Numerical Simulation of H$_2$O/LiBr Falling Film Absorption Process

Lianying Zhang, Yuan Wang, Yongxia Fu, Liu Xing, Liwen Jin*  
Department of Building Environment and Energy Engineering, Xi’an Jiaotong University, Shaanxi and 710049, China

Abstract

Absorber is a critical component of an absorption air-conditioning system. Its performance influences directly the overall efficiency and volume. In this paper, the commercial simulation software CFD-FLUENT was used to simulate the falling film absorption process of the coolant LiBr/H$_2$O solution. This research attempts to know the effects of various Reynolds number on the absorption progress. The simulation results indicated that there was an optimized Reynolds number of liquid film which leads to an averaged maximum mass flux of $2.9 \times 10^{-3}$kg·m$^{-2}$·s$^{-1}$ at the interface. The local interfacial mass transfer coefficient arrives at the maximum at the inlet, then decreases rapidly along the flow direction and approaches to a constant value gradually. It is also find that the local interfacial mass transfer coefficient increases with the increase of Reynolds number while the local heat transfer coefficient exhibits the opposite trend.

Keywords: absorption; numerical simulation; heat and mass transfer; H$_2$O/LiBr

1. Introduction

Absorption air-conditioning system is achieving acceptance as a promising candidate for solar energy and waste heat recovery [1]. Absorption of vapour into a falling liquid film is an important chemical process for absorption air-conditioning. There were plenty of researches that have been carried out on the combined heat and mass transfer in the absorber. Nakoryakov and Grigoreva [2] obtained analytical solutions for combined heat and mass transfer by Fourier separation of variables techniques. After that, in
1983 Grossman [3] developed the parabolic velocity profile to replace the uniform velocity, that is, the velocity in the inlet is corresponded to Nusselt solution. Grossman [4] considered the falling film model with the complete form governing equations to evaluate the contribution of the inter-diffusion and obtained a short-exposure time solution. Since that time the model has been extended to film thickness, shear stress and latent heat at the free surface and so on. Conlisk [5] found that the heat transfer coefficient increases with a decrease of film thickness; while the mass transfer coefficient decreases with a decrease of film thickness. There were also other studies focused on the mathematical model of coupled heat and mass transfer during the absorption process [6-8]. In addition, there were many authors have studied the different factors which influence the absorption process. Such as Hamza [9] studied the effect of the non-absorbable gases on the absorption efficiency and so on.

Despite of the large amount of knowledge of falling film acquired, there are still many improvements for its model. In particular, as we all know, falling film flows are classified in non-wavy laminar, wavy and turbulence according to the Reynolds number variations [10]. We can learn that the Reynolds number has significant influence on the absorption process. However, there are few authors to study the effects of Reynolds number on the absorption process.

In this paper, the commercial simulation software CFD-FLUENT was used to simulate the falling film absorption process of the coolant LiBr/H₂O solution. The lithium bromide aqueous solution properties and absorption heating were expressed by the User Defined Functions (UDF) which is an extended function of the Fluent. The concentration of the lithium bromide aqueous solution was defined by UDS (User Defined Scalars). The diffusion coefficient was assumed to be constant with considering the molecular diffusion and convective diffusion. The change of variables was gotten by UDM (User Define Memory). It was obtained that the wall temperature and the interfacial mass flux along the falling film change with the different Reynolds number. The interfacial local mass transfer and heat transfer coefficient along the falling film were discussed.

