EVAPORATION OF A BINARY LIQUID FILM BY FORCED CONVECTION

by

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This paper deals with a numerical analysis of the evaporation of a thin binary liquid film by forced convection inside a channel constituted by two parallel plates. The first plate is externally insulated and wetted by a thin water ethylene glycol film while the second 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 set of non-linear and coupled equations expressing the conservation of mass, momentum, energy, and species in the liquid and gas mixtures is solved numerically using a finite difference method. Results concerns with the effects of inlet ambience conditions and the inlet liquid concentration of ethylene glycol on the distribution of the temperature, concentrations profiles, and the axial variation of the evaporation rate of species i.

Key words: *binary liquid film, forced convection, combined heat and mass transfer*

Introduction

The evaporation of the multi-components liquid film in air is important in heat and mass transfer and exists in different industrial applications such as, combustion premixing, industry, desalting, drying, film cooling, and air conditioning. The case of evaporation of pure and binary liquid has also received considerable attention in many theoretical and experimental studies. Ali Cherif *et al.* [1] considered thin binary liquid film evaporation by mixed convection falling on one of the two parallel plates' channel. The wetted plate is subjected to a constant uniform heat flux while the other is insulated. They show that the volatilities of the mixture influence the heat transferred through the latent mode, which is more pronounced for mixture composed of volatile components. For the ethanol-water liquid mixture, the results seem to be foreseeable while it is different for the second mixture "ethylene glycol-water". They show, for example, that for a particular ethylene glycol-water mixture, 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.* [2] presented a numerical analysis of the heat and mass transfer in a binary thin film flowing on an inclined plate. The most interesting results

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are obtained in forced convection, particularly in the case of ethylene glycol-water mixture. In fact, the obtained results have shown that it is possible to increase the accumulated evaporation rate when the molar fraction of ethylene glycol is less than 40%. Palen *et al.* [3] studied experimentally the evaporation of a liquid mixture; ethylene glycol-water inside a vertical tube of circular section. They observed that for some experimental conditions, the local heat transfer coefficient between the gas and the liquid mixture can fall of 80% in relation to the relative value to the pure water, value that is lower to the one gotten with the pure ethylene glycol in the same conditions. Hoke *et al.* [4] presented a numerical study of the evaporation of a binary liquid film on a vertical plate. They showed that the value of the Sherwood number was roughly two times the value of the Nusselt number for the case of heat transfer if the experimental conditions are reversed. It was shown that the influence of the evaporation on the Sherwood number was especially weak for constant debits of the considered constituent. Vijay *et al.* [5] presented a study of the isotherm evaporation of a binary liquid film. They could measure the diffusion coefficient during the evaporation of a binary liquid in a Stefan tube while observing the position of the liquid-gas interface. Baumann *et al.* [6] studied the heat and mass transfer in evaporating two component (benzene-methanol) liquid film flow. For the two-phase multicomponent flow in two-component liquid film evaporation a physical model has been proposed. The prediction for the evaporation of benzene-methanol mixtures in a hot tubular air stream clearly shows the influence of the phase equilibrium and its interaction with the local transport processes. El Armouzi *et al.* [7, 8] investigated numerically the evaporation by mixed convection of a binary liquid film flowing down of two coaxial cylinders. They showed that the volatilities of the mixture influenced the heat transferred through the latent mode, which is more pronounced for mixture composed of volatile components. They also showed that the mass and heat transfers were more important near the inlet of the channel and increased with the wall heat flux density. For the same inlet air velocity, the concentration and the liquid film thickness were the critical parameters, which governed the transfers during its evaporation.

It can be concluded from this review that the evaporation of a thin binary liquid film and the effect of inlet conditions on the heat and mass transfer have not been studied yet. A particular attention will be addressed to the effects of inlet ambience conditions and the liquid concentration of ethylene glycol on the distribution of the temperature, concentrations profiles and the axial variation of the evaporation rate of species *i*.

Analysis

The present work deals with a numerical analysis of evaporation of water-ethylene glycol into hot humid air and superheated steam by forced convection in a channel (fig. 1). The channel is made up of two parallel plates. The first plate is externally insulated and wetted by a thin water-ethylene glycol film while the second one ($y = d$) is dry and isothermal and maintained at T_w.

One can note that, since the wet plate is externally insulated, the energy required for evaporation comes entirely from ambient stream.

