EVAPORATION AND CONDENSATION OF FALLING BINARY LIQUID FILM

by

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This paper investigates a numerical analysis of coupled heat and mass transfer during the simultaneous evaporation and condensation in the presence of a binary liquid film flowing on one of two parallel vertical plates under mixed convection. The first plate of a vertical channel is externally insulated and wetted by a binary liquid film while the second one is dry and isothermal. The liquid mixture consists of water (the more volatile component) and ethylene glycol while the gas mixture has three components: dry air, water vapour and ethylene glycol vapour. The conducted simulations enable the analysis of the heat and mass transfer during water evaporation and ethylene glycol condensation for different inlet gas properties. It is found that an increase of the inlet vapour concentration of ethylene glycol enhances the water evaporation while the increase of the inlet vapour concentration of water slightly enhances the ethylene glycol vapour condensation. The increase of inlet gas temperature considerably benefits the water evaporation and slightly influences the ethylene glycol condensation.

Key words: *binary liquid film, condensation, evaporation, heat and mass transfer, mixed convection.*

Introduction

The evaporation and condensation of the liquid film in air exist in different industrial applications such as desalination plants, drying, air-conditioning equipment, and desalting. One of the important works on condensation of pure vapours on plates is that of Minkowycz and Sparrow [1]. In fact, they presented a theoretical study of falling film condensation by free convection on an isothermal vertical plate. They showed the importance of the effect of non-condensable gas at lower pressure levels. Yang [2] studied the condensation characteristics by free convection inside a vertical tube. Siow *et al*. [3] conducted a numerical study of the laminar film condensation of vapour-gas mixtures in horizontal channels. They analysed the effects of gas concentration, Reynolds number, pressure, and the inlet-to-wall temperature difference on the film thickness and on the heat and mass transfers. Agrawal *et al*. [4] presented a study of the heat transfer augmentation by coiled wire inserts during forced convection condensation of R22 inside horizontal wetted tubes. Panday [5] numerically treated the film condensation of vapour flowing in a vertical tube and between parallel plates. They take into account the turbulence

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in the vapour and in the condensate film. They presented the heat flow rate for the condensation of R123 and the mean heat transfer coefficients for the condensation of vapour mixture R123/R134a. Chung *et al*. [6] presented the experimental results comparing film and drop condensations. They showed that in the pure steam cases, the heat transfer rates of drop condensations are much higher than of film condensations. Yan and Lin [7] studied the evaporation and condensation by natural convection along the wetted walls in vertical annuli. In this study, the walls are wetted by an extremely thin liquid film. They examined the effects of the wetted wall temperature, inlet relative humidity, and radii ratio on coupled heat and mass transfers. Using an parabolic formulation, Feddaoui *et al*. [8] provided a numerical computation of the evaporative cooling of falling water film in turbulent mixed convection inside a vertical tube. Zheng Hongfei [9] experimentally studied the falling film evaporation and condensation in the closed circulation solar still. Their findings show that the thermal performance of the solar still is greatly improved because of the technology of the forced thin layer evaporation and film condensation used. Khalal *et al*. [10] reported a numerical study of the heat and mass transfer during evaporation of a turbulent binary liquid film. They showed that the heat transferred through the latent mode is more pronounced when the concentration of volatile components is higher in the liquid mixture. Nasr *et al*. [11, 12] presented a numerical analysis of the evaporation of binary liquid film flowing on a vertical channel by mixed convection. They showed that when the inlet liquid composition of ethylene glycol is less than 40%, it is possible to evaporate more water than if the film at the entry was pure water only. This result has been explained by the fact that an increase in the inlet liquid composition of ethylene glycol has two opposed effects on the accumulated evaporation rate of water. Ali Cherif and Daif [13] numerically investigated the evaporation of binary liquid film flowing on the vertical channel. The wetted plate is subjected to uniform heat flux while the other is dry and adiabatic. They showed the importance of taking into account of film thickness and mixture composition in the mass and thermal transfers. They showed that for a particular liquid composition of ethylene glycol, it is possible to evaporate more water than if the film at the entry was pure water only. Agunaoun *et al*. [14] numerically examined the evaporation of a binary liquid film flowing on an inclined plate. They showed that the water evaporation can increase when the inlet liquid composition of ethylene-glycol is less than 40%. Oubella *et al*. [15] numerically studied the heat and mass transfer with film evaporation in a vertical channel. They showed that the influence of the latent Nusselt numbers on the cooling of induced flows by evaporation depend largely on the inlet temperature and Reynolds number. They displayed that the better mass transfer rates related with film evaporation are found for a system with low mass diffusion coefficient. Senhaji *et al*. [16] conducted a simultaneous heat and mass transfer inside a vertical tube in evaporating a heated falling alcohols liquid film into a stream of dry air. They analysed the influence of the inlet liquid flow, Reynolds number in the gas flow and the wall heat flux on the intensity of heat and mass transfers.

