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Research Paper

Heat and mass transfer in binary film evaporation and condensation in vertical channel

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Abstract

Evaporation and condensation in the presence of binary liquid film flowing on one of two parallel vertical plates by mixed convection have been studied numerically. The first plate is adiabatic and wetted by a binary liquid film while the second one is dry and isothermal. The results concern the effects of the inlet parameters on the ethylene glycol evaporation and on the water condensation. Results obtained show that the increase of the inlet vapor concentration of water benefits its condensation and the increase of the inlet vapor concentration of ethylene glycol inhibits its evaporation.

Keywords: *Binary Liquid Film; Condensation; Evaporation; Heat and Mass Transfer; Mixed Convection.*

1. Introduction

The understanding and modeling of heat and mass transfers during evaporation and condensation of multicomponent liquid film is an important problem in various industrial applications such as desalination plants, drying, heat exchangers, air-conditioning equipment and desalting. Siow et al. [1] numerically investigated the laminar film condensation of vapour–gas mixtures in horizontal channels. They presented the effects of pressure, gas concentration, Reynolds and the inlet-to-wall temperature difference on the heat and mass transfers and on the film thickness. Yang [2] conducted a numerical study of the condensation under natural convection on a vertical tube A. Nasr et al. [3] numerically investigated the falling binary liquid film evaporation on a vertical plate by mixed convection. They showed that it is possible to increase the water and the liquid mixture evaporation rate when the inlet liquid composition of ethylene glycol is less than 40%. This result has been explained by the fact that an increase of the inlet liquid concentration of ethylene glycol has two opposed effects on the water evaporation rate. Ali cherif et al. [4] numerically treated the evaporation of a binary liquid film flowing on a vertical channel. They showed the importance of taking into account of mixture composition and of film thickness in the mass and thermal transfers. Minkowycz and Sparrow [5] theoretically studied the condensation of film flowing on an isothermal vertical plate by natural convection. They showed that the effect of non-condensable gas is important at lower pressure levels. El Armouzi et al. [6] numerically studied the evaporation by mixed convection of a binary liquid film flowing down of two coaxial cylinders. They showed that the mixture volatilities have an important effect on the heat transferred through the latent mode. This effect is more pronounced for a mixture composed of volatile components. Agunaoun et al. [7] numerically investigated 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%. Debbissi Hfaiedh et al. [8] conducted a numerical analysis of evaporation of water-ethylene-glycol binary liquid film falling down on one plate of a vertical channel under mixed convection. They showed that from a definite distance and from a certain value of the inlet liquid mass fraction of ethylene glycol, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only.

To the author's knowledge, the previous studies concerned with a numerical study of the evaporation and condensation under mixed convection in the presence of a binary 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 effect of inlet parameters on the evaporation and condensation rates.

2. Analysis

The present work deals with a numerical study of evaporation of binary liquid film by mixed convection flowing along one of the channel vertical plates (Fig. 1.a). The studied channel is made up of two vertical and parallel plates. The first plate is subjected to a uniform heat flux q1 and wetted by a binary liquid film (water–ethylene glycol) while the second one (y=d) is dry and isothermal. The air enters the channel with a velocity u0, a temperature T0 and a water and ethylene-glycol vapor concentrations c01 and c02. The liquid film flowing down with an inlet temperature T0L and an inlet mass flow rate mL0 and an inlet liquid composition of ethylene glycol cLiq, ethylene glycol.

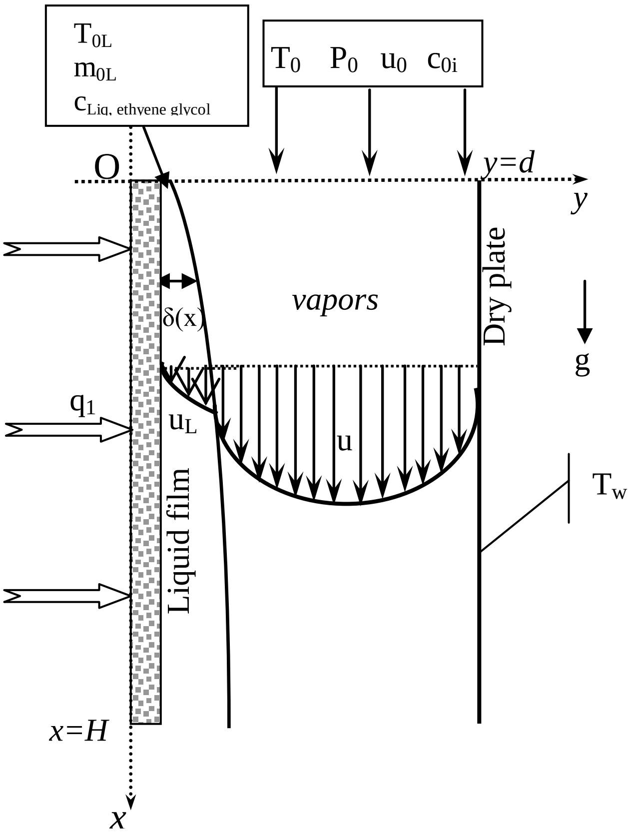


Fig. 1: Physical Description of the System

2.1. Assumptions

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

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

2.2. Governing equations

In order to fix the position of the liquid-gas interface, we introduce the following transformations [4, 7]:
In the gaseous phase:
$\eta = (y - \delta)/(d - \delta)$, $\xi = x/H$
In the liquid phase:

$\eta L = y/\delta$, $\xi = x/H$
Adopting these transformations, the equations governing the flow and heat and mass transfers in the liquid and in the gas phases are [1], [3], [4], [7], [8] follows.

