Numerical Simulation of Heat and Mass Transfer in the Evaporation of Glycols Liquid Film along an Insulated Vertical Channel

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Received 4 December 2014; Published online 28 March 2015

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Abstract

A numerical study is reported to investigate the evaporation in mixed convection of a pure glycol liquid film such as ethylene and propylene glycol. The model solves the coupled governing equations in both phases together with the boundary and interfacial conditions. The systems of equations obtained by using an implicit finite difference method are solved by TDMA method. The influence of inlet temperature of liquid film and inlet pressure in the gas flow are examined. The results indicate that the propylene glycol evaporates in more intense way in comparison to ethylene glycol, due to the volatility difference. Additionally, In the operating system, the heat transfer by sensible mode is more important than latent mode.

Keywords: Mixed convection; Heat and mass transfer; Evaporation, Ethylene and propylene glycol; Vertical channel

1. Introduction

Heat and mass transfers are important in many processes such as evaporative cooling for waste heat disposal, cooling of a high temperature surface by coating it with a phase-change material, liquid film evaporators, turbine blade cooling, combustion premixing, and distillation of a volatile component from a mixture with in volatiles. The evaporation of liquid film in air is an essential physical phenomenon that may be encountered in the most diverse fields. Because of its practical importance, a large number of theoretical analyses have been made concerning the evaporation of liquid film.

A vast amount of works relating to water have been conducted by many authors. Chang et al. (1986) solved the Navier-Stokes equations using the thin shear flow assumption. The wall of the
tube was considered to be covered by a stationary water film at a specified uniform temperature. This study was extended later by Chiang and Kleinstreuer (1991) by allowing the liquid film to fall under the action of gravity and removing the thin shear flow assumptions. Both studies involve Boussinesq approximation and the flow was assumed to be laminar. The evaporative cooling of liquid film in mixed convection channel flows was explored by Yan et al. (1991); Yan and Lin (1991). Their results show that the liquid film cooling is mainly caused by latent heat transfer associated with its evaporation. The evaporation of the pure liquid film by mixed convection of humid air in a vertical channel has been studied by Yan (1992). Their study shows that the assumption of extremely thin film thickness is valid only for low mass flow rate. He et al. (1998) interested in cooling of the wall in a vertical tube uniformly heated by a water film. Turbulent flow is considered in the gas flow and laminar in the liquid film. Two different modes of heat transfer are identified. When water is supplied at relatively high temperature, the system operates in evaporating mode. When it is low the system operates in the direct film cooling mode. Debbissi et al. (2001) investigated numerically the coupled heat and mass transfers by natural convection during water evaporation into air in a vertical heated channel by including radiative heat transfer between plates. They observed that the evaporative cooling disturbs considerably the velocity and temperature profiles in particular near the exit section of the channel. Feddaoui et al. (2001, 2003b) studied the thermal transfer taking place in the event of film evaporation in the presence of a gas flow inside a vertical heated tube. They reported that the evaporation is improved for a system with higher heat flux and smaller inlet liquid film. They also treated the case of insulated wall for both cylindrical configuration and vertical channel (Feddaoui et al. (2003a, 2006)) for examining the effectiveness of evaporative cooling process.

As far as the evaporation of other pure liquids films was concerned, Tsay et al. (1990) undertook a numerical and experimental study of cooling wall by using an ethanol film on a vertical plate in the presence of a co-current gas flow. It was observed that the interfacial heat flux is predominantly determined by latent heat transfer connected with film evaporation, and significant results are obtained for the system with a high inlet liquid temperature or a low inlet liquid film. Senhaji et al. (2009) conducted a numerical study of evaporating liquid film of pure alcohol by mixed convection. They considered turbulent liquid film falling on the inner face of a vertical tube with a laminar flow of dry air entering the tube with a constant temperature. Recently, Oubella et al. (2014) presents a numerical simulation of the evaporation in laminar mixed convection along a vertical channel formed by two parallel plates; one is isothermal and wetted by a thin liquid film of water or acetone, the second plate is insulated. They showed that the dimensionless mass evaporating rate increases noticeably with the decrease of inlet temperature and the use of more volatile liquid film.

