

SIMULTANEOUS HEAT AND MASS TRANSFER DURING EVAPORATION AND CONDENSATION OF A BINARY LIQUID FILM

By

^{ab}Abdelaziz NASR, ^bAbdulmajeed S. AL-GHAMDI

^aLaboratory of Thermal and Energy Systems Studies, Monastir University,
Ibn Eljazzar Street, 5019 Monastir, Tunisia
+ Corresponding author. Tel. +966 1252 700 70, Fax. +966 1252 700 27
Email: abdelaziz.nasr@ymail.com

^bMechanical Engineering Department, College of Engineering, Umm Al-Qura
University, Makkah P.O. BOX 5555, Kingdom of Saudi Arabia
+ Corresponding author. Tel. +966 1252 700 70, Fax. +966 1252 700 27

The purpose of the present study is to investigate numerically the evaporation and condensation of binary liquid film flowing on one of two parallel vertical plates under mixed convection. The results concern the effects of the inlet parameters in the liquid film on the ethylene glycol evaporation and on the water condensation. The results indicate that increasing the amount of liquid film or reducing its inlet temperature benefits the water condensation and disadvantages the ethylene glycol evaporation. It was observed that an increase of the inlet liquid concentration of ethylene glycol enhances the water vapor condensation and the ethylene glycol evaporation.

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

1. INTRODUCTION

The evaporation and condensation in the mixture liquid films are important in many processes such as desalination, distillation of a volatile component from a mixture with in volatiles, evaporative cooling for waste heat disposal, in refrigeration and in air-conditioning equipment. The numerical study of the evaporation of liquid film has been extensively investigated [1-17]. The case of experimental investigation of liquid film has also received considerable attention in many studies [18-21].

Khalal et al. [1] 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. Yang [2] investigated the condensation characteristics by natural convection inside a vertical tube. Film condensation of vapor flowing in a vertical tube and between parallel plates was recently treated numerically by Panday [3]. Turbulence in the vapor and in the condensate film was taken into account. The heat flow rate for the condensation of R123 and the mean heat transfer coefficients for the condensation of vapor mixture R123/R134a were presented. Oubella et al. [4] 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 Re . They displayed that the better mass transfer rates related with film evaporation are found for a system with low mass diffusion coefficient. Han et al. [5] reveals the effect of liquid film evaporation on flow boiling heat transfer in a micro tube. They investigated the relationship between liquid film thickness and heat transfer coefficient. Agrawal et al. [6] studied the heat transfer

augmentation by coiled wire inserts during forced convection condensation of R22 inside horizontal wetted tubes. The use of helically coiled wires was found to increase the condensing heat transfer coefficients by as much as 100% above the plain tube values on a nominal area basis. Yan and Lin [7] examined 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. Panday [8] numerically treated the film condensation of vapor flowing in a vertical tube and between parallel plates. They take into account the turbulence in the vapor 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 vapor mixture R123/R134a. Minkowycz and Sparrow [9] presented a theoretical investigation of laminar falling film with condensation by natural convection on an isothermal vertical plate. Results were obtained for a wide range of governing parameters (ambient pressure, concentration and temperature). They showed, in particular, that the influence of non-condensable gas is important at lower pressure levels. Jingchun Min and Yicun Tang [10] reported a theoretical analysis of water film evaporation characteristics on an adiabatic solid wall. They showed that when the water evaporation starts, the water surface temperature drops instantly, as time goes on, the water surface temperature declines continuously until it reaches the air wet-bulb temperature. Nasr et al. [11] numerically investigated the evaporation of binary liquid film flowing on a vertical channel by mixed convection. They showed that it is possible to increase the accumulated evaporation rate of water and of the liquid mixture when the inlet liquid concentration 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. Agrawal et al. [12] presented a study of the heat transfer augmentation by coiled wire inserts during forced convection condensation of R22 inside horizontal wetted tubes. Siow et al. [13] presented a numerical study for the fully coupled solution of a two phase model for laminar film condensation of vapor–gas mixtures in horizontal channels. The effects of four independent parameters gas concentration, Reynolds numbers, pressure and the inlet-to-wall temperature difference on the film thickness and on the heat and mass transfers were analyzed. Debissi et al. [14] reported a numerical study of the evaporation of binary liquid film. As concluded by the authors, 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. They showed that the existence and the value of the inversion distance essentially depend on the value of the heat flux density. In paper of Ali Cherif and Daif [15], the evaporation by mixed convection of binary liquid film streaming on the internal face of one of the two parallel plates has been numerically analysed. The wetted plate undergoes a constant uniform heat flux while the other is adiabatic. They showed the film thickness importance and mixture composition in the mass and thermal transfers. For the ethanol–water liquid mixture, the results seem to be foreseeable while it is different for the second mixture (ethylene glycol–water). They showed, for example, that for a particular ethylene glycol–water mixture concentration at the canal entry, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only. Agunaoun et al. [16] reported 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. In fact, they show the possibility to increase the cumulated evaporation rate of water when the inlet liquid concentration of ethylene-glycol is less than 40%. Nasr et al. [17] numerically examined the evaporation and condensation of a binary liquid film on a vertical plate. They presented the effect of the inlet parameters on the ethylene glycol evaporation and water condensation. Huang et al. [18] studied the falling film evaporation in large scale rectangular channel experimentally. They analysed the effects of air flow rate, film temperature and film flow rate on falling film evaporation. They show that the increase of the air flow rate enhance the evaporation rate. Narayanan et al. [19] presented a computational analysis by comparison the numerical and experimental study of heat and mass transfer during evaporation of thin liquid films confined by nanoporous membranes subjected to air jet impingement. Gonda et al. [20] presented an experimental results on the study of falling water film evaporation on a single vertical corrugated plate are presented and compared to

various correlations found in the literature. They showed that when the surface is invaded by the film, decreasing film flow-rate provides higher ratio of wetted surface compared to increasing film flow rate. They presented a new correlation to predict the evaporative heat transfer by falling film. Monnier et al. [21] experimentally investigated the evaporation of a falling liquid film in vertical micro channels. The results show that, it is possible to optimize the geometry of the apparatus in order to intensify the heat transfer during evaporation of a falling liquid film in vertical channel.

