

Computational study on the evaporation of water and glycols between vertical parallel plates with asymmetric heating

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Abstract— Simultaneous heat and mass exchanges during the evaporation of water or glycols between vertical parallel plates were numerically studied. The liquid film falls along a left plate which is externally subjected to uniform heat flux while the right plate is assumed to be dry and thermally insulated. The set of non-linear and coupled equations expressing the conservation of mass, momentum, energy, and mass fraction in both phases is solved numerically using a finite difference method. The influence of the inlet liquid flow, Reynolds number in the gas flow and the wall heat flux on the intensity of heat and mass transfers are examined. A comparison between the results obtained for studied glycols and water in the same conditions is made.

Keywords— Heat and mass exchanges, mixed convection, evaporation, glycols, vertical channel.

LIST OF SYMBOLS

C_p	specific heat [$Jkg^{-1}K^{-1}$]
C_{pa}	specific heat of air [$Jkg^{-1}K^{-1}$]
C_{pv}	specific heat of species vapour [$Jkg^{-1}K^{-1}$]
D	mass diffusivity [m^2s^{-1}]
Nus	local Nusselt number of sensible heat transport
Nul	local Nusselt number of latent heat transport
Nux	overall Nusselt number
Sh	interfacial Sherwood number
q_{SI}	sensible heat flux [Wm^{-2}]
q_{LI}	latent heat flux [Wm^{-2}]
q_{TI}	total heat flux [Wm^{-2}]
η	thermal efficiency of evaporation
g	gravitational acceleration [ms^{-2}]
P	mixture pressure [Pa]
\dot{m}_l	evaporating mass flux
Re	Reynolds number of the gas stream
Re_L	liquid film Reynolds number
T	Temperature [K]
T_{L0}	inlet liquid film temperature [K]
T_0	inlet temperature [K]
T_w	wall temperature [K]
T_i	gas-liquid interface temperature [K]
M_r	nondimensional accumulated mass evaporation rate
M_a	molar mass of air [$kg.mol^{-1}K^{-1}$]
M_v	molar mass of vapour [$kg.mol^{-1}K^{-1}$]

u	axial velocity [ms^{-1}]
u_0	inlet axial velocity [ms^{-1}]
v	transversal velocity [ms^{-1}]
w	mass fraction of vapour
w_i	mass fraction of vapor at gas-liquid interface
x	coordinate in the flow direction [m]
y	coordinate in the transverse direction [m]
d	channel width [m]

Greek symbols

Γ_0	inlet liquid mass flow rate [$kg.m^{-1}s^{-1}$]
δ_x	local liquid film thickness [m]
h_{fg}	latent heat of vaporisation [Jkg^{-1}]
γ	aspect ratio of the channel
λ	thermal conductivity [$Wm^{-1}K^{-1}$]
μ	dynamic viscosity [$kg.m^{-1}s^{-1}$]
ν	kinematics viscosity [m^2s^{-1}]
ρ	density [$kg.m^{-3}$]

Subscripts

I	condition at the gas-liquid interface
G	mixture (gas + vapour)
L	liquid film
0	condition at inlet
v	vapour
w	condition at wall
b	bulk quantity

I. INTRODUCTION

Gas-liquid flow systems with coupled heat and mass transfer through a liquid film with evaporation occur in many engineering applications, such as cooling electronic systems, distillation, cooling towers and thermal protection of heated walls. Since the number of independent variables influencing the hydrodynamic, thermal and concentration fields is important, their control in experimental installations is difficult. That's why they have been extensively numerically studied. Due to their widespread applications, heat and mass transfer between flowing hot liquid film and a cold air stream has received considerable attention.

Whereas a large number of investigations have been made concerning the case of a single component film. Yan et al. [1-4] and Feddaoui and his co-workers [5-9] investigate the evaporation of pure liquid film in turbulent mixed convection heat and mass exchanges. He et al. [10] was interested in cooling of the wall in a vertical tube uniformly heated by a water film. Turbulent flow is considered in the gas flow and laminar in the liquid film. Two different modes of heat transfer are identified. When water is supplied at relatively high temperature, the system operates in evaporating mode. When it is low the system operates in the direct film cooling mode.