2.2.1. For the liquid phase

The liquid mixture has two components: the water and the ethylene-glycol.
Continuity equation

$$\frac{\partial \rho_L u_L}{\partial \xi} - \frac{\eta_L}{\delta}\frac{\partial \delta}{\partial \xi}\frac{\partial \rho_L u_L}{\partial \eta_L} + \frac{H}{\delta}\frac{\partial \rho_L v_L}{\partial \eta_L} = 0 \tag{1}$$

X-momentum equation

$$u_L \frac{\partial u_L}{\partial \xi} + (v_L \frac{H}{\delta} - u_L \frac{\eta_L}{\delta}\frac{\partial \delta}{\partial \xi})\frac{\partial u_L}{\partial \eta_L} = -\frac{1}{\rho_L}\frac{dP}{d\xi} - \frac{H}{\rho_L \delta^2}\frac{\partial}{\partial \eta_L}\left[\mu_L \frac{\partial u_L}{\partial \eta_L}\right] + gH \tag{2}$$

Energy equation

$$u_L \frac{\partial T_L}{\partial \xi} + (u_L \frac{\eta_L - 1}{\delta}\frac{\partial \delta}{\partial \xi} + \frac{H}{\delta} v_L)\frac{\partial T_L}{\partial \eta} = \frac{1}{\rho_L C_{pL}}\left\{\frac{H}{\delta^2}\frac{\partial}{\partial \eta_L}(\lambda_L \frac{\partial T_L}{\partial \eta_L})\right.$$
$$\left. + \rho_L D_L \sum_{i=1}^{2}\left(C_{pL,1} - C_{pL,2}\right)\frac{H}{\delta^2}\frac{\partial T_L}{\partial \eta_L}\frac{\partial c_{L,1}}{\partial \eta_L}\right\} \tag{3}$$

Where DL is the mass diffusivity of species i in the binary liquid mixture given by [4], [7], [12], [15-17].
Species diffusion equations

$$u_L \frac{\partial c_{Li}}{\partial \xi} + (u_L \frac{\eta_L - 1}{\delta}\frac{\partial \delta}{\partial \xi} + \frac{H}{\delta} v_L)\frac{\partial c_{Li}}{\partial \eta_L} = \frac{1}{\rho_L}\frac{H}{\delta^2}\frac{\partial}{\partial \eta_L}\left(\rho_L D_L \frac{\partial c_{Li}}{\partial \eta_L}\right); \quad i = 1,2 \text{ Where cL1+cL2=1} \tag{4}$$

The overall mass balance described by the following equation should be satisfied at every axial location:

$$\int_0^1 \delta \rho_L u_L d\eta_L = \left[m0L - H\int_0^{\xi} \rho v(\xi, \eta = 0) d\xi\right] \tag{5}$$

2.2.2. For the gaseous phase

The gas mixture has three components: dry air, water vapor and ethylene-glycol vapor.
Continuity equation

$$\frac{\partial \rho u}{\partial \xi} + \frac{\eta - 1}{d - \delta}\frac{\partial \delta}{\partial \xi}\frac{\partial \rho u}{\partial \eta} + \frac{H}{d - \delta}\frac{\partial \rho v}{\partial \eta} = 0 \tag{6}$$

X-momentum equation

$$u\frac{\partial u}{\partial \xi} + (\frac{\eta - 1}{d - \delta}\frac{\partial \delta}{\partial \xi} u + \frac{H}{d - \delta} v)\frac{\partial u}{\partial \eta} = -\frac{1}{\rho}\frac{dP}{d\xi} - g\,\beta H(T - T_0) - g\beta^* H \sum_{i=1}^{2}\left(c_i - c_0\right)$$
$$+ \frac{1}{\rho}\frac{H}{\left(d - \delta\right)^2}\frac{\partial}{\partial \eta}(\mu \frac{\partial u}{\partial \eta}) \tag{7}$$

Energy equation

$$u\frac{\partial T}{\partial \xi} + (u\frac{\eta - 1}{d - \delta}\frac{\partial \delta}{\partial \xi} + \frac{H}{d - \delta} v)\frac{\partial T}{\partial \eta} = \frac{1}{\rho C_p}\left\{\frac{H}{\left(d - \delta\right)^2}\frac{\partial}{\partial \eta}(\lambda \frac{\partial T}{\partial \eta})\right.$$
$$\left. + \rho \sum_{i=1}^{2}\left(D_{g,im} C_{pi} - D_{g,am} C_{pa}\right)\frac{H}{(d - \delta)^2}\frac{\partial T}{\partial \eta}\frac{\partial c_i}{\partial \eta}\right\} \tag{8}$$

Where Dg,im and Dg,am are respectively the mass diffusivity of species i vapor and of dry air given by [7], [14], [17].
Species diffusion equations

$$u\frac{\partial c_i}{\partial \xi} + (u\frac{\eta - 1}{d - \delta}\frac{\partial \delta}{\partial \xi} + \frac{H}{d - \delta} v)\frac{\partial c_i}{\partial \eta} = \frac{1}{\rho}\frac{H}{\left(d - \delta\right)^2}\frac{\partial}{\partial \eta}(\rho D_{g,im}\frac{\partial c_i}{\partial \eta}); \quad i = 1,2,3 \tag{9}$$

Where c1+c2+c3=1
The overall mass balance described by the following equation should be satisfied at every axial location:

$$\int_0^1 \rho(d-\delta)u(\xi,\eta)d\eta = \left[(d-\delta_0)\rho_0 u_0 + H\int_0^\xi \rho v(\xi,\eta=0)d\xi\right] \tag{10}$$

2.3. Boundary conditions

* At ξ=0 (inlet conditions) :

$$T(0,\eta)=T_0\ ;c1(0,\eta)=c_{01}\ ;\ c2\ (0,\eta)=c_{02}\ ;\ u(0,\eta)=u_0\ ;\ P=P0 \tag{11}$$

$$T_L\ (0,\eta_L)=T_{0L}\ \ ;\delta(0)=\delta 0\ ;\ \int_0^L \rho_{0L}\delta_0 u_L(0,\eta_L)d\eta_L = m_{0L}\ ;cLi(0,\eta_L)=c0Li \tag{12}$$

* At η=1(dry plate) :

$$u(\xi,1)=0\ ;\ v\ (\xi,1)=0\ ;\ T\ (\xi,1)=Tw\ ;\ \left.\frac{\partial c_i}{\partial\eta}\right)_{\eta=1}=0 \tag{13}$$

* At ηL = 0 (wet plate) :

$$u_L(\xi,0)=0\ \ ;v_L(\xi,0)=0\,q1=-\lambda_L\left.\frac{1}{\delta}\frac{\partial T_L}{\partial\eta_L}\right)_{\eta_L=0}\ ;\ \left.\frac{\partial c_{Li}}{\partial\eta_L}\right)_{\eta_L=0}=0 \tag{14}$$

with cLi is the mass fraction of species i in the liquid film mixture.