The previous review reveals that the simultaneous evaporation and condensation under mixed convection in the presence of a liquid film flowing along one of channel vertical plates, despite their practical importance, have not been studied. The objective of this work is to study the combined heat and mass transfers during evaporation and condensation in the presence of a binary liquid film flowing down. The main objective of this work is to analyse the effect of inlet gas properties on the heat and mass transfer and on the evaporation and condensation processes.

Analysis

The present work consists of a numerical analysis of coupled heat and mass transfers with evaporation and condensation under mixed convection in the presence of a binary liquid

film flowing along one of the vertical plates, fig. 1. The first plate is externally insulated and wetted by a water-ethylene glycol liquid film while the second one is dry and isothermal. The binary liquid film enters the channel with an inlet temperature, T_{0L}, inlet mass flow rate, m_{L0}, and an inlet concentration of ethylene glycol, $c_{\text{Liq,ethy glycol}}$. The air enters the channel with a temperature, T_0, a water and ethylene-glycol vapour concentrations, c_{01} and c_{02}, and velocity, u_0.

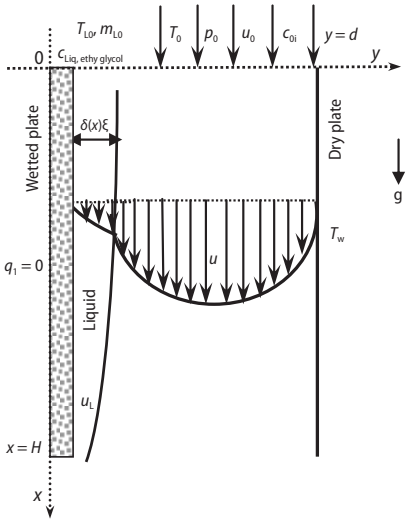

Figure 1. Physical model

Assumptions

For mathematical model of the problem, the following simplifying assumptions are introduced:

- Flows and transfers in the two phases are steady, laminar, and 2-D.
- Vapour mixture is ideal gas.
- Liquid mixture is ideal.
- The boundary layer approximations are used.
- Viscous dissipation and radiative heat transfer are negligible.
- The effect of the superficial tension is negligible. The gas-liquid interface is in thermodynamic equilibrium.
- Dufour and Soret effects are negligible.

Governing equations

The numerical mode that has been presented by Nasr *et al*. [11] and Hfaiedh *et al*. [17] is used in this paper with following prescribed boundary conditions which describe the evaporation and condensation of the physical model under investigation:

- for inlet conditions (at $\xi = 0$):

$$T(0,\eta) = T_0, \quad c_1(0,\eta) = c_{01}, \quad c_2(0,\eta) = c_{02}, \quad u(0,\eta) = u_0, \quad p = p_0 \tag{1}$$

$$T_L(0,\eta_L) = T_{0L}, \quad \delta(0) = \delta_0 \int_0^L \rho_{0L}\delta_0 u_L(0,\eta_L)\,\mathrm{d}\eta_L = m_{L0}, \quad c_{Li}(0,\eta_L) = c_{0Li} \tag{2}$$

- for dry plate (at $\eta = 1$):

$$u(\xi,1) = 0, \quad v(\xi,1) = 0, \quad T(\xi,1) = T_w, \quad \left.\frac{\partial c_i}{\partial \eta}\right|_{\eta=1} = 0 \tag{3}$$

- for wet plate (at $\eta_L = 0$):

$$u_L(\xi,0) = 0, \quad v_L = (\xi,0) = 0, \quad q_1 = -\lambda_L \frac{1}{\delta}\left.\frac{\partial T_L}{\partial \eta_L}\right|_{\eta_L=0}, \quad \left.\frac{\partial c_{L_i}}{\partial \eta_L}\right|_{\eta_L=0} = 0 \tag{4}$$

Here c_{Li} is the mass fraction of species i in the liquid film mixture.

- for gas-liquid interface (at $\eta = 0$ and $\eta_L = 1$):
  - the continuities of the velocities and temperatures are give:

$$u_{\mathrm{L}}\left(\xi,\eta_{\mathrm{L}}=1\right)=u\left(\xi,\eta=0\right),\quad T_{\mathrm{L}}(\xi,\eta_{\mathrm{L}}=1)=T(\xi,\eta=0) \tag{5}$$

– the heat balance at the interface implies [13, 14]:

$$-\frac{1}{\delta}\lambda_{\mathrm{L}}\left.\frac{\partial T_{\mathrm{L}}}{\partial\eta_{\mathrm{L}}}\right|_{\eta_{\mathrm{L}}=1}=-\frac{1}{d-\delta}\lambda\left.\frac{\partial T}{\partial\eta}\right|_{\eta=0}-\dot{m}L_v\quad\text{with}\quad\dot{m}=-\frac{\rho\sum_{i=1}^{2}D_{\mathrm{g}.i\mathrm{m}}\left.\frac{\partial c_i}{\partial\eta}\right|_{\eta=0}}{(d-\delta)\left[1-\sum_{i=1}^{2}c_i(\xi,\eta=0)\right]} \tag{6}$$

Here L_v is the latent heat of evaporation of binary liquid mixture.