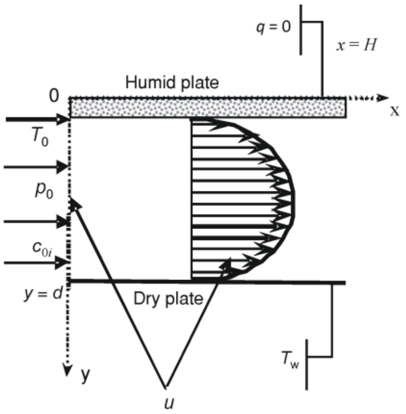

Figure 1. Physical description of the system

For mathematical formulation of the problem, the following simplifying assumptions are used:

- the liquid film is assumed to be thin. Under this assumption, transport in the liquid film can be replaced by approximate boundary conditions for gas flow [8, 9, 11],
- the boundary layer approximations are valid,
- the viscous dissipation and the pressure work are negligible,
- the Dufour and Soret effects are negligible,
- the thermal radiation is negligible.
- the vapor mixture is an ideal gas, and
- the liquid mixture is ideal.

The heat and mass transfer for the laminar forced convection, with the usual boundary layer approximation, are described by the following equations [12-16]):

- continuity equation

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}=0 \tag{1}$$

- x-momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}x}+\frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \tag{2}$$

- energy equation

$$\rho c_\mathrm{p}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\sum_{i=1}^{2}\rho(D_{\mathrm{m}i}c_\mathrm{pvi}-D_\mathrm{am}c_\mathrm{pa})\frac{\partial T}{\partial y}\frac{\partial c_i}{\partial y} \tag{3}$$

- species diffusion equations

$$u\frac{\partial c_i}{\partial x}+v\frac{\partial c_i}{\partial y}=\frac{1}{\rho}\frac{\partial}{\partial y}\left(\rho D_\mathrm{in}\frac{\partial c_i}{\partial y}\right) \tag{4}$$

The second term in the right side of the energy equation presents the energy transport through the inter-diffusion of species. Thermo-physical properties of gas mixture are considered as variable with temperature and concentration. The correlations used in this study were given in [11] for viscosity, heat capacity, and mass diffusion coefficients and in Missenard [17] for thermal conductivity.

In this study, the overall mass balance is described by the following equation:

$$\int_0^d \rho u(x,y)\mathrm{d}y = d\rho_0 u_0+\int_0^x \rho v(x,0)\mathrm{d}x \tag{5}$$

The boundary conditions are:

- at $x = 0$ and $0 < y < d$

$$u=u_0,\quad T=T_0,\quad c_1=c_{01},\quad c_2=c_{02} \tag{6}$$

– at $y = 0$ and $0 < x < H$ (isolated plate)

$$u = 0 \quad \text{and} \quad q = 0.$$

The transverse velocity of gas is deduced by assuming that the air-ethylene glycol-water interface is semi-permeable [1, 2]:

$$v(x,0) = -\frac{1}{1-c_1(x,0)-c_2(x,0)}\left(D_{1\mathrm{m}} \left.\frac{\partial c_1}{\partial y}\right|_{y=0} + D_{2\mathrm{m}} \left.\frac{\partial c_2}{\partial y}\right|_{y=0} \right) \tag{7a}$$

The energy balance at the insulated interface ($y = 0$) is evaluated by:

$$-\lambda\frac{\partial T}{\partial y} - \frac{\rho L_\mathrm{v}}{1-c_1(x,0)-c_2(x,0)}\left(D_{1\mathrm{m}} \left.\frac{\partial c_1}{\partial y}\right|_{y=0} + D_{2\mathrm{m}} \left.\frac{\partial c_2}{\partial y}\right|_{y=0} \right) = 0 \tag{7b}$$

According to Daltons law and by assuming the interface to be at thermodynamic equilibrium and the air-vapor mixture is an ideal gas mixture, the concentration of vapor can be evaluated by [1, 2] :

$$c_1(x,0) = \frac{P_{\mathrm{vs1}}^*}{P_{\mathrm{vs1}}^* + \left[P_{\mathrm{vs2}}^* \frac{M_2}{M_1} \right] + \left[P - P_{\mathrm{vs1}}^* - P_{\mathrm{vs2}}^* \right] \frac{M_\mathrm{a}}{M_1}} \tag{7c}$$

$$c_2(x,0) = \frac{P_{\mathrm{vs2}}^*}{P_{\mathrm{vs2}}^* + \left[P_{\mathrm{vs1}}^* \frac{M_1}{M_2} \right] + \left[P - P_{\mathrm{vs1}}^* - P_{\mathrm{vs2}}^* \right] \frac{M_\mathrm{a}}{M_2}} \tag{7d}$$

$$P_{\mathrm{vs}i}^* = P_{\mathrm{vs}i}^* \; X_{\mathrm{L}i}, T \; = X_{\mathrm{L}i}\, P_{\mathrm{vs}i}(T); \quad i = 1,\ 2$$

$$X_{\mathrm{L}i} = c_{\mathrm{L}i}\frac{M}{M_i} \;\; \text{with} \;\; \frac{1}{M} = \frac{c_{\mathrm{L1}}}{M_1} + \frac{c_{\mathrm{L2}}}{\mathrm{M}_2} \tag{7e}$$