The previous review reveals that the evaporation and condensation under mixed convection 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 heat and mass transfers during ethylene glycol evaporation and water vapor condensation in the presence of a binary liquid film. Particular attention was paid to the effect of inlet conditions of the two phases on the evaporation and condensation rates.

2. NUMERICAL MODEL

The present work deals with a numerical analysis of evaporation of binary liquid film by mixed convection flowing along one of the channel vertical plates (Fig. 1). The studied channel is made up of two vertical and parallel plates. The first plate is externally insulated and wetted by a binary liquid film (water–ethylene glycol) while the second one ($y = d$) is dry and isothermal. The binary liquid film flowing down with an inlet temperature T_{0L} and an inlet mass flow rate m_{L0} . The air enters the channel with a temperature T_0 , a water and ethylene-glycol vapor concentrations c_{01} and c_{02} and velocity u_0 .

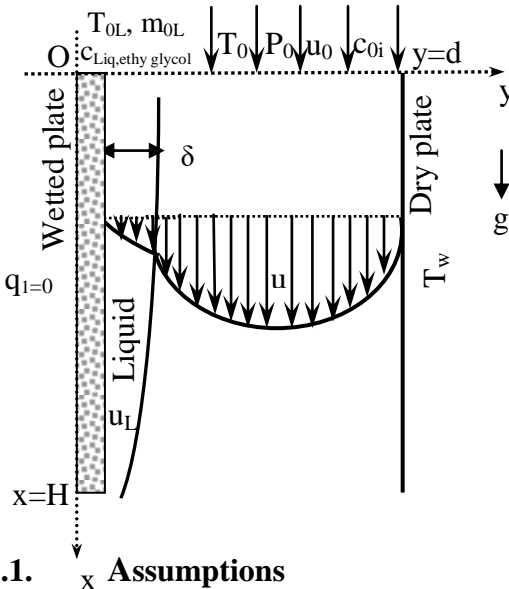


Fig. 1. Physical model

2.1. Assumptions

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

2.2. Governing equations

In order to fix the position of the liquid-gas interface, we introduce the following transformations:

- 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 as follows.

• **For the liquid phase**

The liquid mixture has two components: the water and the ammonia.

Continuity equation

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

x-momentum equation

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

Energy equation

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

Where D_L is the mass diffusivity of species i .

Species diffusion equations

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

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

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

• **For the gaseous phase**

The gas mixture has three components: dry air, water vapour and ammonia vapour.

Continuity equation

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

x-momentum equation

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

Energy equation

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

Where $D_{g,im}$ and $D_{g,am}$ are respectively the mass diffusivity of the vapour i and of dry air.

Species diffusion equations

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

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

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

2.3. Boundary conditions

For inlet conditions (at $\xi=0$):

$$T(0, \eta) = T_0; \quad c_1(0, \eta) = c_{01}; \quad c_2(0, \eta) = c_{02}; \quad u(0, \eta) = u_0; \quad P = P_0 \quad (11)$$

$$T_L(0, \eta_L) = T_{0L}; \quad \delta(0) = \delta_0; \quad \int_0^L \rho_{0L} \delta_0 u_L(0, \eta_L) d\eta_L = m_{0L}; \quad c_{Li}(0, \eta_L) = c_{0Li} \quad (12)$$

For dry plate (at $\eta=1$):

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

For wet plate (at $\eta_L = 0$):

$$u_L(\xi, 0) = 0; \quad v_L(\xi, 0) = 0; \quad q_1 = -\lambda_L \left. \frac{1}{\delta} \frac{\partial T_L}{\partial \eta_L} \right|_{\eta_L=0}; \quad \left. \frac{\partial c_{Li}}{\partial \eta_L} \right|_{\eta_L=0} = 0 \quad (14)$$

Where 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 give:

$$u_L(\xi, \eta_L = 1) = u(\xi, \eta = 0); \quad T_L(\xi, \eta_L = 1) = T(\xi, \eta = 0) \quad (15)$$

The heat balance at the interface implies [11, 14, 15-17]:

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

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 [11, 14, 15-17] :

$$c_1(\xi,0) = \frac{p_{vs,1}^*}{p_{vs,1}^* + \left[p_{vs,2}^* \frac{M_2}{M_1} \right] + \left[p - p_{vs,1}^* - p_{vs,2}^* \right] \frac{M_a}{M_1}} ; c_2(\xi,0) = \frac{p_{vs,2}^*}{p_{vs,2}^* + \left[p_{vs,1}^* \frac{M_1}{M_2} \right] + \left[p - p_{vs,1}^* - p_{vs,2}^* \right] \frac{M_a}{M_2}} \quad (17)$$

Where $p_{vs,i}^*$ is the partial pressure of species i at the gas-liquid interface [11, 14, 15-17]

$P_{vs,i}^* = w_{Li} P_{vs,i}(T)$ ($i=1,2$); $P_{vs,i}(T)$ is the pressure of saturated vapour of species i