According to Dalton's law, and by assuming the interface to be at thermodynamic equilibrium, and the air-vapour mixture is an ideal gas mixture, the concentration of species *i* vapour can be evaluated by [13-15] :

$$\begin{aligned}c_1(\xi,0)&=\frac{p^*_{\mathrm{vs},1}}{p^*_{\mathrm{vs},1}+\left(p^*_{\mathrm{vs},2}\frac{M_2}{M_1}\right)+\left(p-p^*_{\mathrm{vs},1}-p^*_{\mathrm{vs},2}\right)\frac{M_a}{M_1}},\\ c_2(\xi,0)&=\frac{p^*_{\mathrm{vs},2}}{p^*_{\mathrm{vs},2}+\left(p^*_{\mathrm{vs},1}\frac{M_1}{M_2}\right)+\left(p-p^*_{\mathrm{vs},1}-p^*_{\mathrm{vs},2}\right)\frac{M_a}{M_2}}\end{aligned} \tag{7}$$

where $p^*_{\mathrm{vs},i}$ is the partial pressure of species *i* at the gas-liquid interface [13, 14]:

$$p^*_{\mathrm{vs},i}=w_{\mathrm{L}i}\,p_{\mathrm{vs},i}(T),\quad i=1,2 \tag{8}$$

where $p_{\mathrm{vs},i}(T)$ is the pressure of saturated vapour of species *i*:

$$p_{\mathrm{vs},1}=10^{17.443-[2975/\mathrm{T}+3.68\log(\mathrm{T})]}\cdot10^5,\quad p_{\mathrm{vs},2}=6894.8\exp\left[16.44-\frac{10978.8}{(9T/5-49)}\right] \tag{9}$$

The transverse velocity component of the mixture at the interface is obtained by assuming the interface to be semi-permeable [11, 13-15]:

$$v(\xi,\eta=0)=-\frac{\frac{1}{d-\delta}\sum_{i=1}^{2}D_{\mathrm{g},i\mathrm{m}}\left.\frac{\partial c_i}{\partial\eta}\right|_{\eta=0}}{1-\sum_{i=1}^{2}c_i(\xi,\eta=0)} \tag{10}$$

The continuities of shear stress and local evaporated mass flux of species *i* give [13, 14]:

$$\frac{1}{\delta}\mu_L\left.\frac{\partial u_L}{\partial\eta_L}\right|_{\eta_L=1}=\frac{1}{d-\delta}\mu\left.\frac{\partial u}{\partial\eta}\right|_{\eta=0},\quad\dot{m}_i=\dot{m}c_{\mathrm{L}i}-\frac{\rho_1D_1}{\delta}\left.\frac{\partial c_{\mathrm{L}i}}{\partial\eta_1}\right|_{\eta_1=1}=\dot{m}c_i-\frac{\rho D_{\mathrm{g},i\mathrm{m}}}{d-\delta}\left.\frac{\partial c_i}{\partial\eta}\right|_{\eta=0} \tag{11}$$

In order to evaluate the importance of the different processes of energy transfer, the following quantities are used:

– the cumulated evaporation/condensation rate of species *i* at the interface is given by:

$$Mr_{\text{evapi/condi}}(\xi)=\int_0^{\xi}\dot{m}_i(\xi)\mathrm{d}\xi \quad \text{where} \quad \dot{m}_i(\xi)=\dot{m}c_1-\frac{\rho D_{\text{g,im}}}{d-\delta}\frac{\partial c_i}{\partial y}\bigg|_{\eta=0} \tag{12}$$

– the cumulated evaporation/condensation rate of mixture at the interface is given by:

$$Mr_{\text{evapt/condt}}(\xi)=\int_0^{\xi}\dot{m}(\xi)\mathrm{d}x=\sum_{i=1}^{2}Mr_{\text{evapi/condi}} \tag{13}$$

Solution method

The present conjugated problem defined by the system of equations with the boundary and interfacial conditions is solved numerically using a finite difference marching procedure in the downstream direction using rectangular grids in the liquid and gas regions. The mesh is characterised by a longitudinal step $\Delta\xi = 1/(N_\xi - 1)$ and a transversal step $\Delta\eta_L = 1/(N\eta_L - 1)$ in liquid and $\Delta\eta = 1/(N\eta - 1)$ in gas. A fully implicit scheme where the axial convection terms were approximated by the upstream difference and the transverse convection and diffusion terms by the central difference is employed. The discrete equations are resolved line by line from the inlet to the outlet of the channel since flows under consideration are a boundary layer type. To ensure that results were grid independent, the solution was obtained for different grid sizes for a typical case program test. Table 1 shows that the differences in the total evaporating rate obtained using 51×(51+31) and 151×(51+51) grids are always less than 1%.