Studies of liquid film evaporation for other pure substances or mixtures than water have been carried out by a number of investigators. Senhaji and al. [11] conducted a numerical study of evaporating liquid film of pure alcohol by mixed convection. They considered turbulent liquid film falling on the inner face of a vertical tube with a laminar flow of dry air entering the tube with a constant temperature. Baumann and Thiele [12] performed a detailed analysis including transport process in the gas flow and liquid film for turbulent multi-component gas flow with evaporation from a two component liquid film. Their study demonstrate that even small portions of a second component in the liquid film can create significant changes in the temperature levels as well as in the heat and mass transfer. Hoke et al. [13] presented a numerical study of the evaporation of a binary liquid film on a vertical plate. They presented the evolution of Sherwood and Nusselt numbers. Palen et al. [14] conducted an experimental study in the case of mixtures of water - ethylene glycol and water - propylene glycol in a vertical tube. They observed that for some experimental conditions, the local heat transfer coefficient between the partition and the liquid mixture can fall by 80% in relation to the relative value of the pure water, a value that is as low as the one got with the pure ethylene glycol in the same conditions. Agunaoun et al. [15] presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. The most interesting results are obtained in mixed convection, particularly in the case of ethylene glycol water mixture. Ali Cherifet al. [16] considered the evaporation of a thin binary liquid film by mixed convection in a vertical channel. They showed the importance of the film thickness and composition in the mass and heat transfers. Recently, Nasr et al. [17] performed a numerical analysis of the evaporation of binary liquid film. The film is falling down on one plate of a vertical channel under mixed convection channel. The first plate of a vertical channel is externally submitted to a uniform heated flux while the second one is dry and isothermal. The liquid mixture consists of water and ethylene glycol while the gas mixture has three components: dry air, water vapour and ethylene-glycol vapour.

In spite of their importance in industry as the most common antifreeze fluids, it is of interest to study the heat and mass exchanges during the evaporation of glycols with comparison to water film. A particular attention is addressed to analyse the

effect of liquid feed rate of alcohol component on the effectiveness of heat and mass transfer.

II. PROBLEM STATEMENT

The evaporation of pure liquids (water, ethylene glycol and propylene glycol) takes place between vertical parallel plates (fig 1). The liquid film falls along a left plate which is externally subjected to uniform heat flux q_w while the right plate is assumed to be dry and thermally insulated. At the inlet section, the axial velocity u_0 , temperature T_0 and mass fraction are fixed at uniform value. The liquid film flowing down with an inlet mass flow rate B_0 and the inlet liquid film temperature $T_{\ell 0}$.

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

- The boundary layer approximations are valid,
- The vapour and liquid phases are in thermodynamic equilibrium at the interface.
- Radiation heat transfer, viscous dissipation and other secondary effects are negligible.
- Vapour mixture is ideal gas.

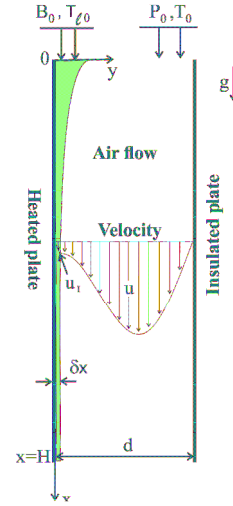


Fig 1: Schematic diagram of the physical system

A. Liquid film equations

Continuity equation

$$\partial(\rho_{\ell} u_{\ell}) / \partial x + \partial(\rho_{\ell} v_{\ell}) / \partial y = 0 \quad (1)$$