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

The transverse velocity component of the mixture at the interface is obtained by assuming the interface to be semi-permeable [11, 14, 15-17] :

$$v(\xi, \eta = 0) = - \frac{\frac{1}{d - \delta} \sum_{i=1}^2 D_{g,im} \frac{\partial c_i}{\partial \eta} \Big|_{\eta=0}}{1 - \sum_{i=1}^2 c_i(\xi, \eta = 0)} \quad (18)$$

The continuities of shear stress and local evaporated mass flux of species i [11, 14, 15-17] give:

$$\left. \frac{1}{\delta} \mu_L \frac{\partial u_L}{\partial \eta_L} \right|_{\eta_L=1} = \left. \frac{1}{d - \delta} \mu \frac{\partial u}{\partial \eta} \right|_{\eta=0} ; \dot{m}_i = \dot{m}_{c_{Li}} - \left. \frac{\rho_i D_i}{\delta} \frac{\partial c_{Li}}{\partial \eta_L} \right|_{\eta_L=1} = \dot{m}_{c_i} - \left. \frac{\rho D_{g,im}}{d - \delta} \frac{\partial c_i}{\partial \eta} \right|_{\eta=0} \quad (19)$$

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

1. The cumulated evaporation/condensation rate of species i at the interface is given by:

$$Mr_{evapi/cond}(\xi) = \int_0^\xi \dot{m}_i(\xi) d\xi \text{ where } \dot{m}_i(\xi) = \dot{m}_{c_i} - \left. \frac{\rho D_{g,im}}{d - \delta} \frac{\partial c_i}{\partial \eta} \right|_{\eta=0} \quad (20)$$

2. The cumulated evaporation/condensation rate of mixture at the interface is given by:

$$Mr_{evapt/condt}(\xi) = \int_0^\xi \dot{m}(\xi) dx = \sum_{i=1}^2 Mr_{evapi/condi} \quad (21)$$

3. SOLUTION METHOD

The equations in the liquid and in the gaseous phases (1–10) and their boundary conditions given by Eqs (11-19) are numerically solved using an implicit finite difference method. The flow area is divided into a regular mesh placed in axial and transverse direction in the liquid and gas regions and a 51x(51+31) grid is retained in present computations. The axial convection terms were approximated by the upstream difference and the transverse convection and diffusion terms by the central difference. To ensure that results were grid independent, the solution was obtained for different grid sizes for typical case program test. Table 1 shows that the differences in the total evaporating rate obtained using 51x(51+31) and 151x(51+51) grids are always less than 1%.

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

Ix(J+K) 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.

4. RESULTS AND DISCUSSIONS

All the results of this study have been obtained for the case of $T_0=293.15\text{K}$, $T_w=293.15\text{K}$, $u_0=0.8 \text{m/s}$, the geometrical ratio is $d/H=0.015$ and the imposed wall heat flux is $q_1=0$.

Fig.2 shows that the temperature increases along the channel. It indicates that gas mixture condensates on the interface liquid-gas. Fig.3 illustrates the axial development of the concentrations profiles of water and ethylene glycol vapor. Fig. 3.a shows 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. The general form of these curves suggests, following the Fick's law, that diffusion of the water vapor mass to the wetted plate takes place. This figure also shows that the water vapor concentration decrease if we move downstream of the channel. But in Fig.3.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.4 illustrates the evolution the phase change process (evaporation or condensation) of species i and of mixture along the channel. Fig.4 shows that we treat the problem of the vapor water condensation and the ethylene glycol evaporation. It is important to mention that the total mixture tend to condense. This result has been justified 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. 5-8 illustrate the influence of the inlet liquid mass flow m_{0L} on the heat and mass transfer during water vapor condensation and ethylene glycol evaporation. It is shown from Fig.5 that an increase of the inlet liquid mass flow advantages the cooling of the mixture especially near the liquid region. Consequently, a more quantity of the water vapor is condensed and the vapor concentration in the gas mixture decreases (Fig. 6.a). It is also observed that increasing the inlet liquid mass flow increases the gradient concentration of water vapor and consequently enhances the water vapor condensation (Fig.7.b). We can see from Fig. 6.b that an increase of the inlet liquid mass flow induces a decrease of the gradient concentration of ethylene glycol vapor and consequently disadvantages the ethylene glycol evaporation (Fig. 7.a). It can be said from Fig.8 that an increase of the inlet liquid temperature causes an increase of the temperature at the channel exit. Fig.9 presents the influence of the inlet liquid temperature on the concentrations of water and of ethylene glycol vapor at the channel exit. Fig. 9.a shows that the water vapor concentration c_{01} increases along the channel when we increase the inlet liquid temperature. This result has been attributed to the fact that an increase of the inlet liquid temperature induces an increase of the temperature (Fig.8) and consequently an increase of the water vapor concentration along the channel. It can be seen also that the concentration gradient of water vapor decrease when we increase the inlet liquid temperature T_{0L} causes consequently a decrease of the water vapor condensation (Fig.10.a). Fig.9.b reveals that, near the channel entry, the ethylene glycol vapor concentration is reduced along the channel when we reduce the inlet liquid temperature. It can be also said that the concentration gradient of ethylene glycol vapor increase when we increase the inlet liquid temperature and consequently of the ethylene glycol evaporation increase (Fig.10.b).