### Nomenclature

- **c**: solution concentration (kg/m³)
- **c₀**: the initial solution concentration (%)
- **Cₚ**: Specific heat capacity (J/kg·K)
- **Cₘ**: Inlet concentration
- **D**: Mass diffusivity (m²/s)
- **g**: Gravitational acceleration (m/s²)
- **hₘ**: Local mass transfer coefficient (m/s)
- **hᵢ**: Absorption heat (KJ/kg)
- **k**: Thermal conductivity /W/m·K
- **L**: Plate length (m)
- **𝑚ₓ**: is mass flux (kg/m²·s)
- **P**: Pressure(Pa)
- **y**: Axis perpendicular to flow direction (m)
- **v**: Velocity in y direction (m/s)
- **T**: temperature(°C)
- **Tₘ**: Inlet temperature
- **Tₜ**: wall temperature (°C)
- **Tₜw**: wall temperature(°C)
- **t**: time(s)
- **u**: mean flow rate (m·s⁻¹)
- **ui**: interfacial velocities of the falling film(m/s)
- **ρ**: solution density (kg/m³)
- **Γ**: is the Film flow rate (kg·m⁻³·s⁻¹)
- **δ**: Film thickness (m)
- **μ**: dynamic viscosity (Pa·s)
- **x**: Axis to flow direction (Pa·s)
- **u**: Velocity in x direction (m/s)
2. Analysis model and governing equations

The system analyzed in the present study is depicted schematically in Fig. 1. A falling film of the LiBr aqueous solution flows into a full of water vapor absorber along the vertical wall.

In addition, to simplify the governing equations, the following assumptions were made:
1) The density and specific heat are constant, the pressure $p$ throughout the lithium bromide aqueous solution is constant;
2) The heat conductivity coefficient and viscosity depend on temperature and concentration of the lithium bromide aqueous;
3) The liquid film is flat without surface waves;
4) Vapor pressure is constant and the resistance of mass transfer is ignored;
5) The interface of vapor-liquid is in a state of equilibrium; the concentration of the film is dependent on the temperature and pressure.
6) The film thickness and flow velocities are considered as constant; Absorption heat is added by source item and conducted to the lithium bromide aqueous.
7) The solution is a Newtonian binary mixture where the absorbent is non-volatile and the flow is a laminar flow;
8) The heat flux transfer to the gas phase can be neglected.
9) Ignoring the influence of non-absorbable gases.
Under the above assumptions, the 2D control equation could be reduced as follows:

Continuity equation
\[
\nabla (\rho \vec{v}) = 0
\]

Momentum equation
\[
\frac{\partial \vec{v}}{\partial t} + \nabla (\rho \vec{v} \vec{v}) = -\nabla p + \nabla (\mu \nabla \vec{v}) + g
\]

Energy equation
\[
\frac{\partial T}{\partial t} + \nabla (\rho \vec{v} T) = -\nabla (k \nabla T) - \frac{\partial (m_i h_i)}{\partial y}
\]

Mass transfer equation
\[
\frac{\partial c}{\partial t} + \nabla (\vec{v} c) = D \nabla (\nabla c)
\]

The boundary condition and initial condition are as follows:

1) The boundary conditions are as follows:
\[
u=0; \quad v=0; \quad \frac{\partial c}{\partial x} = 0 \quad ; \quad T = T_w
\]

2) At the entrance, the concentration of the solution is in equilibrium at its pressure and temperature. According to the Nusselt theory, transverse velocity \( v \) is zero and the downstream velocity profile \( u \) is given as follows:
\[
c = c_0, \quad u(y) = \frac{3}{2} u(2\frac{y}{\delta} - (\frac{y}{\delta})^2)
\]

where
\[
\vec{u} = \frac{\Gamma}{\rho \delta}, \quad \delta = \frac{3\Gamma \mu}{\rho g}, \quad Re = \frac{4.0 \Gamma}{\mu}
\]

3) At the interface, LiBr/H\(_2\)O solution is in thermodynamic equilibrium state. Under the low Reynolds number, the molecule diffusion plays a main role on the mass transfer in the lithium bromide aqueous solution. Fick’s law is used to determine the mass flux \( m \) as follow:
\[
c = c(P_i, T_i), \quad u_i = 1.5 \vec{u}, \quad h_i = m_i h_i, \quad m_i = \frac{\rho D}{c_i} (\frac{\partial \vec{C}}{\partial y})_{y=0}
\]