Momentum equation

$$\partial(\rho_{\ell} u_{\ell} u_{\ell}) / \partial x + \partial(\rho_{\ell} v_{\ell} u_{\ell}) / \partial y = -dp/dx + \partial[\mu_{\ell} \partial u_{\ell} / \partial y] / \partial y + \rho_{\ell} g$$

Energy equation

$$\partial(\rho_{\ell} c_{p\ell} u_{\ell} T_{\ell}) / \partial x + \partial(\rho_{\ell} c_{p\ell} v_{\ell} T_{\ell}) / \partial y = \partial[\lambda_{\ell} \partial T_{\ell} / \partial y] / \partial y \quad (3)$$

TABLE 1: COMPARISON OF THERMAL EFFICIENCY OF EVAPORATION η
FOR VARIOUS GRIDS, WITH $T_0 = T_{i0} = 20^\circ\text{C}$, $\gamma = 0.01$,
 $q_w = 2000\text{W}/\text{m}^2$, $\text{Re} = 2000$

ξ	2	16	49	100
$51 \times (51 + 21)$	0.130	0.119	0.183	0.338
$101 \times (51 + 21)$	0.133	0.119	0.181	0.336
$101 \times (101 + 41)$	0.136	0.118	0.178	0.334
$101 \times (201 + 81)$	0.137	0.117	0.177	0.332
$201 \times (201 + 81)$	0.139	0.117	0.178	0.330

B. Gas flow equations

Continuity equation

$$\partial(\rho_g u_g)/\partial x + \partial(\rho_g v_g)/\partial y = 0 \quad (4)$$

Momentum equation

$$\begin{aligned} \partial(\rho_g c_{pg} u_g T_g)/\partial x + \partial(\rho_g c_{pg} v_g T_g)/\partial y = -dp_d/dx + \partial[\mu_g \partial u_g/\partial y] / \partial y \\ + (\rho_g - \rho_0)g \end{aligned} \quad (5)$$

Energy equation

$$\begin{aligned} \partial(\rho_g c_{pg} u_g T_g)/\partial x + \partial(\rho_g c_{pg} v_g T_g)/\partial y = \partial[\lambda_g \partial T_g / \partial y] / \partial y \\ + \partial[\rho_g D(c_{pv} - c_{pa})T_g \partial w / \partial y] / \partial y \end{aligned} \quad (6)$$

Concentration equation of vapour

$$\partial(\rho_g u_g w)/\partial x + \partial(\rho_g v_g w)/\partial y = \partial[\rho_g D \partial w / \partial y] / \partial y \quad (7)$$

C. Boundary and interfacial conditions

The boundary conditions are:

$$x = 0 : u_g = u_0, \quad T_g = T_0,$$

$$w_g = w_0, \quad T_\ell = T_{\ell 0}$$

$$y = 0 : u_\ell = v_\ell = 0 - \lambda_\ell (\partial T_\ell / \partial y) = q_w$$

$$y = d : u_g = v_g = 0 \quad \partial T_g / \partial y = \partial w / \partial y = 0 \quad (8)$$

The interfacial matching conditions specified at $y = \delta_x$ are described as follows:

Continuities of velocity and temperature:

$$u_I(x) = u_{g,I} = u_{\ell,I}, \quad T_I(x) = T_{g,I} = T_{\ell,I} \quad (9)$$

D. Continuity of shear stress

$$\tau_I = [\mu \partial u / \partial y]_{\ell,I} = [\mu \partial u / \partial y]_{g,I} \quad (10)$$

Transverse velocity of the air-vapour mixture is deduced by assuming that the interface is semipermeable [18] that is, the

solubility of air in the liquid film is negligibly small and the y-directed velocity of air is zero at the interface:

$$v_I = -D(\partial w / \partial y) / (1 - w_I) \quad (11)$$

By assuming the interface is in thermodynamic equilibrium and the air-vapour mixture is an ideal gas mixture [18] the mass fraction of water or glycols vapour at the interface can be evaluated by the relation:

$$w_I = M_v P_{v,I} / (M_a (P - P_{v,I}) + M_v P_{v,I}) \quad (12)$$

Where $P_{v,I}$, is the partial pressure of vapour at the interface, and M_v and M_a , are, respectively, the molar masses of vapour and air;