Computational studies of liquid film evaporation for glycols have been carried out by a number of investigators. Palen et al. (1994) conducted an experimental study in the case of mixtures of water-ethylene glycol and water-propylene glycol in a vertical tube. They observed that for some experimental conditions, the local heat transfer coefficient between the partition and the liquid mixture can fall by 80% in relation to the relative value of the pure water, a value that is as low as the one got with the pure ethylene glycol in the same conditions. Agunaoun et al. (1998) presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. The most interesting results are obtained in mixed convection, particularly in the case of ethylene glycol water mixture. Cherif and Daif (1999) considered the evaporation of a thin binary liquid film by mixed convection in a vertical channel. They showed the importance of the film
thickness and composition in the mass and heat transfers. Armouzi et al. (2005) investigated numerically the evaporation by mixed convection of a binary liquid film flowing down of two coaxial cylinders. They showed that the volatilities of the mixture influence the heat transferred through the latent mode, which is more pronounced for a mixture composed of volatile components. Nasr et al. (2011) performed a numerical analysis of the evaporation of binary liquid film. The film is falling down on one plate of a vertical channel under mixed convection. The first plate of a vertical channel is externally submitted to a uniform heated flux while the second one is dry and isothermal. The liquid mixture consists of water and ethylene glycol while the gas mixture has three components: dry air, water vapour and ethylene-glycol vapour. Recently, Debbissi et al. (2013) investigated numerically the evaporation of a binary liquid film flowing on one of two parallel vertical plates under mixed convection channel. This study shows that in some operating conditions, the water evaporates better when mixed with ethylene glycol than water alone.

It is important to note that the evaporation of the pure substances such as ethylene or propylene glycols have not received much attention, despite their importance in industry as the most common antifreeze fluids. In addition most of the studies conducted are not treating the effect of pressure of the surrounding gas on the evaporation phenomena. However, when the gas enters with a high pressure, this will decrease the difference between the gas pressure and its saturation pressure and consequently a disadvantage for the evaporation phenomena. All these considerations motivate the present work by analysing the coupled heat and mass transfers during the evaporation of ethylene glycol and propylene glycol. In the following, the physical and mathematical model will first be presented, and then the numerical approach will be described.

2. Analysis

2.1 Physical model and assumptions

We consider a glycol liquid film falling along the internal face of a vertical channel (Fig 1). The liquid flows down over the left wall with an inlet liquid temperature $T_{L,0}$ and inlet liquid mass flow rate $\Gamma_0$. The flow of dry air enters the channel at temperature $T_o$ and constant velocity $u_0$.

For mathematical formulation of the problem, the following simplifying assumptions are taken into consideration:

- Vapour mixture is ideal gas.
- The gas flow is laminar.
- The vapour and liquid phases are in thermodynamic equilibrium at the interface.
- Radiation heat transfer, viscous dissipation and other secondary effects are negligible.
2.2 Governing equations

2.2.1 Liquid phase

- Continuity equation
\[ \frac{\partial (\rho_L u_L)}{\partial x} + \frac{\partial (\rho_L v_L)}{\partial y} = 0 \]  

- Momentum equation
\[ \frac{\partial (\rho_L u_L u_L)}{\partial x} + \frac{\partial (\rho_L u_L v_L)}{\partial y} = -\frac{dp}{dx} + \frac{\partial}{\partial y} \left[ \mu_L \frac{\partial u_L}{\partial y} \right] + \rho_L g \]  

- Energy equation
\[ \frac{\partial (\rho_L C_{pl} u_L T_L)}{\partial x} + \frac{\partial (\rho_L C_{pl} v_L T_L)}{\partial y} = \frac{\partial}{\partial y} \left[ \lambda_L \frac{\partial T_L}{\partial y} \right] \]  

2.2.2 Gas stream

- Continuity equation
\[ \frac{\partial (\rho_G u_G)}{\partial x} + \frac{\partial (\rho_G v_G)}{\partial y} = 0 \]  