Table 1. Comparison of total evaporating rate (10^5·Mr) [kgs^{-1}m^{-2}] for various grid arrangements for: T_{0L} = 20 °C, m_{L0} = 0.015 kg/ms, T_w = 20 °C, T_0 = 20 °C, c_{01} = 0, c_{02} = 0, $c_{\text{Liq,water}}$ = $c_{\text{Liq,ethylene glycol}}$ = 0.5 (50% water-ethylene glycol mixture), d/H = 0.015, u_0 = 1 m/s, q_1 = 3000 W/m^2, and p_0 = 1 atm

I×(J+K) grid point	ξ = 0.2	ξ = 0.4	ξ = 0.6	ξ = 0.8	ξ = 1
51×(51+31)	5.05546	10.49324	18.59606	30.02837	43.29377
101×(51+31)	5.08366	10.35767	18.48970	29.97913	43.37085
101×(31+31)	4.98680	10.27552	18.28331	30.02837	43.37085
101×(51+51)	5.08068	10.34552	18.48310	30.03837	43.40185
151×(51+51)	5.10368	10.55152	18.69310	30.04137	43.41085

I: total grid points in the axial direction; *J*: total grid points in the transverse direction in the gaseous phase; *K*: total grid points in the transverse direction in the liquid phase.

To verify the adequacy of the numerical scheme adopted in the present work, the procedure has been tested by comparing the present solutions for the total evaporating rate, Mr^*, and the interfacial temperature ($T_w - T_0$) for different values of heat flux with the results of Ali Cherif and Daif [13] for the case of the evaporation of the binary liquid film, figs. 2(a) and 2(b). The comparison has been done for T_0 = 293.15 K, c_{01} = 0, c_{02} = 0, T_{0L} = 293.15 K, q_2 = 0, m_{L0} = 0.02 kg/ms, Re = 1000, the geometrical ratio is d/H = 0.015, the imposed wall heat flux is q_1 = 3000 W/m², and the inlet film composition of ethylene-glycol is $c_{\text{Liq, ethylene glycol}}$ = 0.5 (50% water-ethylene glycol mixture). It is seen from figs. 2(a) and 2(b) that the agreement between our results and those obtained by Ali Cherif and Daif [13] is satisfactory.

Results and discussions

In this study, the results have been obtained for the case of T_{0L} = 293.15 K, T_w = 293.15 K, m_{L0} = 0.015 kg/ms, u_0 = 1 m/s, the geometrical ratio is d/H = 0.015, and the imposed wall heat flux is q_1 = 0.

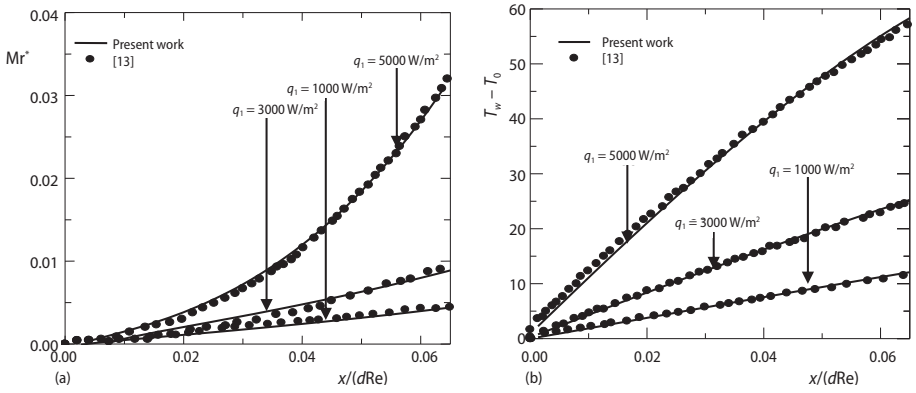

Figure 2. Comparison of present work with these of Ali Cherif and Daif [13] with $c_{Liq,ethylene\ glycol} = c_{Liq,water} = 0.5$ (50% water-ethylene glycol mixture): (a) validation of calculated total evaporating rate along the channel, (b) validation of calculated interfacial temperature along the channel

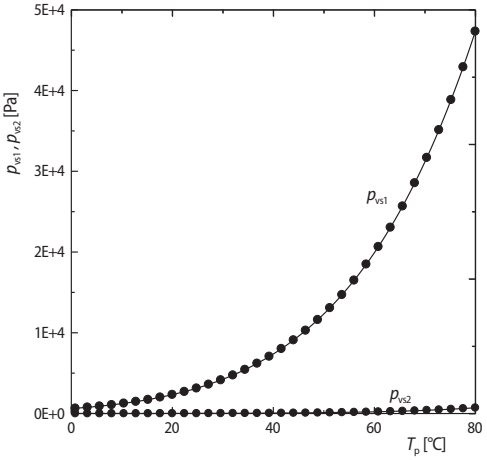

Figure 3. The saturated pressure profiles of water, p_{vs1}, and of ethylene glycol, p_{vs2}, with the wall temperature