* At $\eta=0\,(\eta_L=1)$ (gas-liquid interface):

The continuities of the velocities and temperatures give:

$$u_L(\xi,\eta_L=1)=u(\xi,\eta=0)\ ;\ T_L\ (\xi,\eta_{L=1})=T\ (\xi,\eta_{=0}) \tag{15}$$

The heat balance at the interface implies [4, 7]:

$$-\frac{1}{\delta}\lambda_L\left.\frac{\partial T_L}{\partial\eta_L}\right)_{\eta_L=1}=-\frac{1}{d-\delta}\lambda\left.\frac{\partial T}{\partial\eta}\right)_{\eta=0}-\dot{m}L_V\quad \text{With}\quad \dot{m}=-\frac{\rho\sum\limits_{i=1}^{2}D_{g,im}\left.\frac{\partial c_i}{\partial\eta}\right)_{\eta=0}}{(d-\delta)\left(1-\sum\limits_{i=1}^{2}c_i(\xi,\eta=0)\right)} \tag{16}$$

Where Lv 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-vapor mixture is an ideal gas mixture, the concentration of species i vapor can be evaluated by [4], [7], [8], and [11]:

$$c_1(\xi,0)=\frac{p^*_{vs,1}}{p^*_{vs,1}+\left[p^*_{vs,2}\frac{M_2}{M_1}\right]+\left[p-p^*_{vs,1}-p^*_{vs,2}\right]\frac{M_a}{M_1}}\ ;$$

$$c_2(\xi,0)=\frac{p^*_{vs,2}}{p^*_{vs,2}+\left[p^*_{vs,1}\frac{M_1}{M_2}\right]+\left[p-p^*_{vs,1}-p^*_{vs,2}\right]\frac{M_a}{M_2}} \tag{17}$$

Where p*vs,i is the partial pressure of species i at the gas-liquid interface given by [4], [7] :

$P^*_{vs,i}=w_{Li}P_{vs,i}(T)$ (i=1, 2); $P_{vs,i}(T)$ is the pressure of saturated vapor of species i given by [7], [8]: (18)

$$P_{vs,1}=10^{17.443-[2975/T+3.68\log(T)]}\times 10^5\ ;\ P_{vs,2}=6894.8\exp[16.44-10978.8/(9T/5-49)] \tag{19}$$

The transverse velocity component of the mixture at the interface is obtained by assuming the interface to be semi-permeable [4], [7]:

$$v(\xi,\eta=0)=-\frac{\frac{1}{d-\delta}\sum\limits_{i=1}^{2}D_{g,im}\left.\frac{\partial c_i}{\partial\eta}\right)_{\eta=0}}{1-\sum\limits_{i=1}^{2}c_i(\xi,\eta=0)} \tag{20}$$

The continuities of shear stress and local evaporated mass flux of species i [4], [7], [8] give:

$$\frac{1}{\delta}\mu_L\left.\frac{\partial u_L}{\partial\eta_L}\right)_{\eta_L=1}=\frac{1}{d-\delta}\mu\left.\frac{\partial u}{\partial\eta}\right)_{\eta=0}\ ;\ \dot{m}_i=\dot{m}c_{Li}-\frac{\rho_l D_l}{\delta}\left.\frac{\partial c_{Li}}{\partial\eta_l}\right)_{\eta_l=1}=\dot{m}c_i-\frac{\rho D_{g,im}}{d-\delta}\left.\frac{\partial c_i}{\partial\eta}\right)_{\eta=0} \tag{21}$$

In order to evaluate the importance of the different processes of energy transfer, the following quantities are used [4], [6], and [7]:

The cumulated evaporation (condensation) rate of species i at the interface am given by:

$$\mathrm{Mr}_{\mathrm{evap/cond}i}(\xi)=\int_{0}^{\xi}\dot{\mathrm{m}}_{\mathrm{i}}(\xi)\mathrm{d}\xi \text{ avec } \dot{\mathrm{m}}_{\mathrm{i}}(\xi)=\dot{\mathrm{m}}\mathrm{c}_{1}-\frac{\rho \mathrm{D}_{\mathrm{g,im}}}{d-\delta}\frac{\partial \mathrm{c}_{\mathrm{i}}}{\partial y}\bigg)_{\eta=0} \tag{22}$$

The cumulated evaporation (condensation) rate of mixture at the interface is given by:

$$\mathrm{Mr}_{\mathrm{evapt/condt}}(\xi)=\int_{0}^{\xi}\dot{\mathrm{m}}(\xi)\mathrm{dx} \tag{23}$$

3. Solution method

The system of equations (1-10) is solved numerically using a finite difference method. A fully implicit marching 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 to transform the governing equations into finite difference equations. To account for the change in the liquid film thickness δ due to the binary liquid film evaporation, the finite difference computational grid used must comply with the variations of computation domains with ξ . This was accomplished by first locating the interface at every axial location, and then dividing the liquid film and gas regions into J and K points, respectively. The interface position has to be recalculated during iteration by satisfying the overall conservation of mass in the liquid film. During the program tests, solutions for typical case were obtained using different grid sizes to ensure that the solution is grid-independent. The results from the computation for various grids arrangement ranging from 51x (51+31) to 151x (51+51) show that the difference in the total evaporating rate is always within 1 percent (Table 1). In light of those results all further calculations were performed with the 51x (51+31) grid.