X_{L1} and X_{L2} are the molar concentrations of water liquid and ethylene glycol liquid. P_{vs1} and P_{vs2} are the equilibriums pressures of water and ethylene glycol vapor in the mixture [2, 18]

– at $y = d$ and $0 < x < H$ (isothermal plate)

$$u = 0; \quad v = 0; \quad T = T_\mathrm{w} \tag{7f}$$

The impermeability of the dry plate (y = d) to the water and ethylene glycol vapor can be described by:

$$\frac{\partial c_i}{\partial y} = 0\ ; \quad i = 1,\ 2 \tag{7g}$$

The local evaporation rate of species i is given by [1]:

$$\dot{m}_i = \rho v(x,0) c_i(x,0) - \rho D_{mi} \left.\frac{\partial c_i}{\partial y}\right|_{y=0} \tag{8a}$$

The average evaporation rate of species *i* is given by:

$$\bar{\dot{m}}_i = \frac{1}{H}\int_0^H \dot{m}_i \mathrm{d}x \tag{8b}$$

The latent heat of evaporation in the case of the thin film of liquid mixture is calculated from the expression [1]:

$$L_\mathrm{v} = c_{\mathrm{L}1} L_{\mathrm{v}1} + c_{1,2} L_{\mathrm{v}2}$$

The thermo-physical properties in the gas mixture to three constituents depend on the temperature and concentrations. These properties are calculated in [2].

Solution method

The presented system of eqs. (1)-(5) is solved numerically using finite difference method. The flow area is divided in a regular mesh placed in axial and transverse direction and a (51 × 31) grid is retained in actual computations. 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 in the finite difference equations. The resolution of the obtained algebraic equations was marched in downstream direction since flow under consideration is a boundary layer type.

For given thermal and mass boundary conditions, the solution procedure is briefly outlined as:

Step 1. Give the inlet known velocity u_0.

Step 2. For the given axial location *I*, guess the wetted wall temperature T^* and solve the finite difference form of species equation for water and ethylene glycol.

Step 3. Solve the finite difference form of energy equation and compare the new value T of wetted temperature to T^* by testing if:

$$\left|\frac{T(I,1) - T^*(I,1)}{T(I,1)}\right| < 10^{-6}$$

If this criteria is not satisfied, return to step 2 and modify the wetted wall temperature by using the bisection method.

Step 4. Guess a pressure *P** at the *I* axial location and solve the momentum and continuity finite difference equations, then verify the satisfaction of the overall conservation of mass expressed by the criteria:

$$\frac{\left|\int_0^d \rho u(x,y)\mathrm{d}y - \left[d\rho_0 u_0 + \int_0^X \rho v(x,0)\mathrm{d}x\right]\right|}{d\rho_0 u_0} < 10^{-6}$$

Step 5. If this condition is not satisfied, return to step 4 and modify the pressure value P^* and repeat the steps (2)-(4).

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 interfacial temperature obtained using 51 × 31 and 100 × 51 grids are always less than 1%.

Table 1. Interfacial temperature $T(x, 0) - T_0$ for different grids

$N_x \times N_y$	$x = 0.2$	$x = 0.4$	$x = 0.6$	$x = 0.8$	$x = 1$
51 × 31	50.66	57.75	61.88	64.75	66.75
101 × 31	50.56	57.72	61.86	64.74	66.83
151 × 31	50.53	57.72	61.	64.74	8466.87
101 × 21	50.97	58.10	62.19	65.07	67.19
101 × 51	50.19	57.42	61.58	64.47	66.61

$T_0 = 20$ °C, $q_1 = 3000$ W/m^2, $q_2 = 0$, $P_0 = 1$ atm, $u_0 = 1$ m/s, $d = 0.015$ m, $H = 1$ m,
$c_{\text{liq,water}} = c_{\text{liq,ethylene glycol}} = 0.5$ (50% water-ethylene glycol mixture), $c_{01} = 0$; $c_{02} = 0$

To check the adequacy of the numerical scheme adopted in the present study, different cases for evaporation of pure and binary liquid were considered. The results for the case of forced convective heat and mass transfer in the case of pure liquid inside a channel have been treated with constant physical properties. The channel is made up of two parallel plates. The first plate is isothermal and impermeable. The second is insulated and kept at constant concentration.