- Momentum equation
\[ \frac{\partial (\rho_G u_G u_G)}{\partial x} + \frac{\partial (\rho_G u_G v_G)}{\partial y} = -\frac{dp}{dx} + \frac{\partial}{\partial y} \left[ \mu_G \frac{\partial u_G}{\partial y} \right] + \rho_G g \]  

- Energy equation
\[
\frac{\partial}{\partial x} \left( \rho_G C_p G u_G T_G \right) + \frac{\partial}{\partial y} \left( \rho_G C_p G v_G T_G \right) = \frac{\partial}{\partial y} \left[ \lambda_G \frac{\partial T_G}{\partial y} \right] + \frac{\partial}{\partial y} \left[ \rho_G D (C_{pv} - C_{pa}) T_G \right] \frac{\partial w}{\partial y}
\]

(6)

Concentration equation of vapour

\[
\frac{\partial}{\partial x} \left( \rho_G u_G w \right) + \frac{\partial}{\partial y} \left( \rho_G v_G w \right) = \frac{\partial}{\partial y} \left[ \rho_G D \frac{\partial w}{\partial y} \right]
\]

(7)

In the above equations, \( \rho, u, v, T, w, \mu, \lambda \) and \( D \), respectively, stand for the density, axial velocity, transverse velocity, temperature, mass fraction of vapour, dynamic viscosity, conductivity and mass diffusivity; \( C_{pg}, C_{pv} \) and \( C_{pa} \) are the specific heat of gas, glycol vapour and air, respectively, and \( g \) is the gravitational acceleration. The subscripts \( L \) and \( G \) denote the liquid and gas phases, and \( 0 \) the condition at inlet. The pressure gradients in equations (2) and (5) can be written as:

\[
\frac{\partial p}{\partial x} = \frac{\partial p_d}{\partial x} + \rho_0 g
\]

Thus the term:

\[
- \frac{\partial p}{\partial x} + \rho g = - \frac{\partial p_d}{\partial x} + (\rho - \rho_0) g
\]

where the term \( (\rho - \rho_0) g \) represents the buoyancy forces due to the variations in temperature and concentration.

2.2.3 Boundary and interfacial conditions

The boundary conditions are:

- \( x = 0 \): \( u_G = u_0 \); \( T_G = T_0 \); \( w = w_0 \); \( T_L = T_{L,0} \)
- \( y = 0 \): \( u_L = v_L = 0 \); \( \frac{\partial T_L}{\partial y} = 0 \)
- \( y = d \): \( u_G = v_G = 0 \); \( \frac{\partial T_G}{\partial y} = 0 \); \( \frac{\partial w}{\partial y} = 0 \)

The interfacial matching conditions specified at \( y = \delta \) are described as follows:

- Continuities of velocity and temperature:
  \( u_l(x) = u_{G,l} = u_{L,l} \); \( T_l(x) = T_{G,l} = T_{L,l} \)

(8)

- Continuity of shear stress
  \( \tau_l = \left[ \mu \frac{\partial u}{\partial y} \right]_{L,I} = \left[ \mu \frac{\partial u}{\partial y} \right]_{G,I} \)

(9)

Transverse velocity of the air-vapor mixture is deduced by assuming that the interface is semipermeable (Eckert and Drake (1972)) that is, the solubility of air in the liquid film is negligibly small and the \( y \)-directed velocity of air is zero at the interface:
By assuming the interface is in thermodynamic equilibrium and the air-vapor mixture is an ideal gas mixture, the mass fraction of water or glycols vapor at the interface can be evaluated by the relation:

\[
w_{ij} = \frac{M_v p_{v,ij}}{M_a (p - p_{v,ij}) + M_v p_{v,ij}}
\]

where \( p_{v,ij} \) is the partial pressure of vapor at the interface, and \( M_v \) and \( M_a \) are, respectively, the molar masses of vapor and air;

- Heat balance at the interface implying

\[
- \lambda \frac{\partial T}{\partial y} \bigg|_{L,ij} = - \lambda \frac{\partial T}{\partial y} \bigg|_{G,ij} + \dot{m}_i h_{fs}
\]

where \( h_{fs} \) is the enthalpy of evaporation and \( \dot{m}_i \), the vapor generation rate \( (\rho_G v_i) \).