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

$$q_I = q_s + q_L = [\lambda \partial T / \partial y]_{g,I} + \dot{m}_I h_{fg} \quad (13)$$

Where h_{fg} is the enthalpy of evaporation and \dot{m}_I the vapour generation rate ($\rho_g v_I$)

The thermal efficiency of evaporation is defined as the ratio of the heat flux used under latent form for evaporation over the heat flux applied on the wetted wall. [19]

$$\eta = q_L / q_w = \dot{m}_I h_{fg} / q_w \quad (14)$$

The thermo-physical properties in the liquid film and gas flow are variables and depend on the temperature and concentrations. These properties are available in [20, 21].

III. NUMERICAL METHOD

The set of coupled non-linear differential equations defined by the parabolic systems, equations (1)-(7) with the appropriate boundary conditions are solved by a finite difference numerical scheme. The axial convection terms are approximated by the backward difference and the transversal convection and diffusion terms are approximated by the central difference. Each system of the finite-difference equations forms a tridiagonal matrix equation which can be solved by the Thomas algorithm (Patankar [22]).

The physical domain was discretized into a structured grid, using the algebraic method for grid generation. A non-uniform grid system was used, with greater node density near the inlet and the gas-liquid interface where the gradients are expected to be more significant. The use of thin grids generates problems of convergence. It is a question of finding an optimum between the computing time and the precision. Several grid sizes have been tested to ensure that the results are grid independent (Table 1). It was found that the

difference in the thermal efficiency of evaporation η , from computations using either $51 \times (51 + 21)$ or $201 \times (201 + 81)$ grids are always less than 3%. Accordingly, the computations involving a $101 \times (101 + 41)$ grid is chosen because it gives results close to those obtained with thin grid, hence it is considered to be sufficiently accurate to describe heat and mass transfers in the tube. All the results presented in the next section were composed using the latter grid.

In order to fix the position of the liquid-gas interface, the Cartesian $x - y$ coordinate transformed into $\xi - Y$ coordinates:

$$\begin{cases} \xi = x/d \\ Y = y/d \end{cases} \text{ for all } x \text{ and } y \quad (15)$$

IV. RESULTS AND DISCUSSIONS

To further check the adequacy of the numerical scheme for the present study, the results of the present model were first compared with those of Yan [2] in the case of water film. Figure 2 shows the axial evolution of total Nusselt number along a vertical channel. Excellent agreement between the present predictions and those of Yan [2] was found. In view of these validations, the present numerical algorithm is adequate to obtain accurate results for practical purpose.

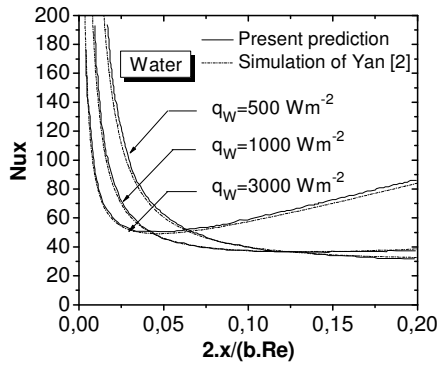


Fig 2. Axial evolution of total Nusselt number Nux for water film for $B_0 = 0.02 \text{ kg m}^{-1} \text{ s}^{-1}$, $Re = 1000$ and $T_0 = T_{i0} = 20^\circ\text{C}$ and $d = 0.015 \text{ m}$.