Figure 3 shows that the saturated pressure of water is more important than the ethylene-glycol and consequently the water is more volatile than the ethylene-glycol. It is noticed that when the wall temperature, T_p, increases, the difference between the saturated pressures of water and of ethylene-glycol becomes more important. Figure 4 illustrates the progress of the phase change process of species i and of the mixture along the channel. It is important to mention that the total mixture has a tendency to condense. This result has been justified by the fact that the total cumulated condensation rate of ethylene glycol vapour is more important to the total cumulated evaporation rate of water and consequently the total mixture has a tendency to condense. Figure 5 indicates the effect of the inlet vapour concentration of ethylene glycol on the temperature profile at the channel exit ($\xi = 1$). It is shown that an increase of the inlet vapour concentration of ethylene glycol induces an increase of the temperature. This result can be explained by the fact that an increase of the inlet vapour concentration of ethylene glycol enhances the ethylene glycol condensation. As a result, the temperature at the interface liquid-gas increases. It can be noted from figs. 6(a) and 6(b) that the concentrations of water and ethylene glycol vapour at the channel exit increase with an increase of the inlet vapour concentration of ethylene glycol.

Figure 7 illustrates the influence of the inlet vapour concentration of ethylene glycol c_{02} on the water evaporation rate. The careful observation of curve given in fig. 7 shows that an increase of the inlet vapour concentration of ethylene glycol enhances the water evaporation. This result has been justified by the fact that an increase of the inlet vapour concentration of ethylene glycol benefits the ethylene glycol condensation, fig. 8, which causes an increase of the temperature at the interface, fig. 5, and consequently improves the water evaporation. As depicted by fig. 9, the temperature at the channel exit increases with the increase of humidity c_{01}.

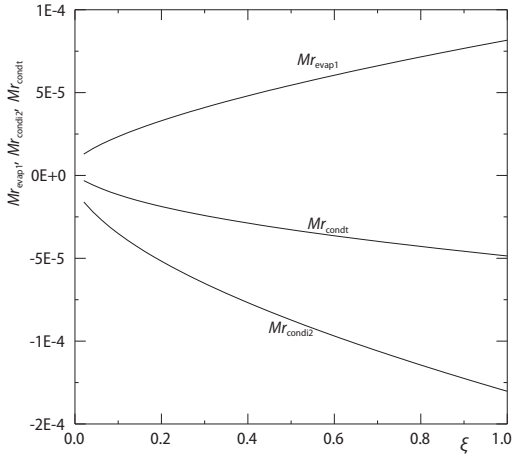

Figure 4. Evolution of the phase change process of species *i* and of the mixture along the channel: $c_{01} = 0$, $c_{02} = 0.3$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = c_{\text{Liq, water}} = 0.5$

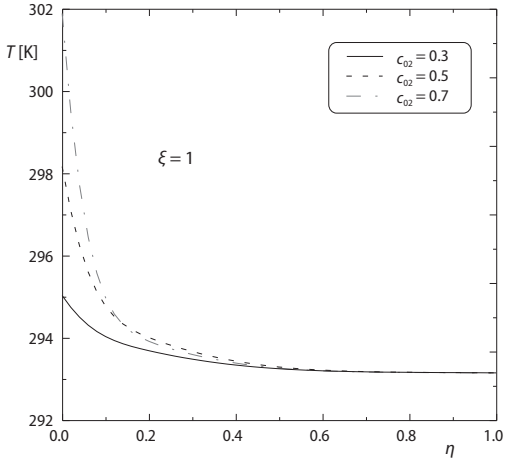

Figure 5. Effect of the inlet vapour concentration of ethylene glycol on the temperature profile at the channel exit ($\xi = 1$): $c_{01} = 0$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

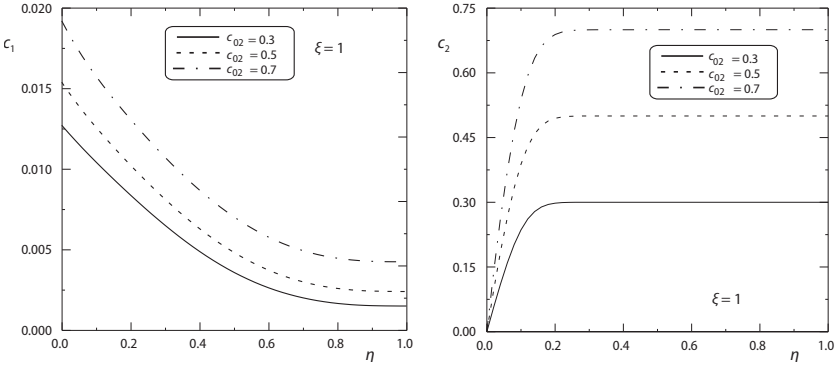

Figure 6. Effect of the inlet concentration vapour of ethylene glycol on the concentrations profiles at the channel exit: (a) water vapour concentration, (b) ethylene glycol vapour concentration, $c_{01} = 0$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