The local heat exchange between the air stream and liquid film depends on two related factors: the interfacial temperature gradient on the air side results in sensible convective heat transfer, and the evaporative mass transfer rate on the liquid film side results in latent heat transfer. The total convective heat transfer from the liquid film to the air stream can be expressed as follows:

\[
q_i = q_{si} + q_{li} = \left[ - \lambda \frac{\partial T}{\partial y} \right]_{G,ij} + \dot{m}_i h_{fs}
\]

The local Nusselt number at the interface defined as:

\[
Nu_x = \frac{h_f (2d)}{\lambda_G} = \frac{q_i (2d)}{\lambda_G (T_i - T_b)}
\]

Can be written as:

\[
Nu_x = Nu_S + Nu_i
\]

where \( Nu_S \), and \( Nu_i \), are, respectively, the local Nusselt numbers for sensible and latent heat transfer, and are defined as:

\[
Nu_S = \frac{q_{si} (2d)}{\lambda_G (T_i - T_b)}
\]

And

\[
Nu_i = \frac{q_{li} (2d)}{\lambda_G (T_i - T_b)}
\]

The local Sherwood number is defined as:

\[
Sh_x = \frac{h_m (2d)}{D} = \frac{\dot{m}_i (1 - w_i) (2d)}{\rho_G D (w_i - w_b)}
\]

where the subscript \( b \) denote the bulk quantities, the local bulk temperature \( T_b \) and the bulk mass fraction \( w_b \) in the channel are respectively defined as follows:
\[
T_b = \frac{\int \rho_G C_{pg} u_G T dy}{\int \rho_G C_{pg} u_G dy}
\]

(19)

And

\[
w_h = \frac{\int \rho_G u_G w dy}{\int \rho_G u_G dy}
\]

(20)

At every axial location, the overall mass balance in the gas flow and liquid film should be satisfied:

\[
(d - \delta_0) \rho_G u_0 = \int_{\delta_x}^{d} \rho_G u_G dy - \int_{0}^{x} \rho_G v_l dx
\]

(21)

\[
\Gamma_0 = \int_{0}^{\delta_x} \rho_L u_L dy + \int_{0}^{x} \rho_G v_l dx
\]

(22)

To improve the understanding of heat and mass transfer process, a cumulative evaporation rate is introduced:

\[
M_r = \int_{0}^{x} \tilde{m}_l dx = \int_{0}^{x} \rho_G v_l dx
\]

(23)

Note that in the above formulation, the variations of the thermophysical proprieties with temperature and air-vapour composition are included. They are calculated from the pure component data by means of mixing rules applicable to any multicomponent mixture. For further details, the thermophysical proprieties are available in (Reid and Sherwood (1984)).

### 3. Numerical Method

The conjugated problem is defined by the parabolic systems equations, (Eqs. 1–7) with the appropriate boundary conditions are solved by a finite difference numerical scheme. Since the impossibility of obtaining an analytic solution for the non-linear coupling differential equations, the axial convection terms are approximated by the backward difference and the transversal convection and diffusion terms are approximated by the central difference. Each system of the finite-difference equations forms a tridiagonal matrix equation which can be solved by the Thomas algorithm (Patankar (1980)).

#### 3.1 Marching procedure

After specifying the flow and thermal conditions, the numerical solution is advanced forward and step by step as follows:

1. For any axial location \( x \), guesses \( \frac{dp_G}{dx} \) and \( \delta_x \).
2. Solve the finite-difference forms of equations (1)-(7) simultaneously for \( u \), \( T \) and \( w \).

   Numerically integrate (1) and (4) to find \( v \).

3. Check the mass conservation of both liquid film and gas flow by examining the satisfaction of the equations (21) and (22). If not, adjust \( \frac{dp}{dx} \) and \( \delta_x \) and repeat procedures 2 to 4.