Table 1: Comparison of Total Evaporating Rate (105.Mr) (Kg.S-1.M-2) for Various Grid Arrangements for T0=20°C; T0L=20°C; M0l=0.015Kg/M.S; Tw=20°C; Q1=3000W/M2; P0=1atm; C01=0; C02=0, Cliq,Water = Cliq, Ethylene Glycol =0.5 (50% Water-Ethylene Glycol Mixture); D/H=0.015; U0=1m/S,

IxJxK grid point	x=0.2	x=0.4	x=0.6	x=0.8	x=1
51x(51+31)	5.05546	10.49324	18.59606	30.02837	43.29377
101x(51+31)	5.08366	10.35767	18.48970	29.97913	43.37085
101x(31+31)	4.98680	10.27552	18.28331	30.02837	43.37085
101x(51+51)	5.08068	10.34552	18.48310	30.03837	43.40185
151x(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 check the adequacy of the numerical scheme adopted in the present study, the procedure has been tested by comparing the present solution for the total evaporating rate (Mr) with the results of Ali Cherif and Daif [4] for the case of the evaporation of the binary liquid film (see Figs. 2). The comparison has been done for T0= 293.15K, c01=0, c02=0, T0L=293.15K, q2=0, m0L=0.02Kg/m.s, Re=1000, the geometrical ratio is d/H=0.015, the imposed wall heat flux is q1=3000W/m² and the inlet film composition of ethylene-glycol is cLiq, ethylene glycol=0.5 (50% water–ethylene glycol mixture). Fig. 2 shows a satisfactory conformity between our results and those obtained by Ali Cherif and Daif [4].

4. Results and discussion

All the results of this study have been obtained for the case of c01=0, c02=0.3, T0=293.15K, T0L=293.15K, Tw=293.15K, m0L=0.015Kg/m.s, u0=1m/s, the geometrical ratio is d/H =0.015 and the imposed wall heat flux is q1 =3000W/m².

Fig. 3 shows that the saturated pressure of ethylene-glycol is less important than the water and consequently the water is more volatile than the ethylene-glycol. It is shown that the modification of the temperature principally affects the saturated pressure of more volatile component (water). It is shown from figure 4 that the temperature increases along the channel. This result has been justified by the fact that the gas mixture condensates on the interface liquid-gaz.

It is observed from Fig. 5a that the water vapor concentration increases along the channel sections. This result has been explained by the fact that the condensation process of water vapor takes place. But in Fig.5.b, we can note that the ethylene-glycol vapor concentration increases along the channel sections. It indicates that the ethylene glycol evaporation takes place. Fig.6 shows the evolution the phase change process of species i and of mixture along the channel. Fig.6 shows that we treat the problem of the water condensation and the ethylene glycol evaporation. It is observed from Fig.6 that the total mixture tend to condense. This result has been explained by the fact that the total cumulated condensation rate of water vapor is more important to the total cumulated evaporation rate of ethylene glycol and consequently the total mixture has a tendency to condense.

Figs. 7-10 illustrate the effect of the humidity c01 on the heat and mass transfer. It is shown from figure 7 that increasing the humidity induces an increase of the temperature at the channel exit (ξ=1). This result has been explained by the fact that an increase of the humidity enhances the water condensation (more volatile component) and consequently the temperature along the channel section increase. Fig.8 reveals the effect of the humidity on the concentrations profiles of water and ethylene glycol vapor at the channel exit. Fig.8.a shows that an increase of the humidity induces an increase of the water vapor concentration. It is also shown that an increase of the humidity induces an increase of the concentration gradient of water vapor and consequently enhances the water condensation (Fig.9). It is shown from Fig.8.b that the inlet concentration of ethylene glycol vapor increases with an increase of the humidity. It can be seen from this figure that an increase of the humidity induces an increase of the concentration gradient of ethylene glycol vapor. Consequently, the ethylene glycol evaporation increases (Fig.10). This result can be explained by the fact that an increase of the humidity enhances the water condensation (Fig.9) which causes an increase of the temperature at the interface (Fig.7) and consequently enhances the ethylene glycol evaporation (Fig.9).

It is shown that the variation of the inlet concentration of ethylene glycol vapor c02 has no effect on the temperature at the channel exit (Fig.11). Fig.12 illustrates the effect of c02 on the concentrations vapor of water and of ethylene glycol. It is shown that the water vapor concentration is not affected by such variation of c02 (Fig. 12.a). Consequently, the water condensation is not affected by such variation of c02 (Fig.13). However, increasing the inlet vapor concentration of ethylene glycol causes an increase of ethylene glycol vapor concentration (Fig. 12.b). It is also shown from this figure that the concentration gradient of ethylene glycol vapor decrease with an increase of c02 causes a decrease of ethylene glycol evaporation (Fig.14).

5. Conclusion

The evaporation and the condensation in the presence of a binary liquid film flowing on a vertical channel by mixed convection have been numerically studied. 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 parameters on the heat and mass transfers has been presented and analysed.

A brief summary of the major results is as follows:

1) The increase of the humidity enhances the ethylene glycol evaporation.
2) The increase of the inlet vapor concentration of water benefits its condensation and the increase of the inlet vapor concentration of ethylene glycol inhibits its evaporation.
3) The heat and mass transfer during condensation and evaporation in the presence of a binary liquid film strongly depends on the inlet composition of liquid film.