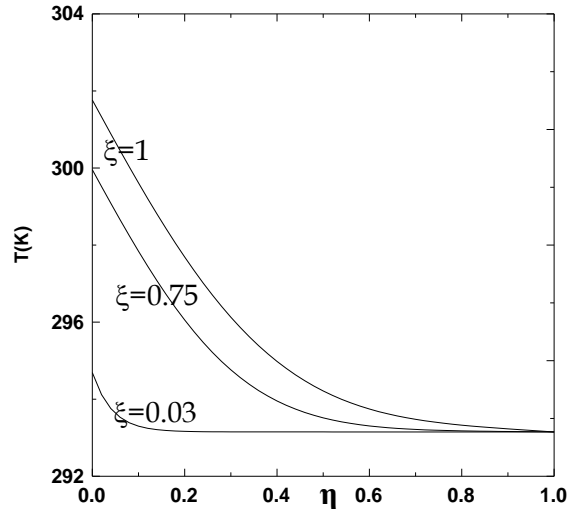


Figure 2. Temperature profile at various channel sections : $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $u_0=1\text{m/s}$, $q_1 = 0$, $c_{\text{Liq, ethylene glycol}}=0.5$ (50% water-ethylene glycol mixture), $m_{0L}=0.015\text{Kg/m.s}$, $T_{0L}=20^\circ\text{C}$

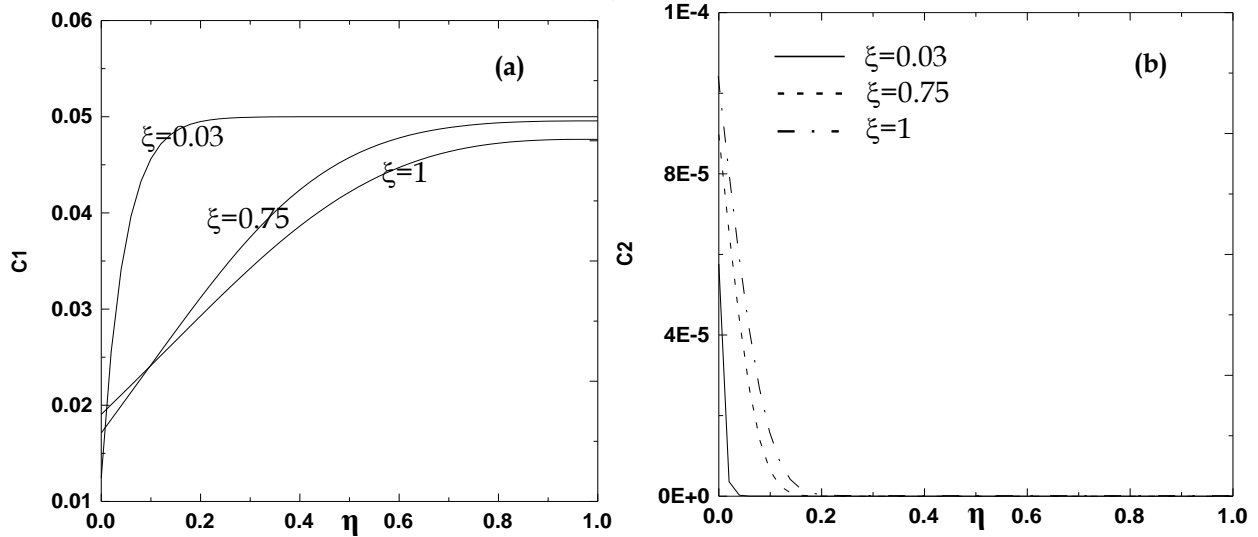


Figure 3. Concentrations profiles at various channel sections : a- concentration of water vapor ; b-concentration of ethylene glycol vapor : $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $u_0=1\text{m/s}$, $c_{\text{Liq, ethylene glycol}}=0.5$, $m_{0L}=0.015\text{Kg/m.s}$, $T_{0L}=20^\circ\text{C}$

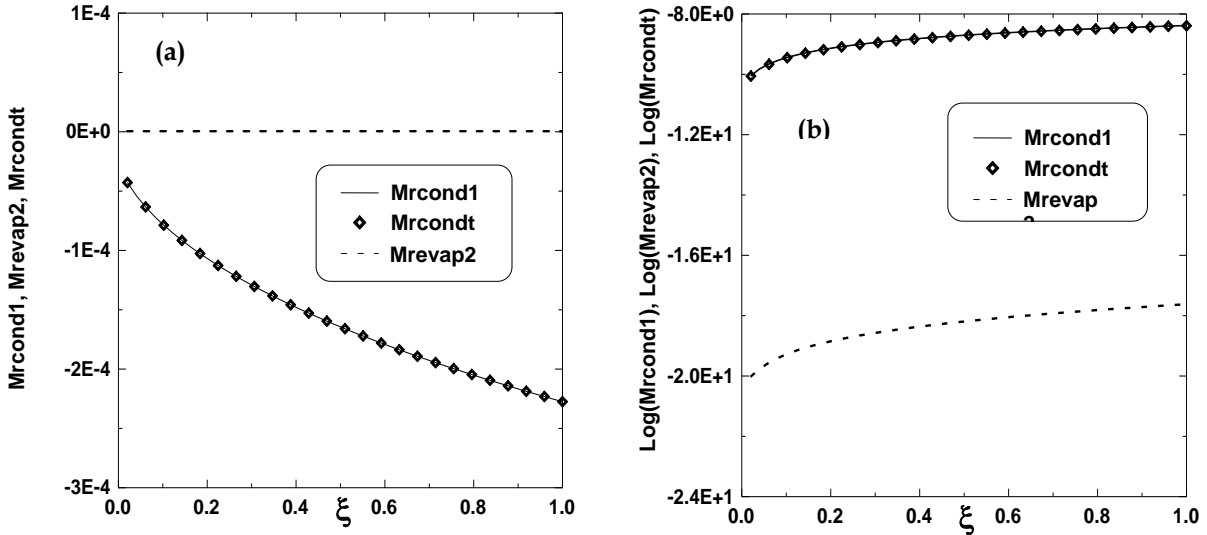


Figure 4. Evolution of the phase change process of species i (Mrcond1and Mrevap2 are respectively the water condensation and the ethylene glycol evaporation) and of the mixture (mixture condensation: Mrcondt) along the channel: $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $T_{0L}=20^\circ\text{C}$, $m_{0L}=0.015\text{Kg/m.s}$, $c_{\text{Liq, ethylene glycol}}=0.5$