4. Check the satisfaction of the convergence of velocity, temperature and mass fraction. If the relative error between two consecutive iterations is small enough, i.e.:

   \[
   \frac{\max |\psi^n_{i,j} - \psi^{n-1}_{i,j}|}{\max |\psi^n_{i,j}|} < 10^{-4}
   \]

   where \( \psi \) represents the variables \( u \), \( T \) and \( w \). If not, repeat procedures 1 to 5.

3.2 Stability mesh

To obtain enhanced accuracy in the numerical computations, grids are chosen to be non-uniform in both axial and transverse directions. Accordingly the grids are compressed towards the interface gas-liquid and towards the entrance of channel. Grid independence tests were carried out by comparing the total heat transfer of ethylene and propylene glycol for different values of \( I \), \( J \) and \( K \) (Table 1). It is noted that the differences in the cumulative evaporation rate from computations using grids ranging from \( 51 \times (51 + 21) \) to \( 201 \times (201 + 61) \) were always less than three percent. In light of those results all further calculations were performed with the \( 101 \times (101 + 41) \) grid.

In order to fix the position of the liquid-gas interface, the cartesian \( y \) coordinate transformed into \( \eta \) coordinates:

\[
\eta = \frac{y - \delta_x}{\delta_x} \quad \text{for} \quad 0 \leq y \leq \delta_x
\]

\[
\eta = \frac{y - \delta_x}{d - \delta_x} \quad \text{for} \quad \delta_x \leq y \leq d
\]

Table 1

<table>
<thead>
<tr>
<th>( \chi/d )</th>
<th>( 51 \times (51 + 21) )</th>
<th>( 51 \times (101 + 21) )</th>
<th>( 101 \times (101 + 41) )</th>
<th>( 201 \times (101 + 61) )</th>
<th>( 201 \times (201 + 61) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. gly</td>
<td>P. gly</td>
<td>E. gly</td>
<td>P. gly</td>
<td>E. gly</td>
<td>P. gly</td>
</tr>
<tr>
<td>1.09</td>
<td>1.78</td>
<td>2.82</td>
<td>1.92</td>
<td>4.12</td>
<td>1.88</td>
</tr>
<tr>
<td>5.07</td>
<td>5.96</td>
<td>8.94</td>
<td>6.82</td>
<td>11.04</td>
<td>6.14</td>
</tr>
<tr>
<td>41.03</td>
<td>20.86</td>
<td>33.82</td>
<td>22.20</td>
<td>35.78</td>
<td>21.78</td>
</tr>
<tr>
<td>66.90</td>
<td>26.90</td>
<td>43.96</td>
<td>28.10</td>
<td>44.90</td>
<td>27.92</td>
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<td>96.08</td>
<td>31.82</td>
<td>51.50</td>
<td>33.16</td>
<td>52.50</td>
<td>33.16</td>
</tr>
</tbody>
</table>
I: total grid points in the axial direction; J: total grid points in the transverse direction at the gas side; K: total grid points in the transverse direction at the liquid side.

3.3 Comparison with previous studies

To further check the adequacy of the numerical scheme for the present study, the results of the present model were compared with study of Yan (1992). The solutions agree well between the present predictions and those of Yan (1992) as shown in figure 2 which presents the axial evolution of local Nusselt number. In view of these validations, the present numerical algorithm and employed grid layout are adequacy to obtain accurate results for practical purposes.

![Graph showing comparison between present prediction and simulation of Yan (1992).](image)

**Fig. 2.** Comparison of our present work with those of Yan (1992). validation of calculated Local Nusselt number along the channel for $Re = 2000$, $T_0 = 20^\circ C$

4. Results and Discussions

In this study, the results were obtained for impure parameters. The range of each parameter for the analysis is listed in Table 2. The chosen common parameters are the length of the channel $L = 2m$, the dry air at $T_0 = 300K$ and the width of the channel $d = 0.02m$.