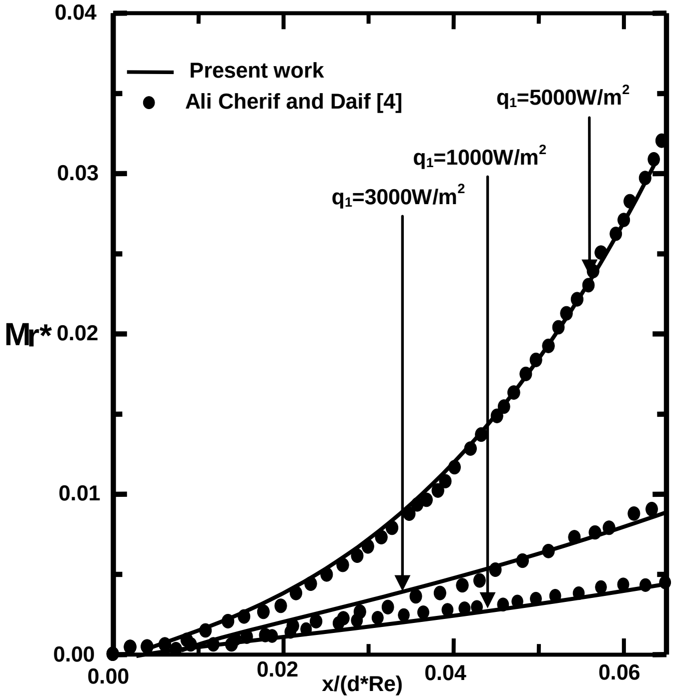


Fig. 2: Comparison of Our Present Work with These of Ali Cherif and Daif [4].

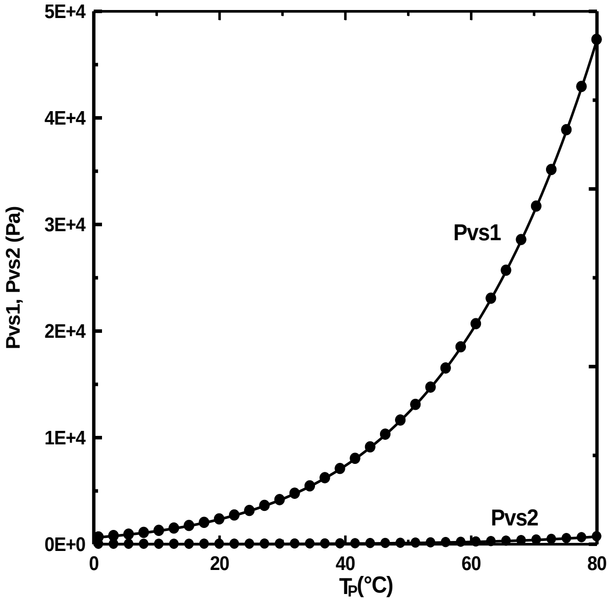


Fig. 3: The Saturated Pressure Profiles of Water and of Ethylene Glycol with the Wall Temperature

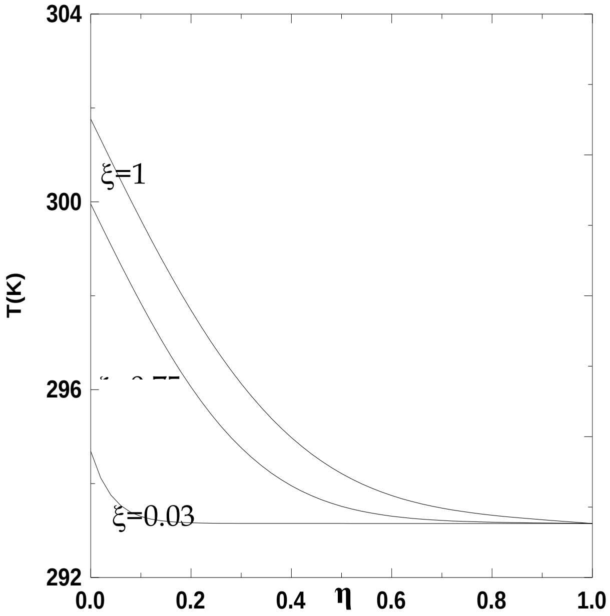
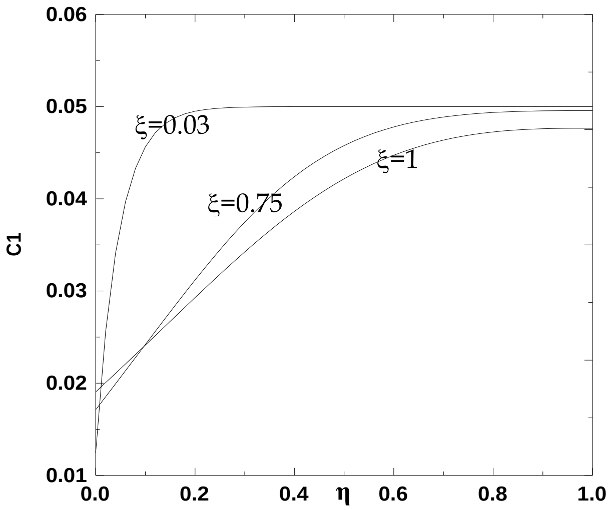


Fig. 4: Temperature Profile at Various Channel Sections: C01=0.05, C02=0, T0=20°C, U0=1m/S, Q1 = 0, Cliq, Ethylene Glycol=0.5 (50% Water-Ethylene Glycol Mixture), M0l=0.015Kg/M.S, T0L=20°C.