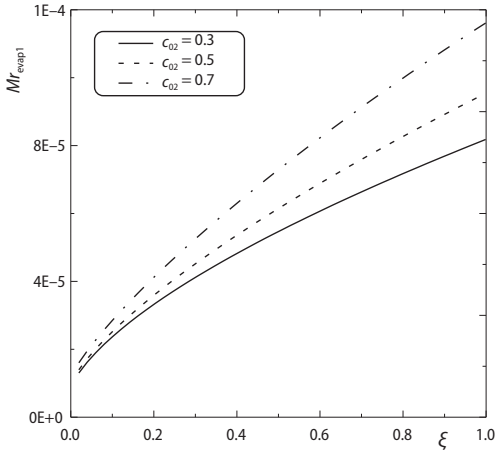

Figure 7. Effect of the inlet vapour concentration of ethylene glycol on the total cumulated evaporation rate of water along the channel: $c_{01} = 0$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

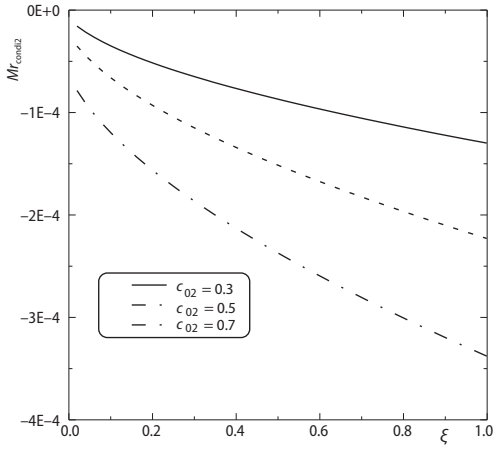

Figure 8. Effect of the inlet vapour concentration of ethylene glycol on the total cumulated condensation rate of ethylene glycol along the channel: $c_{01} = 0$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

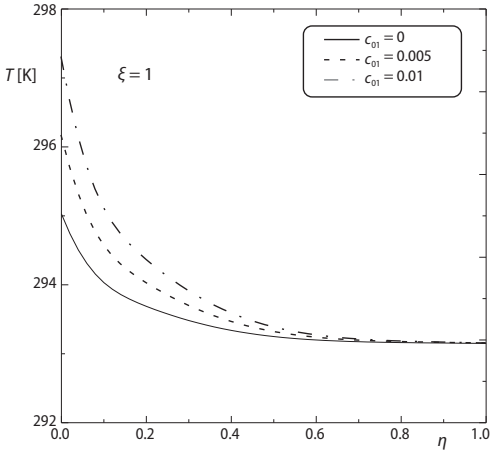

Figure 9. Effect of the inlet vapour concentration of water on the temperature profile at the channel exit: $c_{02} = 0.3$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

This result has been justified by the fact that increasing c_{01} decreases the water evaporation as results the wall cooling decreases. It can be seen from fig. 10(a) that the concentration gradient of water vapour decreases with the increase of c_{01}. Consequently, the water evaporation rate decreases when the humidity c_{01} increases. This result is confirmed with that found in fig. 11. It is shown in fig. 10(b) that the humidity variation has practically no effect on the ethylene glycol vapour concentration and consequently slightly influences the ethylene glycol condensation rate, fig. 12. Figure 13 presents the influence of the inlet gas temperature, T_0, on the temperature profile at the channel exit. It is generally obvious that the temperature at the channel exit decreases as the T_0 decreases. It is observed from fig. 14(a) that the concentration gradient of water vapour increases with the increase of T_0. Thus, the water evaporation becomes more important for higher values of T_0, fig. 15. Observing fig. 14(b), one can see that the inlet gas temperature, T_0, has no effect on the concentration gradient of ethylene glycol vapour and consequently has no effect on the condensation rate of ethylene glycol, fig. 16.

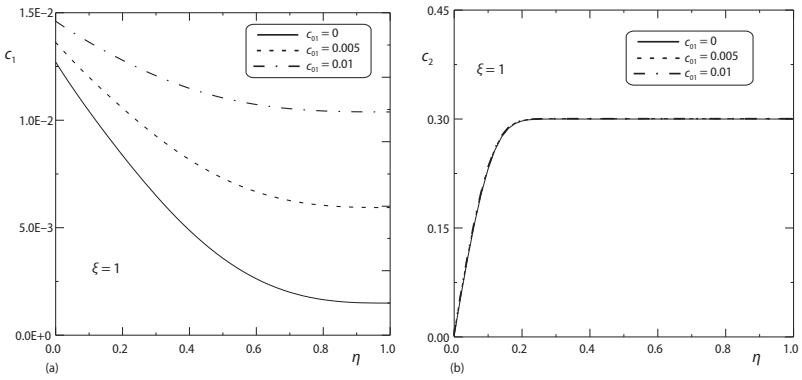

Figure 10. Effect of the humidity on the concentrations profiles at the channel exit: (a) concentration of water vapour, (b) concentration of ethylene glycol vapour $c_{02} = 0.3$, $T_0 = 20$°C, $c_{\text{Liq, ethylene glycol}} = 0.5$