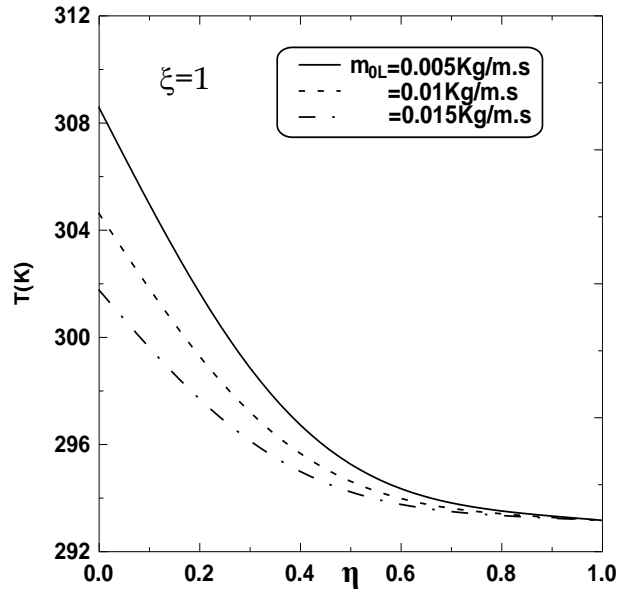


Figure 5. Effect of the inlet liquid mass flow on the temperature profile at the channel exit : $c_{01}=0.05$, $c_{02}=0$, $T_{0L}=20^\circ\text{C}$, $T_0=20^\circ\text{C}$, $c_{\text{Liq, ethylene glycol}}=0.5$

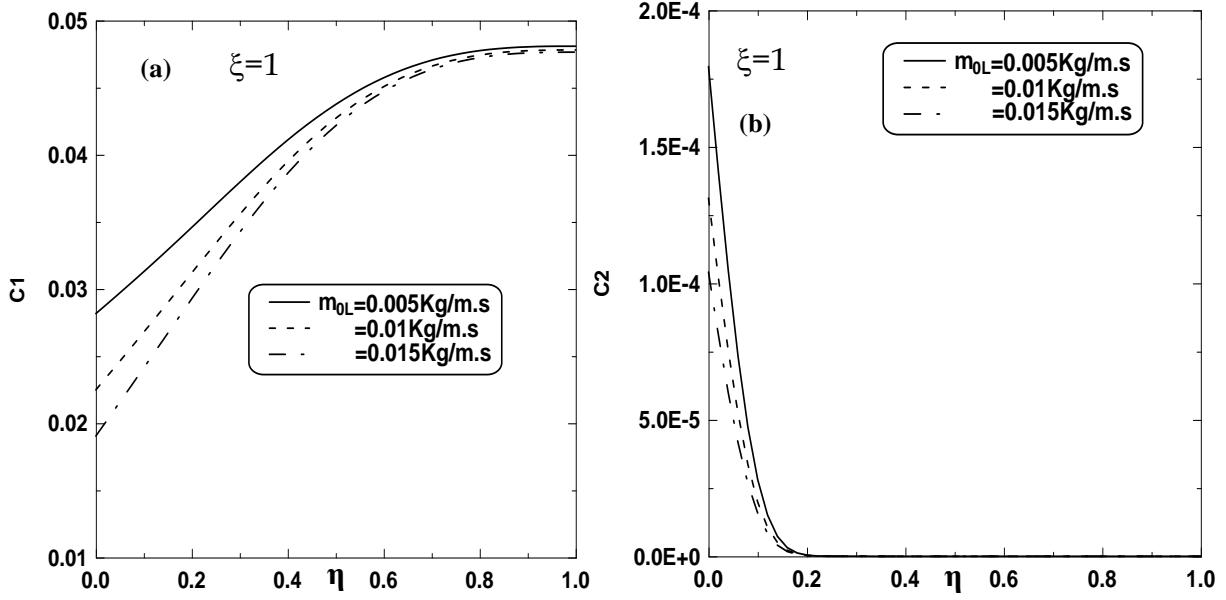


Figure 6. Effect of the inlet liquid mass flow on the concentrations profiles at the channel exit: a- water vapor concentration, b- ethylene glycol vapor concentration : $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $T_{0L}=20^\circ\text{C}$, $c_{\text{Liq, ethylene glycol}}=0.5$