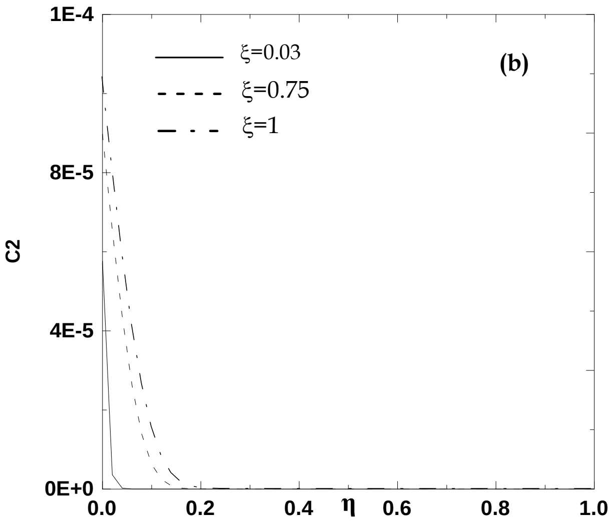


Fig. 5: Concentrations Profiles at Various Channel Sections: A- Concentration of Water Vapor; B-Concentration of Ethylene Glycol Vapor: C01=0.05, C02=0, T0=20°C, U0=1m/S, Q1 = 0, Cliq, Ethylene Glycol=0.5, M0l=0.015Kg/M.S, T0L=20°C

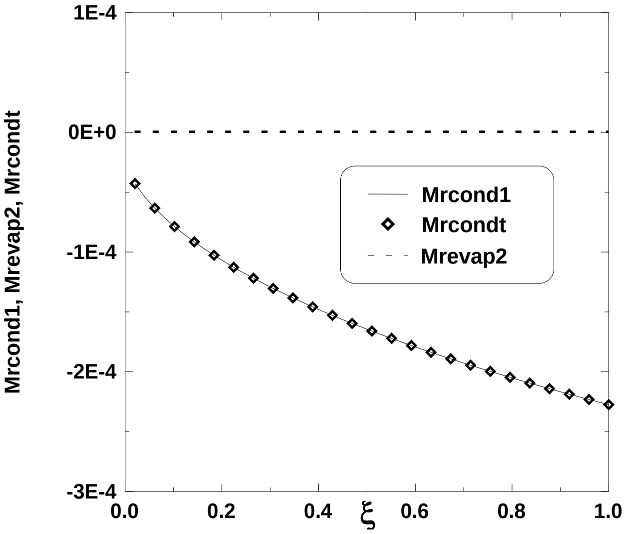


Fig. 6: Evolution of the Phase Change Process of Species I and of Mixture Along the Channel: C01=0.05, C02=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol= Cliq, Water =0.5, Q1 = 0.

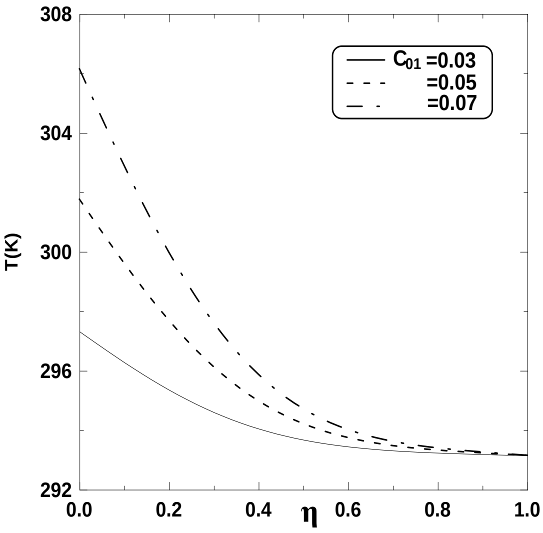


Fig. 7: Effect of the Humidity on the Temperature Profile at the Channel Exit (ξ=1): C02=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0.

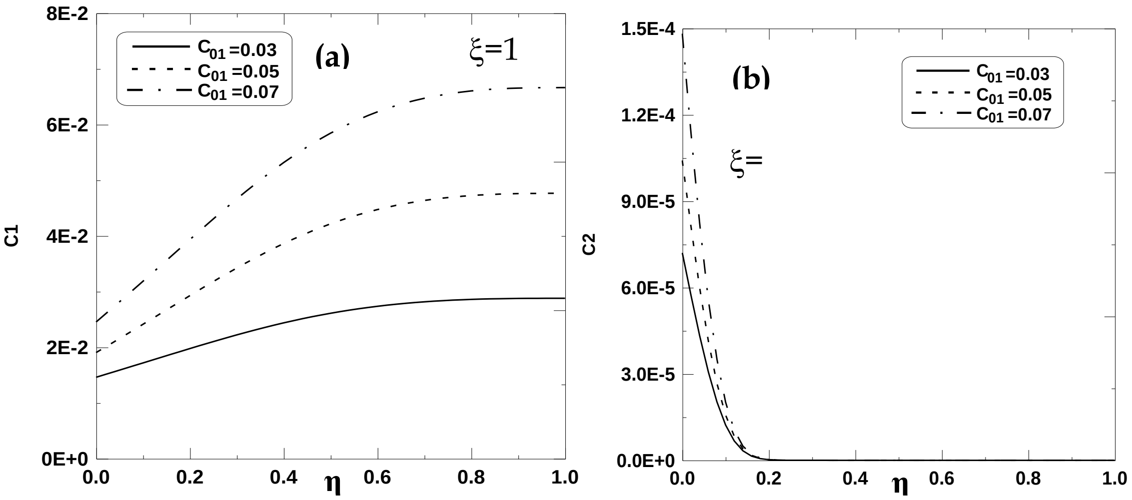


Fig. 8: Effect of the Humidity on the Concentrations Profiles at the Channel Exit: A- Concentration of Water Vapor, B- Concentration En Ethylene Glycol Vapor : C02=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0

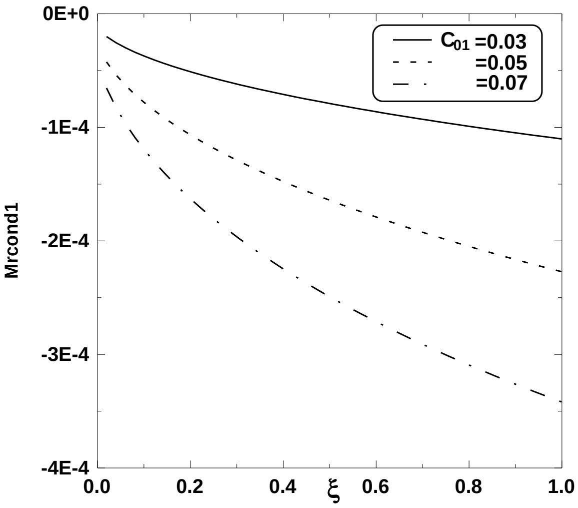


Fig. 9: Effect of the Humidity on the Total Cumulated Condensation Rate of Water Vapor along the Channel: C02=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0.