The comparison is carried out for the case of forced combined heat and mass transfer in a channel made up by a humid insulated plate and the other one is kept at the ambient temperature. The physical properties of humid air flow are considered to be variable. The results for the case of mixed convective heat and mass transfer in the case of binary liquid inside a vertical channel has been tested successfully by comparing the present solutions for the total evaporating rate (M_r) and the interfacial temperature $T_p - T_0$ with the results from [1], figs. 2 and 3. Through these program tests, the present numerical algorithm is considered to be suitable to study the present problem.

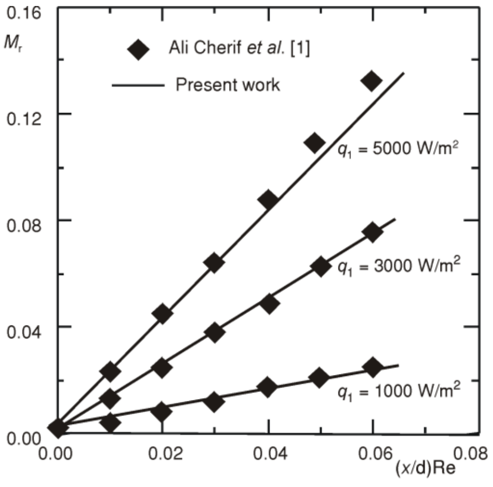

Figure 2. Variation of the total evaporating rate along the channel

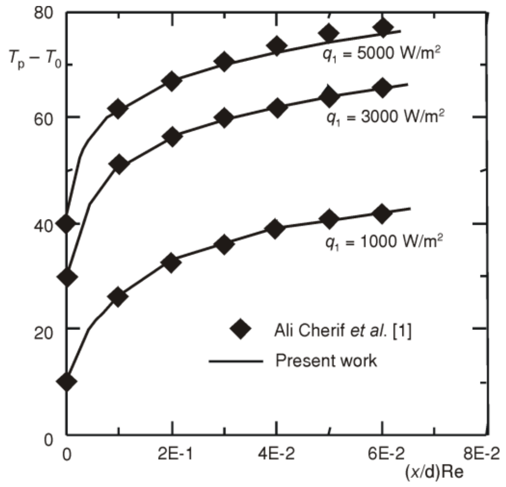

Figure 3. Variation of the interfacial temperature along the channel

Results and discussion

The effect of the inlet liquid concentration of ethylene glycol on the development of temperature and concentration profiles as well as on the characteristics of heat and mass transfer is investigated. The results for evaporative rate of water from wetted plate in a parallel stream of humid air are also presented. All the cases are based on a channel with length of 1 m and width of 0.05 m. Moreover, the dry wall temperature is always kept at $T_\mathrm{w} =$ = 298.15 K.

Figure 4 shows the effects of the inlet liquid concentration of ethylene glycol (ethylene glycol concentration in the liquid mixture) on the temperature and concentration profile at the exit section ($x = H$). Figure 4(a) display that the temperature at the exit section ($x =$ $= H$) increases when one increases the liquid concentration of ethylene glycol. This result can be justified by the fact that the water is more volatile than the ethylene glycol. Figure 4(b) shows that the concentration of vapor ethylene glycol at the section exit ($x = H$) increases when one increases the liquid concentration of ethylene glycol. This result can be justified by an increasing of the liquid concentration of ethylene glycol increases the evaporation of ethylene glycol so the ethylene glycol vapor concentration increases.