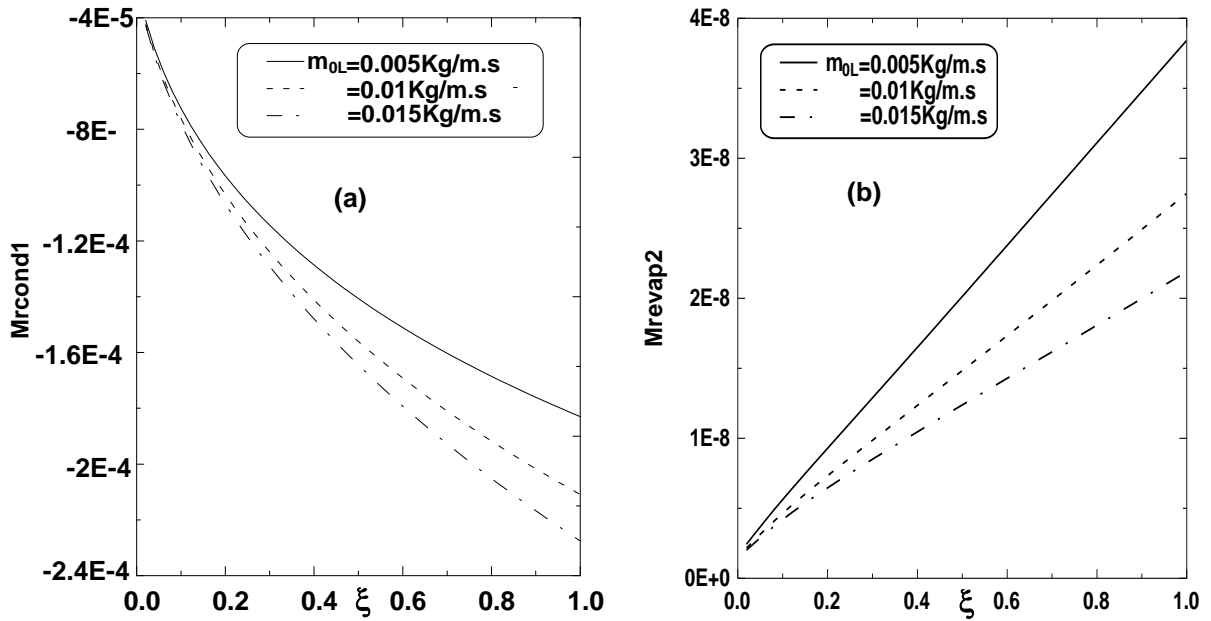


Figure 7. Effect of the inlet mass flow on the total cumulated condensation rate of water and on the total cumulated evaporation rate of ethylene glycol : $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $T_{0L}=20^\circ\text{C}$, $c_{\text{Liq, ethylene glycol}}=0.5$

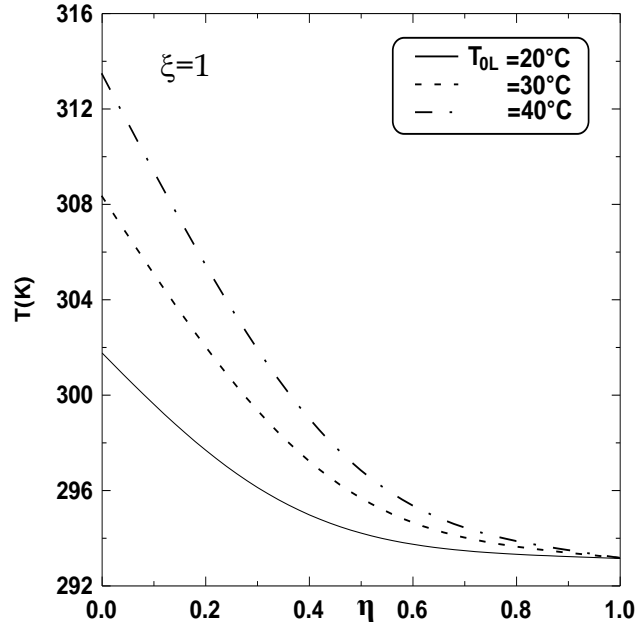


Figure 8. Effect of the inlet liquid temperature on the temperature profile at the channel exit :
 $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $m_{0L}=0.015\text{Kg/m.s}$, $c_{\text{Liq, ethylene glycol}}=0.5$

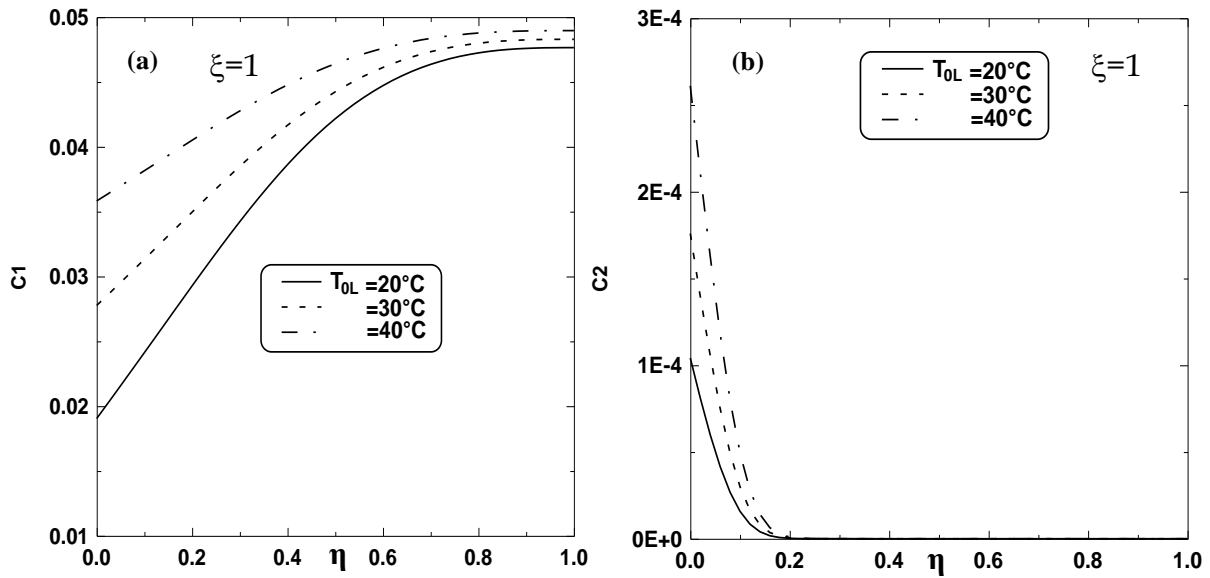


Figure 9. Effect of the inlet liquid temperature on the concentrations profiles at the channel exit;
 a- water vapor concentration, b- ethylene glycol vapor concentration: $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$,
 $T_{0L}=20^\circ\text{C}$, $m_{0L}=0.015\text{Kg/m.s}$, $c_{\text{Liq, ethylene glycol}}=0.5$