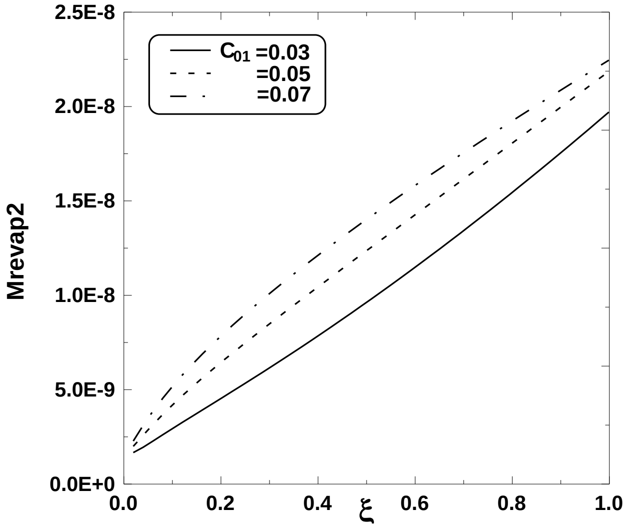


Fig. 10: Effect of the Humidity on the Evaporation Rate of Ethylene Glycol Along the Channel: C02=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0.

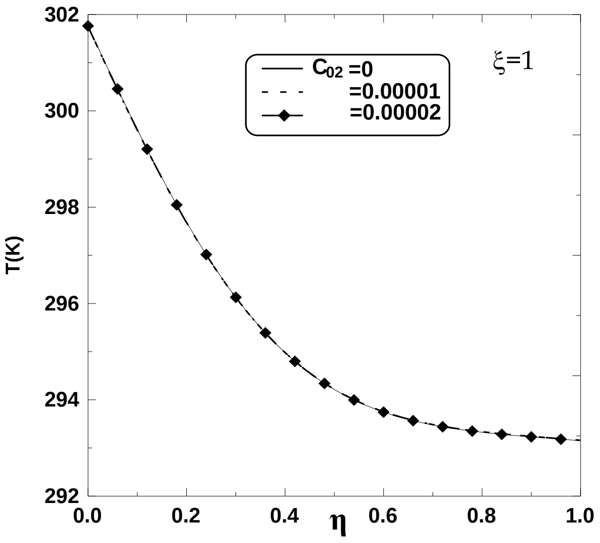


Fig. 11: Effect of the Inlet Vapor Concentration of Ethylene Glycol on the Temperature Profile at the Channel Exit: U0=1m/S, C01=0.05, M0l=0.015Kg/M.S, T0L=20°C, T0=20°C, Cliq, Ethylene Glycol=0.5, Q1=0.

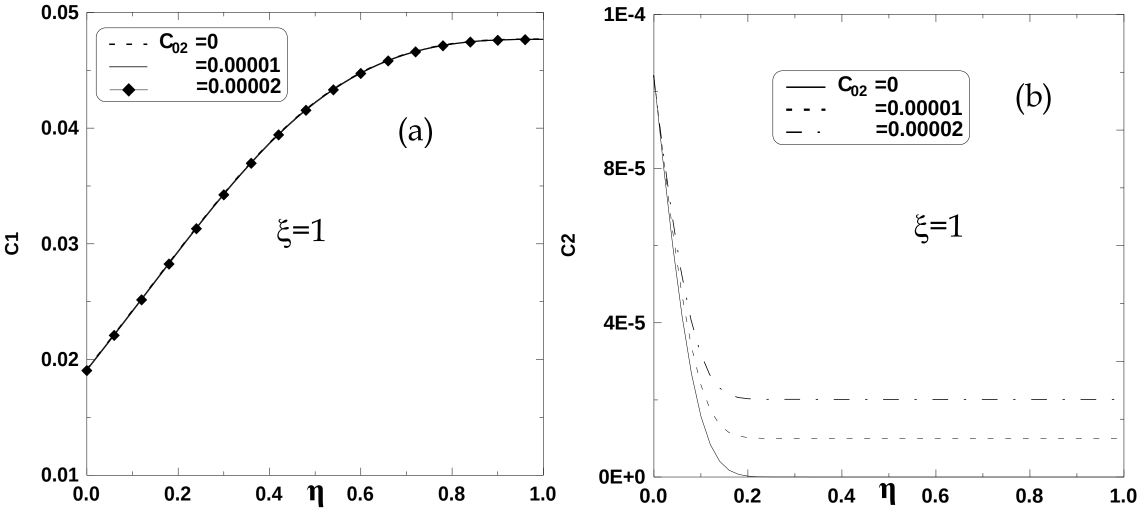


Fig. 12: Effect of the Inlet Vapor Concentration of Ethylene Glycol on the Concentrations Profiles at the Channel Exit A- Concentration of Water Vapor, B- Concentration En Ethylene Glycol Vapor: C01=0.05, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0.