4) At the outlet, the outflow boundary condition is adopted. The exit flow is assumed to be close to fully developed condition.
\[
\frac{\partial c}{\partial x} = 0, \quad \frac{\partial T}{\partial x} = 0
\]

3. Model validation

The simulation software CFD-FLUENT was used to simulate the heat and mass transfer in the falling film absorption process. The CFD-FLUENT employs a control-volume-based technique to convert governing equations into algebraic equations. Pre-processing software Gambit was used to establish physical model. The fixed rectangular domain was adopted which adapted to the computational domain. The mesh number is 5000×20 in direction \( x \) and \( y \). The velocity distribution of the film at the entrance, the concentration distribution in interface, mass flux and the physical property of the LiBr aqueous solution were defined by UDF and their values were obtained by UDS. Second order upwind discretization scheme was used to discretize the Momentum, Energy and Mass transfer governing
equations. PRESTO Interpolation was employed to deal with the pressure item. The PISO method was used to couple the pressure and velocity equations.

The validity of the model was verified by comparing the calculated interfacial temperature and concentration with the results of Kawae [11] under the same conditions, as shown in Fig. 2. It can be learned that the present results agree very well with Kawae’s.

![Fig. 2 Comparison the present work with analytical solution of Kawae](image)

The operating conditions are listed in Table 1. The properties of LiBr solution are collected from the Ref. [12].

Table 1 Operating conditions of absorber parameter

<table>
<thead>
<tr>
<th>Operating parameter</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature $T_w/K$</td>
<td>319.65</td>
</tr>
<tr>
<td>Inlet concentration $C_{in}/\text{wt%}$</td>
<td>0.6012</td>
</tr>
<tr>
<td>Wall temperature $T_w/K$</td>
<td>308.15</td>
</tr>
<tr>
<td>Pressure $P/\text{Pa}$</td>
<td>1000.0</td>
</tr>
<tr>
<td>Length of falling film $L/m$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4. Results and discussion

The Reynolds number has significant influence on the flow of the falling film. Due to the surface tension and gravity, the falling film appears some subtle fluctuation and the wave’s amplitude increases with an increase of Reynolds number. In this article, the effects of various Reynolds number on the heat and mass transfer of the falling film were investigated. The Reynolds number was based on the film thickness. The operating conditions are shown in Table 2.

Table 2 Operating conditions at different Reynolds number

<table>
<thead>
<tr>
<th>Re</th>
<th>thickness of film $\delta/mm$</th>
<th>film flow rate $\Gamma/kg\cdot m^{-2}\cdot s^{-1}$</th>
<th>inlet temperature $T_w/K$</th>
<th>wall temperature $T_{wall}/K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6</td>
<td>0.2</td>
<td>0.0142</td>
<td>319.65</td>
<td>308.15</td>
</tr>
<tr>
<td>20.0</td>
<td>0.25</td>
<td>0.02675</td>
<td>319.65</td>
<td>308.15</td>
</tr>
<tr>
<td>50.0</td>
<td>0.34</td>
<td>0.06699</td>
<td>319.65</td>
<td>308.15</td>
</tr>
<tr>
<td>100.0</td>
<td>0.42</td>
<td>0.13375</td>
<td>319.65</td>
<td>308.15</td>
</tr>
<tr>
<td>150.0</td>
<td>0.48</td>
<td>0.20063</td>
<td>319.65</td>
<td>308.15</td>
</tr>
</tbody>
</table>
4.1 Temperature distribution along the falling film

The variations of temperature along the falling film interface is shown in Fig. 3. Due to the wall cooling and the less absorption along the falling film downward, the interfacial temperature declines gradually. The large temperature difference between the wall and the interface leads to the interfacial temperature declines rapidly at the inlet.