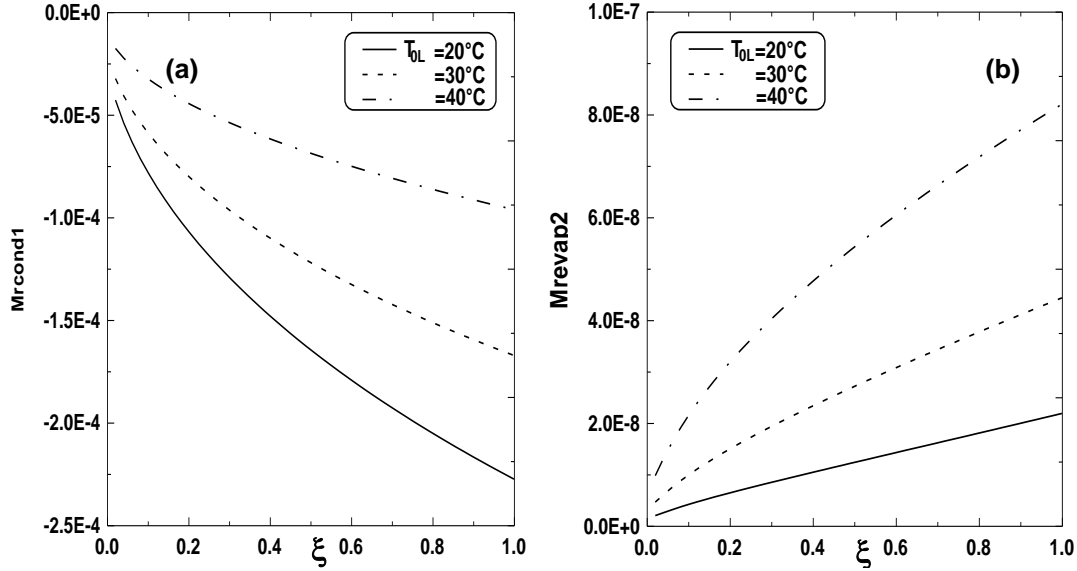


Figure 10. Effect of the inlet liquid temperature on the total cumulated condensation rate of water and on the total cumulated evaporation rate of ethylene glycol along the channel : $c_{01}=0.05$, $c_{02}=0$, $T_0=20^\circ\text{C}$, $m_{0L}=0.015\text{Kg/m.s}$, $c_{\text{Liq, ethylene glycol}}=0.5$

4. CONCLUSIONS

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) It was found that increasing the amount of film or reducing its inlet temperature benefits the water condensation and inhibits the water evaporation.
- 2) It is shown that an increase of the humidity enhances the ethylene glycol evaporation.
- 3) It was observed that an increase of the inlet liquid concentration of ethylene glycol advantages the water vapor condensation and the ethylene glycol evaporation.
- 4) 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.

Nomenclature

c_i	– mass fraction for species i vapor
c_{0i}	– mass fraction for species i vapor in the inlet condition
c_{Li}	– mass fraction for species i in the liquid film ($c_{L1}+c_{L2}=1$)
$c_{\text{Liq,ethylene glycol}}$	– inlet liquid concentration (composition or mass fraction) of ethylene-glycol in the liquid mixture ($c_{\text{Liq,ethylene glycol}}=1- c_{\text{Liq,water}}$)
c_p	– specific heat at constant pressure [$\text{J.kg}^{-1}.\text{K}^{-1}$]
c_{pa}	– specific heat for air [$\text{J.kg}^{-1}.\text{K}^{-1}$]
c_{pvi}	– specific heat for species i vapor [$\text{J.kg}^{-1}.\text{K}^{-1}$]
D_g	– mass diffusivity of species i vapor in the gas mixture [$\text{m}^2.\text{s}^{-1}$]
D_L	– mass diffusivity of species i in the liquid film mixture [$\text{m}^2.\text{s}^{-1}$]
H	– channel length [m]
I	– grid point index number in the flow direction
J	– grid point index number in transverse direction
L_v	– latent heat of evaporation of mixture [J.kg^{-1}]

L_{vi}	– 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 ($\dot{m} = \dot{m}_1 + \dot{m}_2$) [$kg.s^{-1}.m^{-2}$]
m_{L0}	– inlet liquid flow rate [$kg.s^{-1}$]
M_a	– molecular weight of air [$kg.mol^{-1}$]
M_{ri}	– 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 [15] ($M_r^* = M_r/0.004$)
p	– pressure in the channel [$N.m^{-2}$]
p_{vsi}	– pressure of saturated vapor of species i [$N.m^{-2}$]
p_{vsi}^*	– partial pressure of species i at the interface liquid–vapor [$N.m^{-2}$]
p_{vs}	– pressure of mixture vapor at the interface liquid–vapor ($p_{vs1}^* + p_{vs2}^*$) [$N.m^{-2}$]
c_{0Li}	– inlet mass fraction for species i in the liquid film ($c_{011} = c_{Liq,water}$ and $c_{012} = c_{Liq,ethylene\ glycol} = 1 - c_{Liq,water}$)
T	– absolute temperature [K]
q_1	– external heat flux of wetted wall [$W.m^{-2}$]
g	– gravitational acceleration ($m.s^{-2}$)
u	– axial velocity [$m.s^{-1}$]
v	– transverse velocity [$m.s^{-1}$]
x	– coordinate in the axial direction [m]
x^*	– dimensionless axial coordinate.
y	– coordinate in the transverse direction [m]
w_{Li}	– molar fraction of species i in the liquid mixture

