction of average sensible heat flux to the total heat flux was increased but it's slope was reduced.

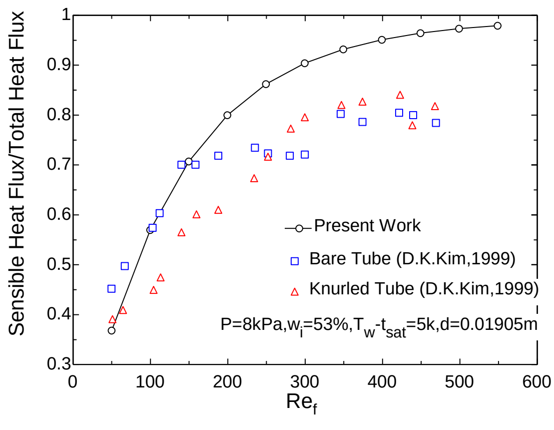

Fig. 3 Ratio of sensible heat flux to wall heat flux vs. film Reynolds number

The effect of wall super heat on heat and mass transfer:

Heat and evaporative mass flux increases linearly with increasing wall super heat. A comparison of average evaporative mass flux over the tube as a function of wall superheat for the present work and the experimental data is given in Fig.4,5.

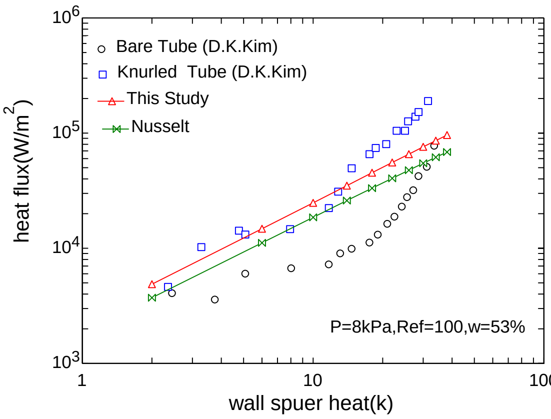

Fig. 4 Heat flux vs. wall super heat

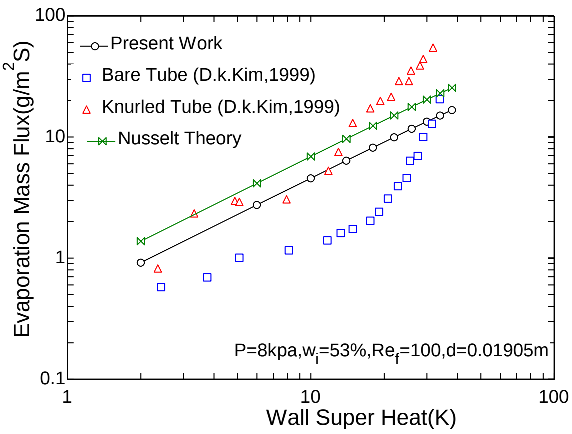

Fig. 5 Evaporative mass flux vs. wall super heat

The effect of concentration on heat and mass transfer:

Figures 6 and 7 show the behavior of heat transfer coefficient and evaporative mass flux as a function of the inlet Li/Br concentration respectively. Increasing of inlet concentration will increase viscosity and increase film thickness of falling film, resulting the wall heat transfer coefficient and evaporative mass flux decrease.