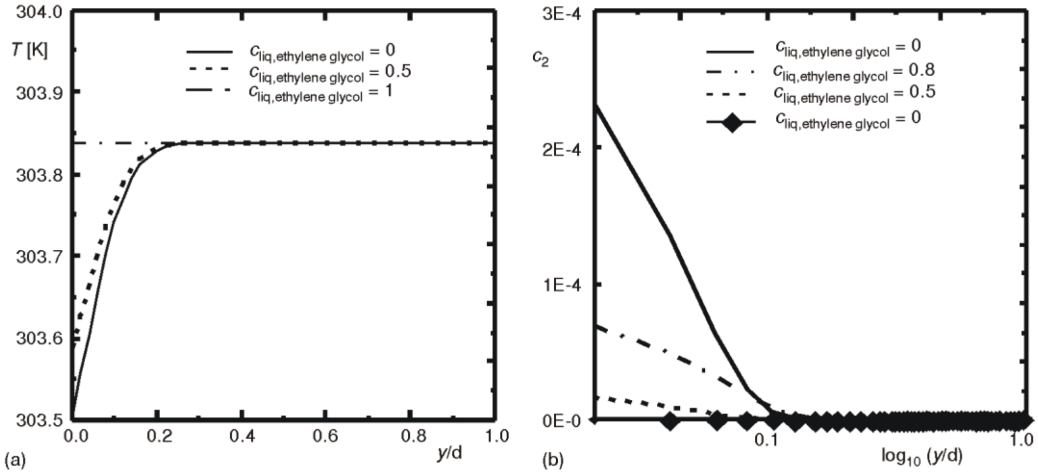

Figure 4. Effect of inlet liquid concentration of ethylene glycol on temperature and concentration of the ethylene glycol vapor *($c_{01} = c_{02} = 0$, $T_w = 298.15$ K, $T_0 = 298.15$ K, $u_0 = 1$ m/s, $d = 0.05$ m)*

Figure 5 illustrates the changing behaviours of concentration profile in transverse direction for the location ($x = H$) with a variation of ambient humidity. This figure indicates that when one increases the ambient humidity, the ethylene glycol vapor concentration near the wetted plate increases. This result can be justified by the fact that an increasing of the ambient humidity reduces the evaporation of water and increases the evaporation of ethylene glycol. The effect of the inlet vapor ethylene glycol concentration c_{02} on the interfacial temperature and water and ethylene glycol vapor concentrations profiles are shown in fig. 6. As seen from this fig. 6(a), an increase of the ethylene glycol concentration reduces the evaporative cooling of the adjacent fluid of the humid plate. This result can be explained by

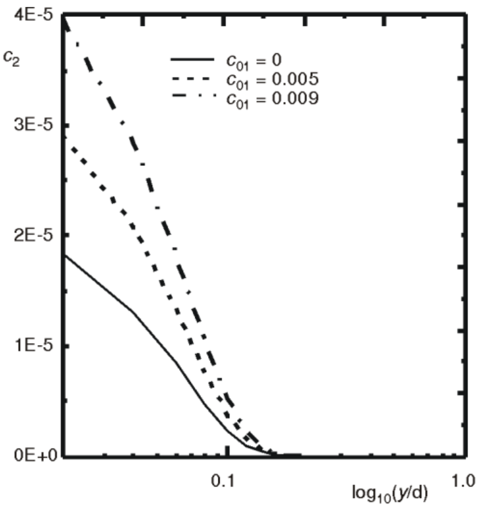

Figure 5. Effect of inlet water vapor concentration on temperature and concentration of the water and ethylene glycol vapor
($c_{liq.ethylen\ glycol}$ = 0.5, c_{02} = 0, T_w = 298.15 K, T_0 = 298.15 K, u_0 =1 m/s,d = 0.05 m)

the evaporation rate of ethylene glycol declines as the inlet vapor ethylene glycol concentration c_{02} rises. Whereas the evaporation rate of water increases as the inlet vapor ethylene glycol concentration c_{02} rises. An increasing of c_{02} induces a increasing of water vapor and ethylene glycol vapor concentration, figs. 6(b) and 6(c).

Figure 7 illustrates the effect of the liquid concentration of ethylene glycol on the interfacial temperature. Figure 7 shows that when one increases the liquid concentration of ethylene glycol, the interfacial temperature increases also. As seen before, this result can be explained by the fact that the volatility of water is more important than that of ethylene glycol. Figure 8 presents the effect of inlet water vapor concentration on the ethylene glycol vapor concentration. It is shown from fig. 8 that the interfacial ethylene glycol concentration is more important when one increases the ambient humidity.