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 [$m^2.s^{-1}$]
ρ	– density of the gas [$kg.m^{-3}$]
δ	– liquid film thickness (m)

Subscripts

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

References

- [1] Larbi khalal, M'barek feddaoui, Touria mediouni, Numerical study of heat and mass transfer during evaporation of a turbulent binary liquid film. *Thermal science, International Scientific Journal*, 2013, doi : 10.2298/TSCI120927025K.
- [2] P. Yang, Condensation characteristics inside a vertical tube considering the presence of mass transfer, vapor velocity and interfacial shear, *International Journal of Heat and Mass Transfer*, 44 (2001), pp. 4475-4482.
- [3] P.K. Panday, Two-dimensional turbulent film condensation of vapors flowing inside a vertical tube and between parallel plates, *Int. J. Refrigeration*, 26 (2003), pp. 492-503.
- [4] M.Oubella, M. Feddaoui, R. Mir, Numerical study of heat and mass transfer during evaporation of a thin liquid film" Thermal Sciences, *International Scientific Journal*, 2013, doi: 10.2298/TSCI130128145O.

- [5] Youngbae Han, Naoki Shikazono, Nobuhide Kasagi, The effect of liquid film evaporation on flow boiling heat transfer in a micro tube, *International Journal of Heat and Mass Transfer*, 55 (2012), pp. 547–555.
- [6] K.N. Agrawal, A. Kumar, M.A. Akhavan Behabad and H.K. Varma, Heat Transfer Augmentation by Coiled Wire Inserts during Forced Convection Condensation of R-22 Inside Horizontal Tubes, *Int. J. Multiphase Flow*, 24 (1998), 4, pp. 635-650.
- [7] W.M. Yan and D. Lin, Natural convection heat and mass transfer in vertical annuli with film evaporation and Condensation, *International Journal of Heat and Mass Transfer*, 44 (2001), pp. 1143-1151.
- [8] P.K. Panday, Two-dimensional turbulent film condensation of vapors flowing inside a vertical tube and between parallel plates, *Int. J. Refrigeration*, 26 (2003), pp. 492-503.
- [9] W W. J. Minkowycz and E. M. Sparrows, The effect of superheating on condensation heat transfer in a forced convection boundary layer flow, *International Journal of Heat and Mass Transfer*, 12 (1969), pp. 147-157.
- [10] Jingchun Min, Yicun Tang, theoretical analysis of water film evaporation characteristics on an adiabatic solid wall, *International Journal of Refrigeration*, 53 (2015), pp.55-61.
- [11] A. Nasr, C. Debbissi Hfaiedh and S. Ben Nasrallah, Numerical study of evaporation by mixed convection of a binary liquid film. *Energy*, 36 (2011), pp. 2316-2327.
- [12] K.N. Agrawal, A. Kumar, M.A. Akhavan Behabad and H.K. Varma, Heat Transfer Augmentation by Coiled Wire Inserts during Forced Convection Condensation of R-22 Inside Horizontal Tubes, *Int. J. Multiphase Flow*, 24 (1998), 4, pp. 635-650.
- [13] E.C. Siow, S.J. Ormiston and H.M. Soliman, Soliman, Fully coupled solution of a two-phase model for laminar film condensation of vapor-gas mixtures in horizontal channels, *International Journal of Heat and Mass Transfer*, 45 (2002), pp. 3689-3702.
- [14] C. Debbissi Hfaiedh, A. Nasr, S. Ben Nasrallah, Evaporation of a binary liquid film flowing down the wall of two vertical plates, *Int. J. Thermal sciences*, 72 (2013), pp. 34-46.
- [15] A. Ali Cherif, A. Daif, Etude numérique du transfert de chaleur et de masse entre deux plaques planes verticales en présence d'un film de liquide binaire ruisselant sur l'une des plaques chauffées. *Int. J. Heat Mass Transfer*, 42 (1999), pp.2399-2418.
- [16] A. Agunaoun, A. Il Idrissi, A. Daif, R. Barriol, Etude de l'évaporation en convection mixte d'un film liquide d'un mélange binaire s'écoulant sur un plan incliné soumis à un flux de chaleur constant. *Int.J. Heat Mass Transfer*, 41 (1998), pp. 2197-2210.
- [17] A.Nasr, C. Debbissi Hfaiedh and S. Ben Nasrallah, Evaporation of a Binary Liquid Film by Forced Convection, *THERMAL SCIENCE, International Scientific Journal*, 15 (2011), pp. 773-784.
- [18] X.G. Huang, Y.H. Yang, P. Hu, Experimental study of falling film evaporation in large scale rectangular channel, *Annals of Nuclear Energy*, 76 (2015), pp. 237–242.
- [19] Shankar Narayanan, Andrei G. Fedorov, Yogendra K. Joshi, Heat and mass transfer during evaporation of thin liquid films confined by nanoporous membranes subjected to air jet impingement, *International Journal of Heat and Mass Transfer* 58 (2013), pp. 300–311.
- [20] Armel Gonda, Philippe Lancereau, Philippe Bandelier, Lingai Luo, Yilin Fan, Sylvain Benezechd, Water falling film evaporation on a corrugated plate, *International Journal of Thermal Sciences*, 81 (2014), pp. 29–37.
- [21] Hubert Monnier, Jean-François Portha, Abdoulaye Kane, Laurent Falk, Intensification of heat transfer during evaporation of a falling liquid film in vertical microchannels—Experimental investigations, *Chemical Engineering Science*, 18 (2012), pp. 152–166.

Paper submitted: 9 November 2016

Paper revised: 27 March 2017

Paper accepted: 17 April 2017