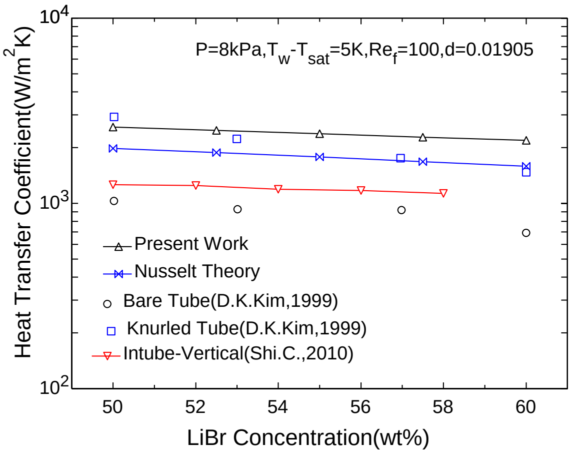

Fig. 6 Heat transfer coefficient vs. Li/Br concentration

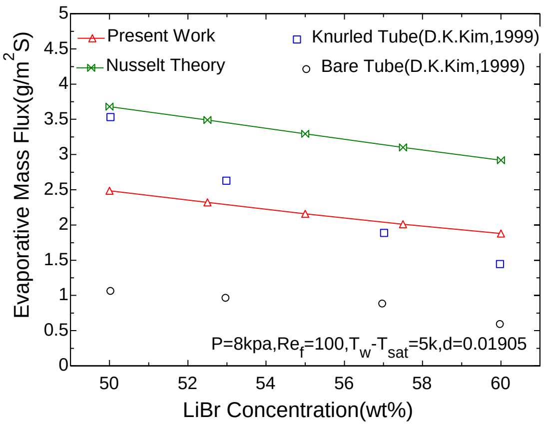

Fig. 7 Evaporative mass flux vs. Li/Br concentration

The effect of system pressure on heat and mass transfer:

Figures 8and 9 show the behavior of heat transfer coefficient and evaporative mass flux vs. the system pressure respectively. Increasing of pressure will increase the saturation of inlet Li/Br solution and decrease the viscosity of solution the result is reduction in film thickness and increase heat and mass transfer coefficient.

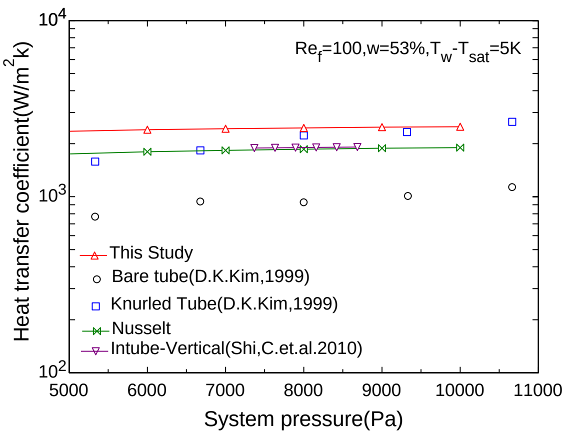

Fig. 8 Heat transfer coefficient vs. system pressure.

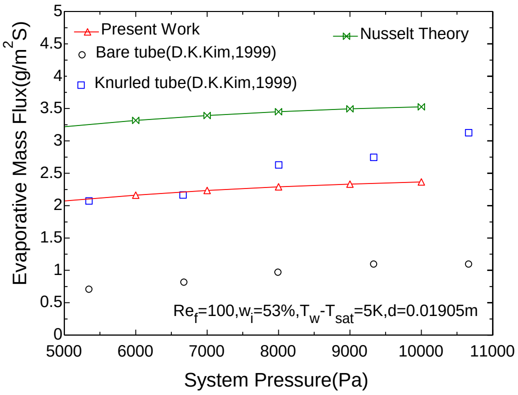

Fig. 9 Evaporative mass flux vs. system pressure.

VI. Conclusion

The basic approach in this analysis which is unique compare to other efforts is to express thermal behavior of falling film heat and mass transfer phenomena over a heated horizontal tube in terms of Sherwood and Nusselt numbers. The Nusselt and Sherwood Number for Li/Br solution falling film over the tube are obtained as a function of Prandtl Number, Schmidt number and Tube geometry.For most of parameters shown; the proposed correlation shows improvement over the Nusselt theory.

The results showed that the Sherwood number is linearly proportion to Re number and is proportion to inverse of Dimensionless diameter of tube. Also the Nusselt Number is independent of Schmidt number of Li/Br solution while the Sherwood number increases with Schmidt number to a power 1.345 for evaporation Li/Br Solution falling film over a heated tube.

The Parametric study show that with increasing the Re number will increase the average Nusselt and Sherwood number over the tube and liquid film thickness, meanwhile the total refrigeration produced will decrease.

Increasing tube wall temperature will linearly increase both the refrigerant flux of evaporation and the heat flux over the tube wall as well.

Increasing inlet concentration will increase viscosity of solution, resulting increase of film thickness and decrease of heat and mass transfer coefficient and mass flux.

Increasing of system pressure will increase heat and mass transfer coefficient.

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