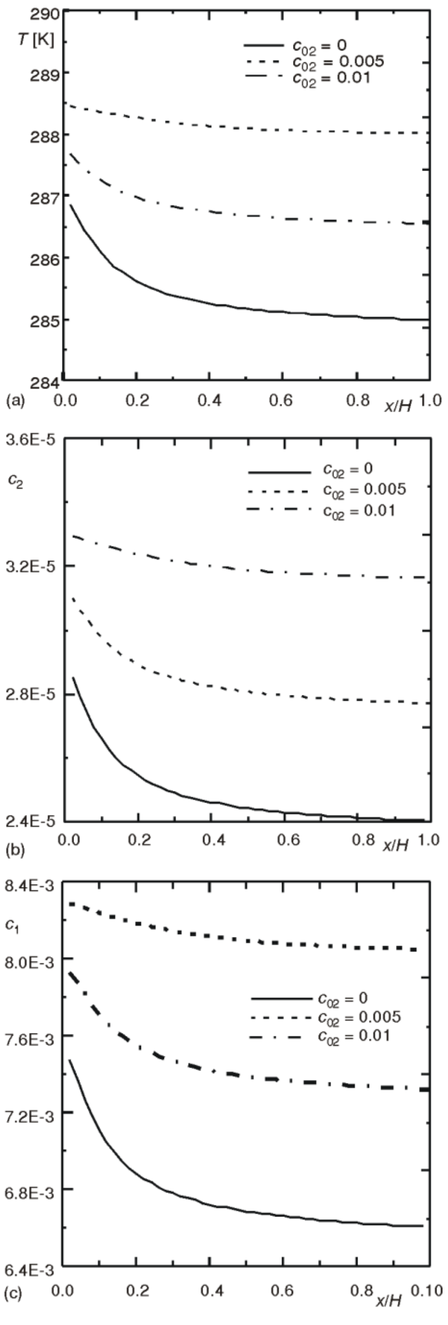

Figure 6. Efect of inlet ethylene glycol vapor concentration on the interfacial temperature, the water and ethylene glycol vapor concentrations
(c_{01} = 0, T_w = 298.15 K, q = 0, T_0 = 298.15 K, u_0 = 1 m/s, d/H = 0.05, $c_{liq.ethulene\ glycol}$ = 0.5, P_0 = 1 atm)

Figure 9 shows the generally accepted fact that water evaporates faster in air than in moist air. Figure 10 shows that the water interfacial evaporating rate $\bar{m}_1$ increases when we increase the ethylene glycol vapor concentration. This result can be explained by the fact that a rising of the ethylene glycol vapor concentration decreases the water interfacial evaporating rate $\bar{m}_2$. Consequently, the water interfacial evaporating rate $\bar{m}_1$ increases.

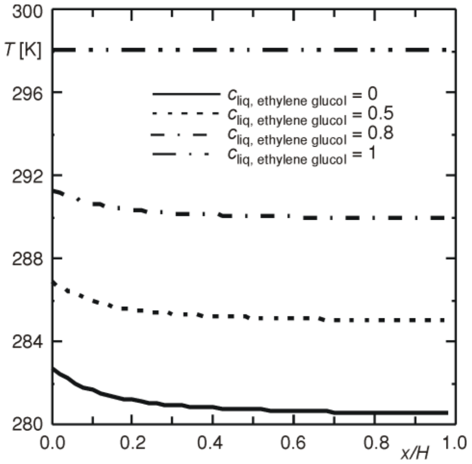

Figure 7. Effect of liquid concentration of ethylene glycol on the interfacial temperature and the ethylene glycol vapor concentration
(c_{01}= 0, c_{02}= 0, T_w=298.15 K, q = 0, T_0=298.15 K, u_0=1 m/s, d/H=0.05, P_0 = 1 atm)

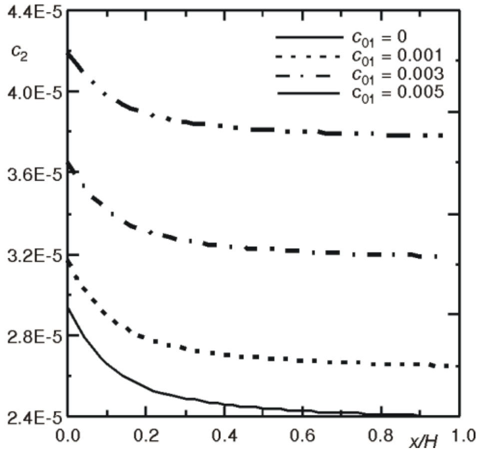

Figure 8. Effect of inlet water vapor concentration on ethylene glycol vapor concentration
(c_{02}= 0, T_w=298.15K, q=0, T_0=298.15K, u_0=1m/s, d/H = 0.05, P_0=1 atm, $c_{liq,ethylene\ glycol}$ = 0.5)