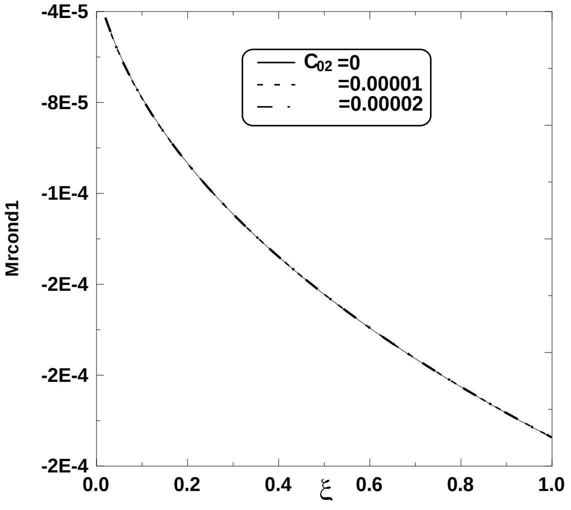


Fig. 13: Effect of the Inlet Vapor Concentration of Ethylene Glycol on the Total Cumulated Condensation Rate of Water along the Channel: U0=1m/S, C01=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0.

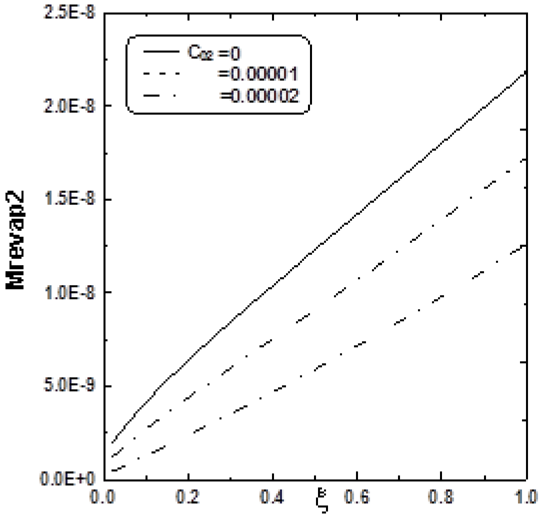


Fig. 14: Effect of the Inlet Vapor Concentration of Ethylene Glycol on the Total Cumulated Evaporation Rate of Water along the Channel: U0=1m/S, C01=0, T0=20°C, U0=1m/S, T0L=20°C, M0l=0.015Kg/M.S, Cliq, Ethylene Glycol=0.5, Q1 = 0

Nomenclature

ci	mass fraction for species i vapor
c0i	mass fraction for species i vapor in the inlet condition
cLi	mass fraction for species i in the liquid film (cL1+ cL2=1)
cLiq,ethylene glycol	inlet liquid concentration (composition or mass fraction) of ethylene-glycol in the liquid mixture (cLiq,ethylene glycol =1- cLiq,water)
cp	specific heat at constant pressure[J.kg-1.K-1]
cpa	specific heat for air [J.kg-1.K-1]
cpvi	specific heat for species i vapor [J.kg-1.K-1]
d	channel width [m]
Dg,im	mass diffusivity of species i vapor in the gas mixture [m2.s-1]
Dg,am	mass diffusivity of dry air in the gas mixture [m2.s-1]
DL	mass diffusivity of species i in the liquid film mixture [m2.s-1]
H	channel length [m]
I	grid point index number in the flow direction
J	grid point index number in transverse direction
Lv	latent heat of evaporation of mixture [J.kg-1]
Lvi	latent heat of evaporation of species i [J.kg-1]
$\dot{m}_i$	Local evaporation (condensation) rate of species i [kg.s-1.m-2]
$\dot{m}$	Local evaporation (condensation) rate of mixture ($\dot{m}=\dot{m}_1+\dot{m}_2$) [kg.s-1.m-2]
mL0	inlet liquid flow rate [Kg.s-1]
M_a	molecular weight of air [kg.mol-1]
Mri	total evaporation (condensation) rate of species i [kg.s-1.m-1]
M_r	total evaporation (condensation) rate of mixture [kg.s-1.m-1]
M_{r*}	total evaporation rate of mixture given by Ali Cherif and Daif [7] ($M_{r*=}$Mr/0.004)
P	pressure in the channel [N.m-2]
pvsi	pressure of saturated vapor of species i [N.m-2]
P*vsi	partial pressure of species i at the interface liquid–vapor [N.m-2]
pvsm	pressure of mixture vapor at the interface liquid–vapor (p*vs1+ p*vs2) [N.m-2]
P0	ambiant pressure [N.m-2]
C0Li	inlet mass fraction for species i in the liquid film (c0L1= cLiq,water and c0L2= cLiq,ethylene glycol)
T	absolute temperature [K]
Ts	interface temperature [K]
Tw	dry wall temperature [K]
Tp	wetted wall temperature [K]
q1	external heat flux of wetted wall [W.m-2]
q2	external heat flux of dry wall [W.m-2]
qLi	latent heat flux of species i
qL	latent heat flux of liquid mixture
qS	Sensible heat flux

g	gravitational acceleration (m.s-2)
Re	Reynolds number (Re=u0.d/ν0)
U	axial velocity [m.s-1]
v	transverse velocity [m.s-1]
x	coordinate in the axial direction [m]
x*	dimensionless axial coordinate.
Y	coordinates in the transverse direction [m]
w_{Li}	Molar fraction of species i in the liquid mixture
w_i	Molar fraction of species i vapor

Greek symbols

λ	thermal conductivity of the fluid [W.m-1.K-1]
μ	Dynamic viscosity of the fluid [kg.m-1.s-1]
ν	Kinematic viscosity of the fluid [m2.s-1]
ρ	density of the gas [kg.m-3]
η	dimensionless coordinate in the transverse direction
ξ	Dimensionless coordinate in the flow direction
δ	liquid film thickness (m)
β	Thermal expansion coefficient $-1/\rho(\partial\rho/\partial T)_{p,c}$ [K-1]
β*	Mass expansion coefficient $-1/\rho(\partial\rho/\partial c)_{p,T}$

Subscripts

i	species i (1 for water vapor, 2 for ethylene-glycol vapor and 3 for dry air)
0	inlet condition
L	liquid phase
0L	inlet condition in the liquid phase
a	dry air
m	mixture
s	interface
am	dry air in the mixture
im	species i in the mixture
Li	species i in the liquid

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