**Table 2** The ranges of the physical parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet liquid temperature, $T_{L0} (K)$</td>
<td>360, 400</td>
</tr>
<tr>
<td>Inlet pressure, $p_0 (atm)$</td>
<td>1, 2</td>
</tr>
<tr>
<td>Inlet liquid mass flow rate, $G_0 (kgm^{-1}s^{-1})$</td>
<td>0.01, 0.02</td>
</tr>
<tr>
<td>Inlet Reynolds number, $Re$</td>
<td>1000, 2000</td>
</tr>
</tbody>
</table>

For comparing the evaporation of some industrial fluids such as ethylene glycol and propylene glycol, it is of interest to study the evolution of some physical properties which control the evaporation phenomena. Figure 3a presents the effect of the liquid temperature on the evolution of saturated pressure for two glycols liquids ethylene and propylene. It is clear that the saturated pressure of propylene glycol is more important than ethylene glycol, consequently propylene glycol
is more volatile than ethylene glycol. The effect of the liquid temperature on the specific heat capacity of the two liquids is illustrated in figure 3b. It is apparent that the specific heat which represents the amount of heat per unit mass required to raise the temperature by one degree Celsius is higher for propylene glycol. This implies that the specific heat for propylene is greater than ethylene. Figure 4 shows the development of the predicted velocity profiles along the channel of glycols film. The velocity profiles develop gradually from the uniform distributions at the inlet towards the parabolic ones when the flow goes downstream, with the maximum velocity shifting towards the insulated wall. The results indicate that in the gas flow, velocity profiles of ethylene and propylene glycol are similar except a small difference in the maximum velocity. Indeed, \( \eta = 0.65 \) speed ethylene glycol is higher than a propylene glycol. This is due to the lower density of ethylene glycol than propylene glycol. Figure 5 presents the distribution of axial temperature profiles along the channel for various sections. In the gas flow the temperature increases as the flow goes downstream which is due to the energy supplied by the liquid film to the gas stream. The later, explains the liquid temperature decreases from the inlet to the outlet channel. It is interesting to observe that distribution of axial temperature profiles along the channel of glycols film develop in very similar fashion. This is apparently due to the small difference between the specific heats of the two glycols studied. In the liquid phase, the temperature seems to be constant. This can be explained by the fact that the liquid film is extremely thin, so the distribution of temperature inside the liquid phase in the transverse direction is approximately constant, except at high inlet liquid film (liquid flowing turbulently) when a slight decrease will be noticed from the temperature at the wall to that at the gas-liquid interface. Figure 6 shows the evolution of the mass fraction of glycols in the gas for different sections of the channel. Also it is noted that the mass fraction of propylene glycol is higher than the mass fraction of the ethylene glycol close to the interface liquid-gas. This increase is much more noticeable for more volatile component, i.e. propylene glycol than ethylene glycol.

Fig. 3. Evolution of thermophysicals propertises of propylene glycol and ethylene glycol with the temperature of: (a) Saturate pressure, (b) Specific heat
Fig. 4. Distributions of axial velocity profile for $T_{L0} = 400K$, $Re = 2000$ and $\Gamma_0 = 0.02\,kgm^{-1}s^{-1}$

Fig. 5. Distributions of axial temperature profile for $T_{L0} = 400K$, $Re = 2000$ and $\Gamma_0 = 0.02\,kgm^{-1}s^{-1}$
Fig. 6. Distributions of axial mass fraction profiles for $T_{L0} = 400K$, Re = 2000 and $\Gamma_0 = 0.02kgm^{-1}s^{-1}$

Fig. 7. Distributions of temperature at the gas-liquid interface along the channel for (a) Ethyleneglycol (b) Propylene glycol, for Re = 2000 and $\Gamma_0 = 0.02kgm^{-1}s^{-1}$
For more detailed analysis of heat and mass transfer characteristics, our attention is focused on the effect of the inlet pressure and inlet liquid temperature. Figure 7 shows the effect of the inlet pressure of the gas and inlet liquid temperature on the interfacial temperature along the channel. It is noticed that the interfacial temperature decreases as the flow goes downstream. This decrease is due to the heat transfer from the liquid film to the gas flow. Also the interfacial temperature profiles for two glycols are develop in very similar fashion except some differences in the output of the channel. It is clear that the interfacial temperature decreases from the inlet to the exit channel for the lower pressure, which is evident for the perfect gas assumed in this study. Indeed when the gas enters with a high pressure, this reduces the intermolecular distance and reduces the evaporation. The distributions of the interfacial mass fraction of glycols vapour along the gas-liquid interface are given in figure 8 for various inlet pressure and inlet liquid temperature. It is shown that the interfacial mass fraction decreases with small inlet liquid temperature or a high inlet pressure. Indeed, for a fixed value of inlet pressure, we observed that the interfacial mass fraction is high for high inlet liquid temperature. The interfacial mass fraction increases with the decrease of inlet pressure whereas the reverse trend is noticed for the effect of the inlet liquid temperature along the channel. This is obviously due to the enhancement of the evaporation in the operating conditions.
Fig. 9. Axial evolution of sensible heat flux for (a) Ethylene glycol (b) Propylene glycol, for $Re = 2000$ and $\Gamma_0 = 0.02 kg m^{-1} s^{-1}$