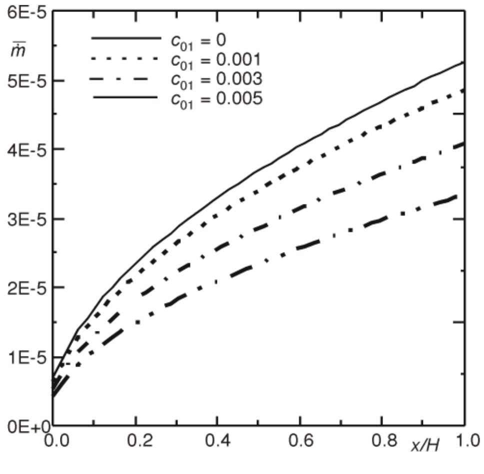

Figure 9. Effect of inlet water vapor concentration on water evaporation rate
(c_{02}= 0, T_w=298.15 K, q = 0, T_0 = 298.15 K, u_0 = 1m/s, d/H = 0.05, P_0 = 1 atm, $c_{liq,ethylene\ glycol}$ = 0.5)

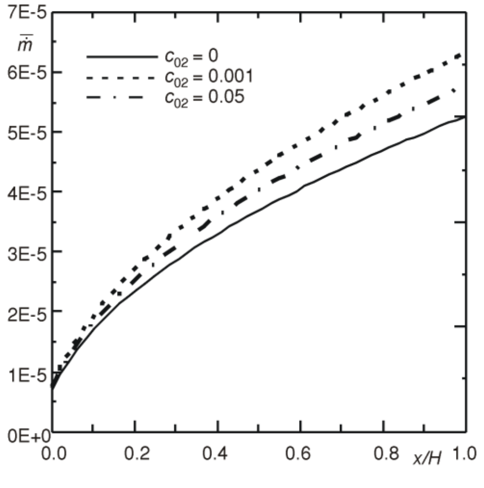

Figure 10. Effect of inlet ethylene glycol vapor concentration on the water evaporation rate
(c_{01} = 0.9, T_w = 298.15 K, q = 0, T_0 = 298.15 K, u_0 = 1 m/s, d/H = 0.05, P_0 = 1 atm, $c_{liq,ethylene\ glycol}$=0.5)

As seen in fig. 11, the ethylene glycol interfacial evaporating rate $\bar{m}_2$ increases when one increases the ambient humidity. This result can be justified by the fact that generally, the rising of the ambient humidity causes a decreasing of water evaporating rate, consequently causes a rising of the ethylene glycol evaporating rate $\bar{m}_2$. Figure 12 illustrates the effect of inlet ethylene glycol vapor concentration c_{02} on the evolution of ethylene glycol evaporating rate $\bar{m}_2$. This figure shows that the rising of c_{02} reduces the evaporation ethylene glycol.

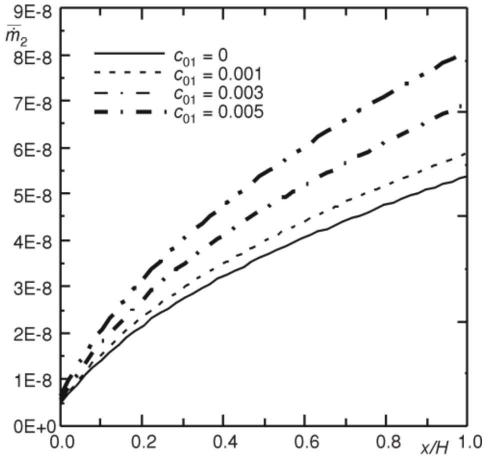

Figure 11. Effect of inlet water vapor concentration on the ethylene glycol evaporation rate
(c_{02} = 0, T_w = 298.15 K, q = 0, T_0 = 298.15 K, u_0 = 1 m/s, d/H = 0.05, $c_{liq,ethylene\ glycol}$ = 0.5, P_0 = 1 atm)

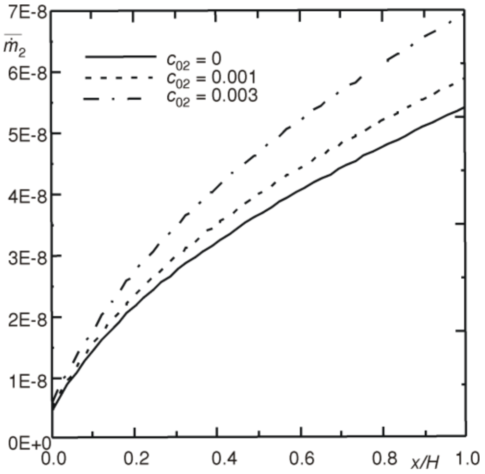

Figure 12. Effect of inlet ethylene glycol vapor concentration on the ethylene glycol evaporation rate
(c_{01} = 0, T_w = 298.15 K, q = 0, T_0 = 298.15 K, u_0 = 1 m/s, d/H = 0.05, P_0 = 1 atm, $c_{liq,ethylene\ glycol}$ = 0.5)