The larger Reynolds number, the higher interface temperature, and the insignificant temperature change. This is because that a larger Reynolds number results in a higher velocity of falling film and then the more heat is taken into the LiBr solution which causes a reduced decline of the falling film temperature.

![Temperature Distribution along the Falling Film](image)

Fig. 3 Variation of interface temperature along the falling film

4.2 Variation of mass transfer flux

The effects of Reynolds number on the mass transfer flux and average mass transfer flux along the falling film are shown in Fig. 4 and Fig. 5. The local interfacial mass transfer flux arrives at the maximum at the inlet, then decrease rapidly along the flow direction and approach to a constant value gradually. The highest concentration of the LiBr aqueous solution results in the largest mass transfer driving force at the inlet. With the solution falling downward, the concentration of solution decreases. Then the mass transfer flux also decreases.

From Fig. 4 we can learn that the larger the Reynolds number of liquid film, the further away from the inlet to the position of the maximum mass transfer flux, and the slower the heat transfer flux decrease. Larger the Reynolds number corresponds to smaller the maximum mass transfer flux. It can be found from Fig. 5 that when the length of the liquid film is 500mm, in the case of Reynolds number 50, the average mass transfer flux arrives the maximum, that is $2.9\times10^{-3}$ kg·m$^{-2}$·s$^{-1}$; while in the case of the Reynolds number 10.2, the average mass transfer flux arrives the minimum, that is $2.21\times10^{-3}$ kg·m$^{-2}$·s$^{-1}$. Therefore, when the length of the liquid film is constant, there is an optimized Reynolds number of liquid film which leads to a maximum average mass transfer flux.
4.3 Local heat transfer and local mass transfer coefficients

The effect of the Reynolds number on the local heat transfer coefficient is shown in Fig. 6. Neglecting the entrance thermal effect (there is a higher heat transfer coefficient at the entrance than that of the full development because the thermal boundary layer at the entrance is thinner), the increase of Reynolds number results in the decrease of local heat transfer coefficient. The smaller Reynolds number indicates the smaller velocity of the falling film and the thinner liquid film, which results in the smaller heat resistance. So that the local heat transfer coefficient is higher with the smaller Reynolds number.

The variation of local mass transfer coefficient along the falling film under different Reynolds number is shown in Fig. 7. Local mass transfer coefficient reduces along the falling film. With the increase of the Reynolds number of the falling film, the interfacial mass transfer coefficient increases. Because the larger Reynolds number conduces to the shorter time for LiBr aqueous solution absorbing the steam, which makes less water vapor being absorbed into the LiBr aqueous solution. Therefore, the subsequent water vapor is easier to be absorbed.

5. Conclusions

The simulation of the falling film absorption process of the coolant LiBr/H₂O solution was numerically investigated by software CFD-FLUENT. The more practical boundary condition in the falling film was considered. At the different Reynolds number, the interface temperature, mass transfer flux, the local heat and mass transfer coefficient were investigated. The obtained results can be summarized as follows:

(1) For the different Reynolds number, the mass transfer flux at the interface increases rapidly to the
maximum at the inlet and then decrease to an approximate constant. The larger the Reynolds number, the slower decrease of the mass transfer flux after reaching their maximum. At the laminar flow, there is an optimized Reynolds number of liquid film which leads to an averaged maximum mass flux at a fixed length of the film.

(2) An increase of the Reynolds number of falling film leads to an increase of local mass transfer coefficient. On the contrary, an increase of the Reynolds number of falling film conduces to a decrease of interfacial local heat transfer coefficient.

(3) The larger the Reynolds number of liquid film, the further away from the inlet to the position of the maximum mass transfer flux. The larger the Reynolds number corresponds to the smaller maximum mass transfer flux.

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References


Biography

Dr. Jin Liwen obtained his Ph.D. from Nanyang Technological University of Singapore and then worked at National University of Singapore. He is currently a professor working at Xi’an Jiaotong University, China. His research interests include building energy analysis, solar heat storage and heat transfer in microchannels.