For comparing the evaporation of some industrial fluids such as glycols and water, it is of interest to study the evolution of some physical properties which control the evaporation phenomena. Figure 3a presents the effect of the liquid temperature on the evolution of saturated pressure for two glycols liquids: ethylene and propylene with comparison to water. It is clear that the saturated pressure of water is more important than glycols. Consequently, water is more volatile than glycols. Also we can notice that when liquid temperature increases, the difference between the saturated pressures of the three liquids decrease, particularly between the more volatile fluid (water) and glycols. The effect of the liquid temperature on the specific heat capacity of the three liquids is illustrated in figure 3b. It is apparent that the specific heat which represents the amount of heat per unit mass required to raise the temperature by one degree Celsius is higher for water. This implies that the water store more energy than the glycols.

By comparing ethylene glycol and propylene glycol, we can note that the specific heat for propylene is greater than ethylene.

In this study, the calculations are made specifically for the two components liquid films glycols: ethylene glycol and propylene glycol in comparison with the water film. Other glycols films may be studied similarly. In the light of practical situations, certain conditions are selected in the computations: the dry air at $T_0 = 20$ or $T_0 = 80^\circ\text{C}$ and 1 atm enters along vertical channel, aspect ratio of the channel $\gamma = 0.005$ or $\gamma = 0.01$ where $\gamma = d/H$, from the top by the combined action of certain external force as well as the buoyancy forces of thermal and mass diffusion. The inlet gas stream Reynolds number $Re = 1000$ or 2000 , the liquid flow rate B_0 is chosen to be $0.02 \text{ kg m}^{-1} \text{ s}^{-1}$, wall heat flux q_w is taken to be 2000 or 3000 W m^{-2} , and inlet liquid temperature $T_{i0} = 20^\circ\text{C}$.

The evolutions of the axial velocity, temperature and mass fraction profiles along the channel are respectively illustrated in Figs. 4, 5 and 6 at different locations for water, ethylene glycol and propylene glycol. As depicted in figure 4, the velocity profiles develop similarly for the three fluids, from uniform inlet velocity profiles at inlet to the parabolic one when the flow goes downstream.

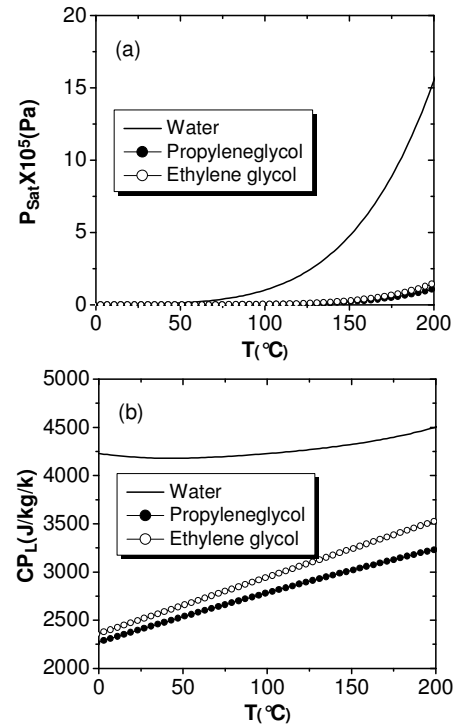


Fig. 3 Evolution of thermophysical properties of water, propylene glycol and of ethylene glycol with temperature.

Furthermore, the velocity profile in the gas is asymmetrical. In fact, the maximum velocity is shifted toward the dry wall. A change in the velocity profiles is noticed from inset plots which show an increase in the case of water compared to glycols. The latter is obviously due to higher density of water than glycols.

Fig. 5 shows an increase of the temperature in the gas as the flow goes downstream, which is experienced by the evaporation of liquid. In quantitative terms, the two glycols vary in the same way, since the temperature at the interface is increased from 20°C to 100°C , the water temperature varies in a lower range. This is experienced by the evaporative cooling in the case of water which is more volatile and release more energy by latent mode. Also, the mass fraction increase from the interface gas-liquid to the insulated wall which is due to the absorbed energy transferred from the liquid film to the gas. The heat capacity of water is more important than glycols (figure 3b) which allows the water to store more energy.