Conclusions

The evaporation in forced convection mode of a binary liquid film in a channel has been numerically studied. The channel is made up of two parallel plates. The first plate is wetted by a thin liquid mixture and externally insulated. The second plate is dry and isothermal. Equations, which govern the transfer in the vapor flow, are solved by an implicit finite difference scheme. The effects of inlet ambiance conditions and the liquid concentration of ethylene glycol on the distribution of the temperature, concentration profiles and the axial variation of the evaporation rate are examined in detail. On the other hand, the effectiveness of the water and ethylene glycol evaporation rate as function of the temperature and vapor concentration of the ethylene glycol and of the water is also studied.

The major results are briefly summarized in the following.

- The ethylene glycol evaporating rate is negligible compared with the water evaporating rate because the latent heat of evaporation of water is more important than the ethylene glycol (the water is more volatile than the ethylene glycol).
- The ethylene glycol evaporating rate $\bar{m}_2$ increases when one increases the ambient vapour concentration of water (the more volatile component).

- The water evaporating rate $\bar{\dot{m}}_1$ increases when one increases the ambient vapour concentration of ethylene glycol (the less volatile component).

Nomenclature

c_i – mass fraction for species *i* vapor
$c_{\mathrm{L}i}$ – mass fraction for species *i* in the liquid film ($c_{\mathrm{L1}} + c_{\mathrm{L2}} = 1$), [–]
$c_{\mathrm{liq,ethylene\ glycol}}$ – mass fraction for ethylene glycol in the inlet film liquid
c_p – specific heat at constant pressure, [$\mathrm{Jkg^{-1}K^{-1}}$]
c_pa – specific heat for air, [$\mathrm{Jkg^{-1}K^{-1}}$]
$c_{\mathrm{pv}i}$ – specific heat for species *i* vapor, [$\mathrm{Jkg^{-1}K^{-1}}$]
c_{0i} – mass fraction ambient for species *i* vapor
$D_{\mathrm{m}i}$ – mass diffusivity of species *i* vapor in the gas mixture, [$\mathrm{m^2s^{-1}}$]
d – channel width, [m]
H – channel length, [m]
I – grid point index number in the flow direction
L_v – latent heat of evaporation of mixture, [$\mathrm{Jkg^{-1}}$]
$\dot{m}_i$ – local evaporation rate of species *i*, [$\mathrm{kgs^{-1}m^{-2}}$]
M_a – molecular weight of air, [$\mathrm{kgmol^{-1}}$]
M_i – molar mass of species *i* vapor, [$\mathrm{kgmol^{-1}}$]
M_r – total evaporation rate of mixture given by [1]
N_x – number of grid points in the x-direction
N_y – number of grid points in the y-direction
P – pressure of the moist air in the channel, [$\mathrm{Nm^{-2}}$]
P_g – motion pressure, [$\mathrm{Nm^{-2}}$]
$P_{\mathrm{vs}i}$ – partial pressure of species saturated *i*, [$\mathrm{Nm^{-2}}$]
P_0 – ambient pressure, [$\mathrm{Nm^{-2}}$]
q – heat flux, [$\mathrm{Wm^{-2}}$]
T – absolute temperature, [K]
T_p – wetted wall temperature, [K]
T_w – dry wall temperature, [K]
u – axial velocity, [$\mathrm{ms^{-1}}$]
v – transverse velocity, [$\mathrm{ms^{-1}}$]
x – axial co-ordinate, [m]
x^* – dimensionless axial co-ordinate
y – co-ordinate in the transverse direction, [m]

Greek symbols

λ – thermal conductivity of the fluid, [$\mathrm{Wm^{-1}K^{-1}}$]
μ – dynamic viscosity of the fluid, [$\mathrm{kgm^{-1}s^{-1}}$]
ρ – density of the fluid, [$\mathrm{kgm^{-3}}$]

Subscripts

a – dry air
i – 1 for water vapor and 2 for ethylene glycol vapor
m – mixture
m*i* – species *i* in the mixture
s – interface
0 – ambient condition

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