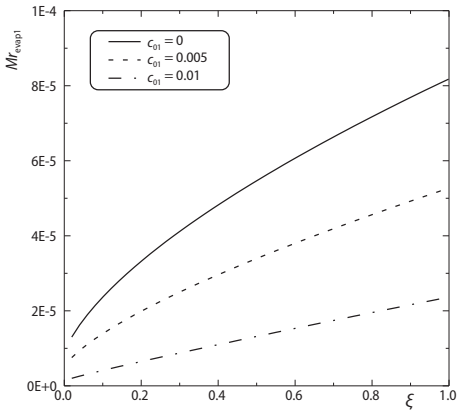

Figure 11. Effect of the humidity on the total cumulated evaporation rate of water along the channel: $c_{02} = 0.3$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

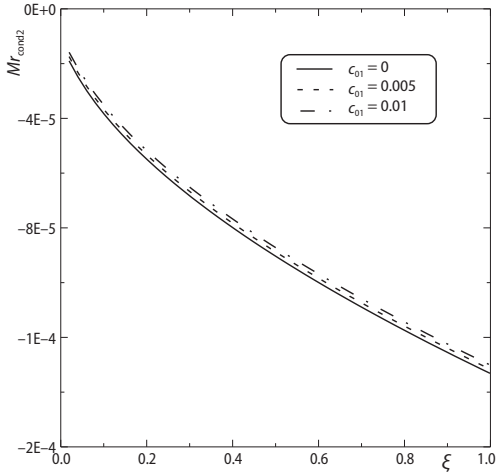

Figure 12. Effect of the humidity on the condensation rate of ethylene glycol along the channel: $c_{02} = 0.3$, $T_0 = 20$ °C, $c_{\text{Liq, ethylene glycol}} = 0.5$

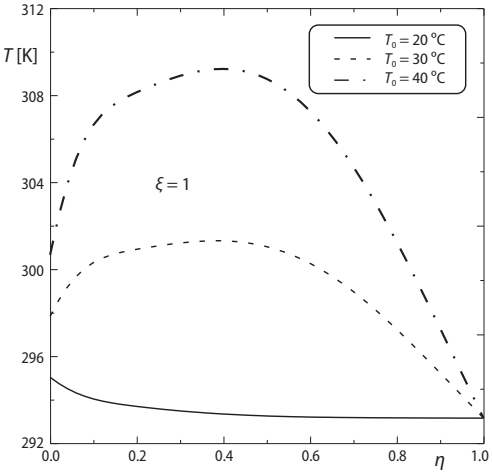

Figure 13. Effect of the inlet gas temperature on the temperature profile at the channel exit: $c_{01} = 0$, $c_{02} = 0.3$, $c_{\text{Liq, ethylene glycol}} = 0.5$

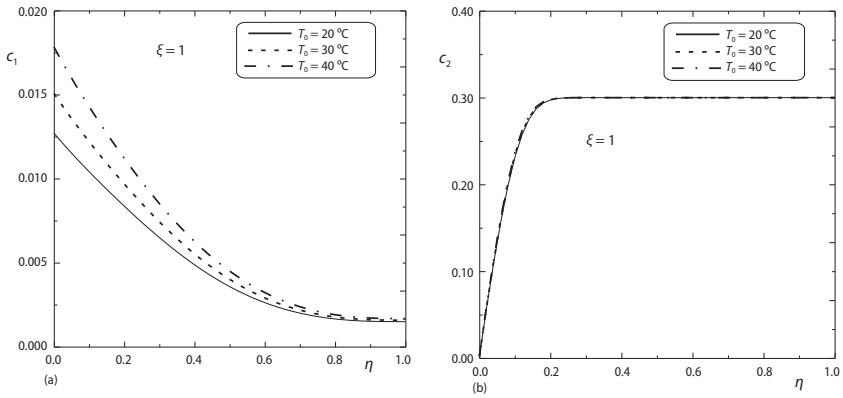

Figure 14. Effect of the inlet gas temperature on the concentrations $c_{01} = 0$, $c_{02} = 0.3$, $c_{\text{Liq, ethylene glycol}} = 0.5$: (a) water vapour concentration, (b) ethylene glycol vapor concentration

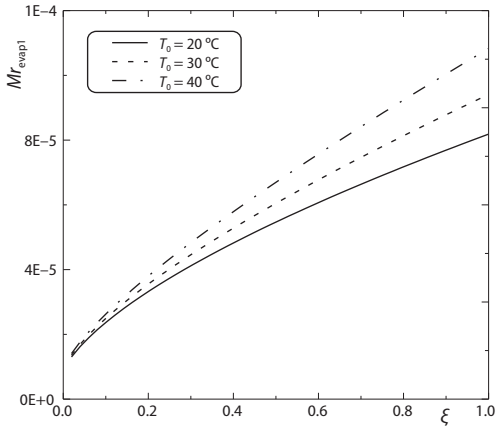

Figure 15. Effect of the inlet gas temperature on the total cumulated evaporation rate of water along the channel: $c_{01} = 0$, $c_{02} = 0.3$, $c_{\text{Liq, ethylene glycol}} = 0.5$