Consequently, as depicted from figure 5, the liquid film temperature of glycols studied is more important than the water as the flow goes downstream.

Figure 6 represents the evolution of the mass fraction of water and glycols in the gas for different sections of the channel. It is noted that the variation of the mass fraction increases gradually from the inlet to outlet of channel, which deals to the evaporation phenomena. This increase is much more noticeable for more volatile component, i.e. water, propylene glycol then ethylene glycol. This result is confirmed by the evolution of saturated pressure with temperature(Fig.3a).

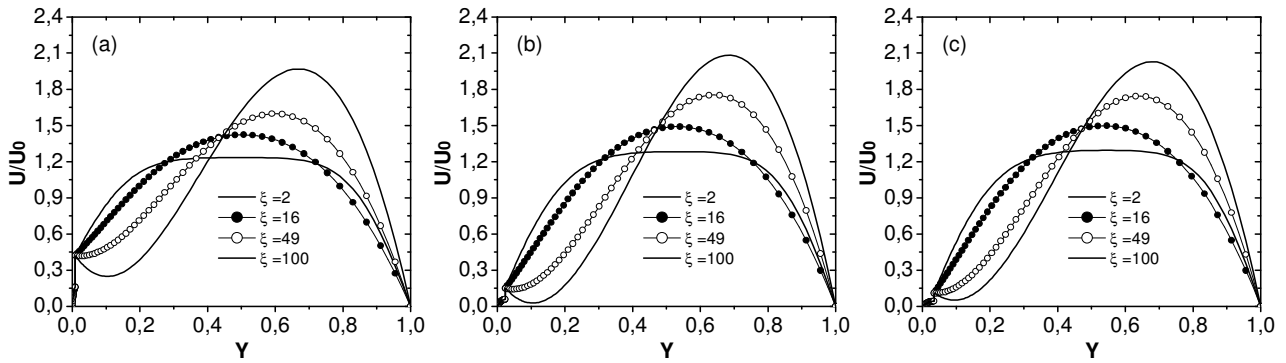


Fig.4: Distributions of axial velocity profiles at different locations for $q_w = 2000\text{Wm}^{-2}$, $\gamma = 0.01$, $\text{Re} = 1000$ and $T_0 = 20^{\circ}\text{C}$.

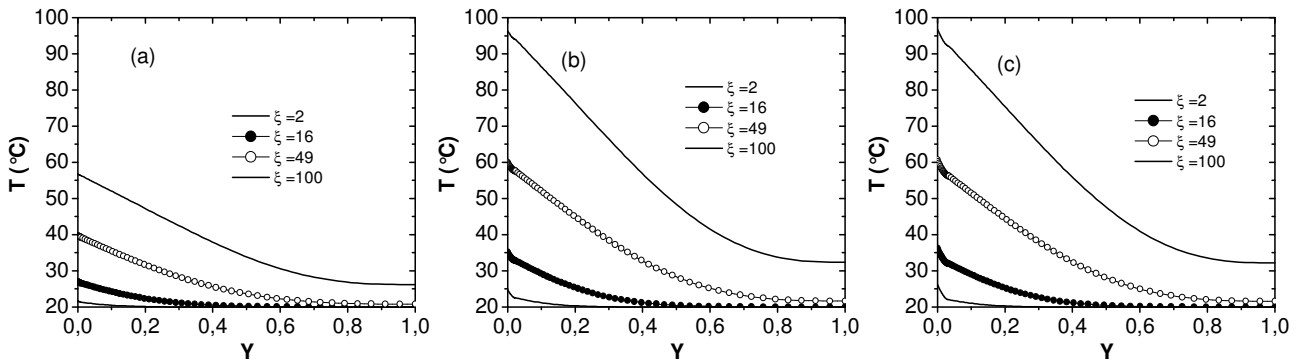


Fig.5: Distributions of temperature profiles at different locations for $q_w = 2000\text{Wm}^{-2}$, $\gamma = 0.01$, $\text{Re} = 1000$ and $T_0 = 20^{\circ}\text{C}$.