Fig. 10. Axial evolution of latent heat flux for (a) Ethylene glycol (b) Propylene glycol, for $Re = 2000$ and $\Gamma_0 = 0.02 kg m^{-1} s^{-1}$

Fig. 11. Axial evolution of cumulative evaporation rate for (a) Ethylene glycol (b) Propylene glycol, for $Re = 2000$ and $\Gamma_0 = 0.02kgm^{-1}s^{-1}$

In figure 9 we present the axial distribution of the sensible heat flux at the interface. It is remarkable that the heat transfer by sensible mode decreases monotonically for both glycols for $(x/d < 20)$ and tends towards an asymptotic value at the channel exit. The later, can be explained by the decrease of the gradient of temperature between the hot liquid film and the cold gas as the flow goes downstream. It is interesting to observe that the distribution of sensible heat flux at the interface along the channel develop in very similar fashion for the two glycols. This is apparently due to the small difference between the specific heat of the two studied glycols (Fig 3b). It is also clear that the sensible heat $q_s$ increases with the increase of the inlet liquid temperature. Whereas, the effect of the inlet gas pressure on the sensible heat transfer is not very pronounced.

The effects of $T_{L0}$ and $P_0$ on the evolution of latent heat transfer are illustrated in figure 10. The first observations to be drawn from these curves indicate that the glycols are varied in similar fashion, with a lower increase for propylene than ethylene. This is due to the higher saturated pressure of propylene compared to ethylene (Fig 3a). It is also noticed that latent heat transfer is higher for a high inlet liquid temperature and lower inlet pressure, indicating the evaporation enhancement in these operating conditions. It remains to notice that the heat transfer by evaporation is lower than the heat transfer by sensible mode due to temperature gradient. This ascertainment is confirmed by figure 11 which represents the evolution of the cumulative evaporation rate along the channel. It is clear that the evaporation rate increases when we increase the inlet liquid temperature of the liquid film. Indeed, when the liquid film enters at $400K$, it is close to its boiling point and hence the evaporation is optimal. However, despite a higher inlet liquid temperature, the effect of the pressure is remarkable. For $T_{L0} = 400K$ and $P_0 = 1atm$ we can reach more than $2.7\%$ for propylene glycol and $1.7\%$ for ethylene glycol, whereas for other inlet liquid temperature and inlet pressure, the cumulated evaporation rate does not exceed $0.8\%$. In
addition, there is a significant difference between the evaporation of the propylene glycol and ethylene glycol, which apparently due to the higher volatility of propylene glycol compared to ethylene glycol as clearly seen from (Fig 3a).

5. Conclusion

The analysis presented in this paper has been developed by comparing the evaporation of two glycols liquid film: ethylene glycol and propylene glycol along a vertical channel. The effect of inlet liquid film temperature and inlet pressure on the momentum, heat and mass transfer in the two phases are examined in detail. Based on the numerical results obtained, the following conclusion can be drawn:

(1). In the operating system, the heat transfer by sensible mode is more important than latent mode.
(2). Heat and mass transfers by latent mode are more enhanced at lower pressure.
(3). Evaporation of glycols is improved for a system with higher inlet liquid film temperature.
(4). Propylene glycol evaporates in more intense way in comparison to ethylene glycol, due to the volatility difference.

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