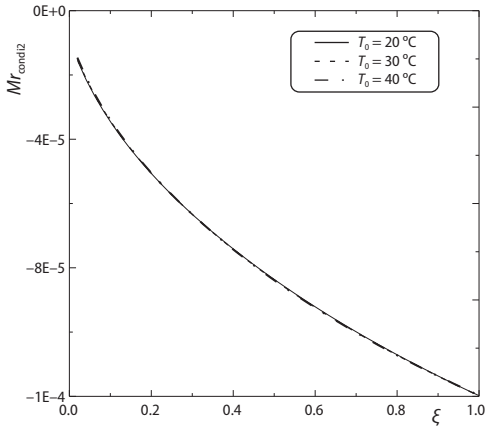

Figure 16. Effect of the inlet gas temperature on the total cumulated condensation rate of ethylene glycol along the channel: $c_{01} = 0$, $c_{02} = 0.3$, $c_{\text{Liq, ethylene glycol}} = 0.5$

Conclusions

The simultaneous evaporation and condensation in the presence of a binary liquid film flowing on a vertical channel by mixed convection have been studied numerically. The binary liquid film (water-ethylene glycol) flows down on one insulated plate of a vertical channel. The second plate is dry and isothermal. The effect of the inlet gas parameters on the heat and mass transfers and on the evaporation and condensation rates has been presented and analysed. A brief summary of the major results are:

- An increase of the inlet vapour concentration of ethylene glycol enhances the water evaporation and the ethylene glycol vapour condensation.
- The increase of the inlet vapour concentration of water slightly influences the ethylene glycol vapour condensation and inhibits the water evaporation.
- The observation reveals that an increase of the inlet gas temperature benefits the water evaporation. On the other hand, the variation of inlet gas temperature has no effect on the ethylene glycol condensation. This result is due to the high volatility of water compared to the ethylene glycol.

Nomenclature

c_i – mass fraction for species i vapour, [–]
c_{0i} – mass fraction for species i vapour in the inlet condition, [–]
$c_{0\text{Li}}$ – inlet mass fraction for species i in the liquid film ($c_{0l1} = c_{\text{Liq,water}}$ and $c_{0l2} = c_{\text{Liq,ethylene glycol}} = 1 - c_{\text{Liq,water}}$)
$c_{\text{L}i}$ – mass fraction for species i in the liquid film ($c_{\text{L1}} + c_{\text{L2}} = 1$), [–]
$c_{\text{Liq,ethylene glycol}}$ – inlet liquid concentration (composition or mass fraction) of ethylene-glycol in the liquid mixture ($= 1 - c_{\text{Liq,water}}$), [–]
$D_{\text{g,im}}$ – mass diffusivity of species i vapour in the gas mixture, [m^2s^{-1}]
d – channel width, [m]
g – gravitational acceleration [ms^{-2}]
H – channel length, [m]
I – grid point index number in the axial direction, [–]
J – grid point index number in transverse direction in gaseous phase, [–]
K – total grid points in the transverse direction in the liquid phase, [–]
L_v – latent heat of evaporation of mixture, [Jkg^{-1}]

M_a – molecular weight of air, [kgmol^{-1}]
Mr – total evaporation (condensation) rate of mixture [kgs^{-1}m^{-1}]
Mr^* – total evaporation rate of mixture given by Ali Cherif and Daif [13] (= Mr/0.004)
$\dot{m}_i$ – local evaporation (condensation) rate of species i, [kgs^{-1}m^{-2}]
$\dot{m}$ – local evaporation (condensation) rate of mixture (= $\dot{m}_1 + \dot{m}_2$), [kgs^{-1}m^{-2}]
m_{L0} – inlet liquid flow rate, [kgs^{-1}]
p – pressure in the channel, [Nm^{-2}]
p_{vsi} – pressure of saturated vapour of species i, [Nm^{-2}]
p^*_{vsi} – partial pressure of species i at the interface liquid-vapour, [Nm^{-2}]
$(p^*_{vs1}+p^*_{vs2})$ – pressure of mixture vapour at the interface liquid-vapour, [Nm^{-2}]
q_1 – external heat flux of wetted wall, [Wm^{-2}]
Re – Reynolds number (= $u_0 d/v_0$), [–]
T – absolute temperature, [K]
u – axial velocity, [ms^{-1}]
v – transverse velocity, [ms^{-1}]
w_{Li} – molar fraction of species i in the liquid mixture, [–]
x – co-ordinate in the axial direction, [m]
y – co-ordinate in the transverse direction, [m]

Greek symbols

δ – liquid film thickness, [mg]
η – dimensional transverse co-ordinate, [= $(y - \delta)/(d - \delta)$], [–]
η_L – dimensional transverse co-ordinate in the liquid phase, (= y/δ), [–]
λ – thermal conductivity of the fluid, [Wm^{-1}K^{-1}]
μ – dynamic viscosity of the fluid, [kgm^{-1}s^{-1}]
ν – kinematic viscosity of the fluid, [m^{2}s^{-1}]
ξ – dimensional axial co-ordinate (= x/H), [–]
ρ – density of the gas, [kgm^{-3}]

Subscripts

0 – inlet condition
i – species i (1 for water vapour, 2 for ethylene-glycol vapour and 3 for dry air)
L – liquid phase

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