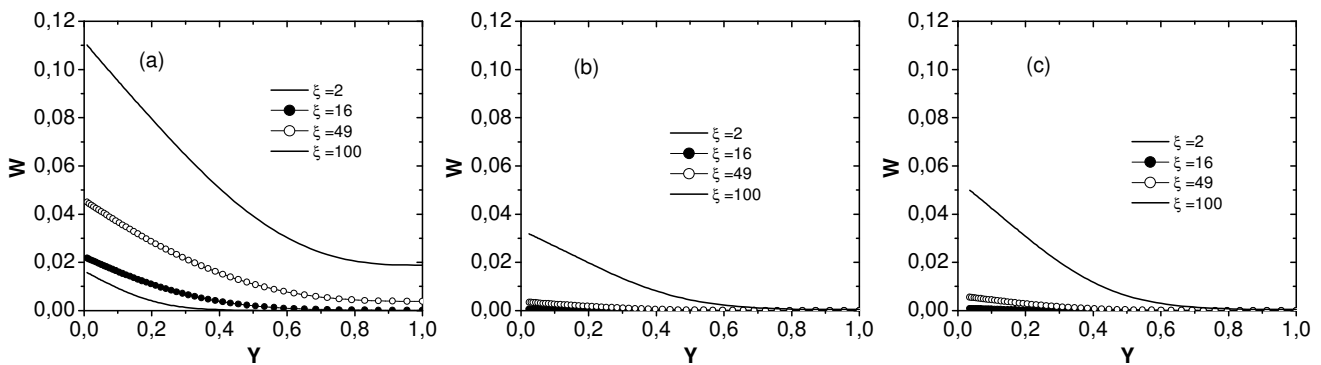


Fig.6: Distributions of mass fraction profiles at different locations for $q_w = 2000\text{Wm}^{-2}$, $\gamma = 0.01$, $\text{Re} = 1000$ and $T_0 = 20^{\circ}\text{C}$.

The effects of flow parameters on the evolution of sensible heat flux are illustrated in figure 7. It is seen that the sensible heat flux increases in the flow direction, with increasing q_w , γ , Re . This stems from the fact that larger convection is noted for a system with higher heat flux density imposed to the internal wall, inlet liquid mass flow rate and higher Reynolds number of the gas stream. It is also of interest to note the sensible heat flux of glycols is more important than water. This due to evaporative cooling of water which is more volatile than glycols. The negative values of sensitive flows can be explained by the direction of heat transfer from gas to liquid in the case where ($T_0 > T_{i0}$) at inlet of channel as shown from Figs 7b. Under the same parameters, The evolution of thermal efficiency of evaporation is depicted in figure 8. The first observation to be drawn from these curves indicates that the thermal efficiency of the ethylene glycol is less than that of propylene glycol and water. It is also noticed that thermal efficiency of evaporation increase for a higher q_w , large aspect ratio of the channel γ and more for Reynolds number Re or T_0 . These hangs of thermal efficiency of evaporation versus the parameters of calculation are due to the enhancement of the evaporation of the liquid film at a high wall heat flux or at

high aspect ratio of the channel. It becomes apparent, by comparing the magnitude of thermal efficiency of evaporation, that 50% of energy supplied from the wall is transported by latent mode using a water film 13 % for propylene glycol and only 10% for ethylene glycol. the evaporation is much more important for water due to the volatility which is related to the latent heat.

In order to quantify the film evaporation a dimensionless accumulated mass evaporation rate Mr is introduced.

$$Mr = \left(\int_0^x \dot{m}_l dx \right) / B_0 = \left(\int_0^x \rho_g v_l dx \right) / B_0 \quad (16)$$

The distributions of Mr for various cases are depicted in Fig.9. The larger film evaporation is found for systems for higher q_w or higher Reynolds number Re . Also mentioning that the increase aspect ratio of the channel and inlet liquid temperature of the gas stream cause a greater film evaporation and Mr increase with ξ as the flow goes downstream. It is interesting to note that the largest accumulated mass evaporation rate Mr is about 3%. This clearly indicates the larger heat transport in connection with the greater liquid film evaporation.

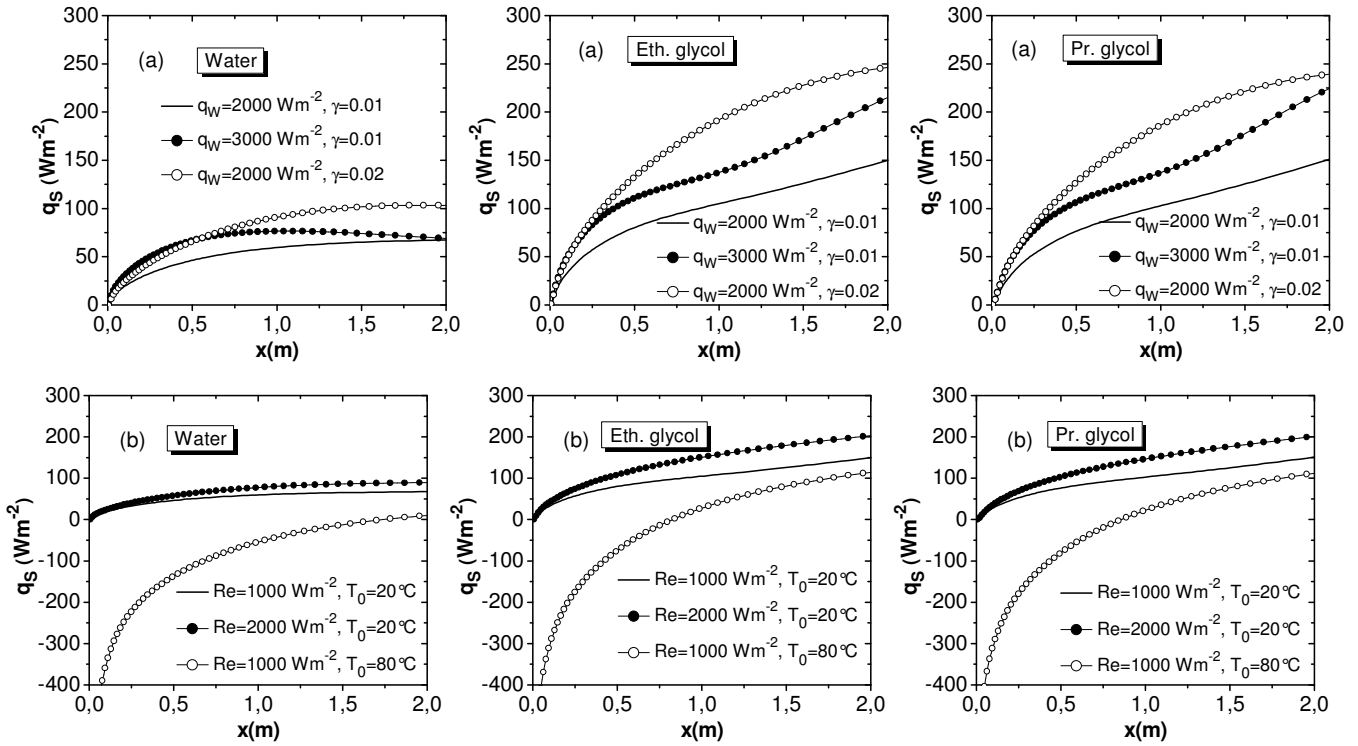


Fig.7: Comparing profiles of sensible heat flux along the channel of Water, Ethylene glycol and Propylene glycol for: (a) $Re = 1000$, $T_0 = 20^\circ C$, (b)

$$q_w = 2000 Wm^{-2}, \gamma = 0.01.$$

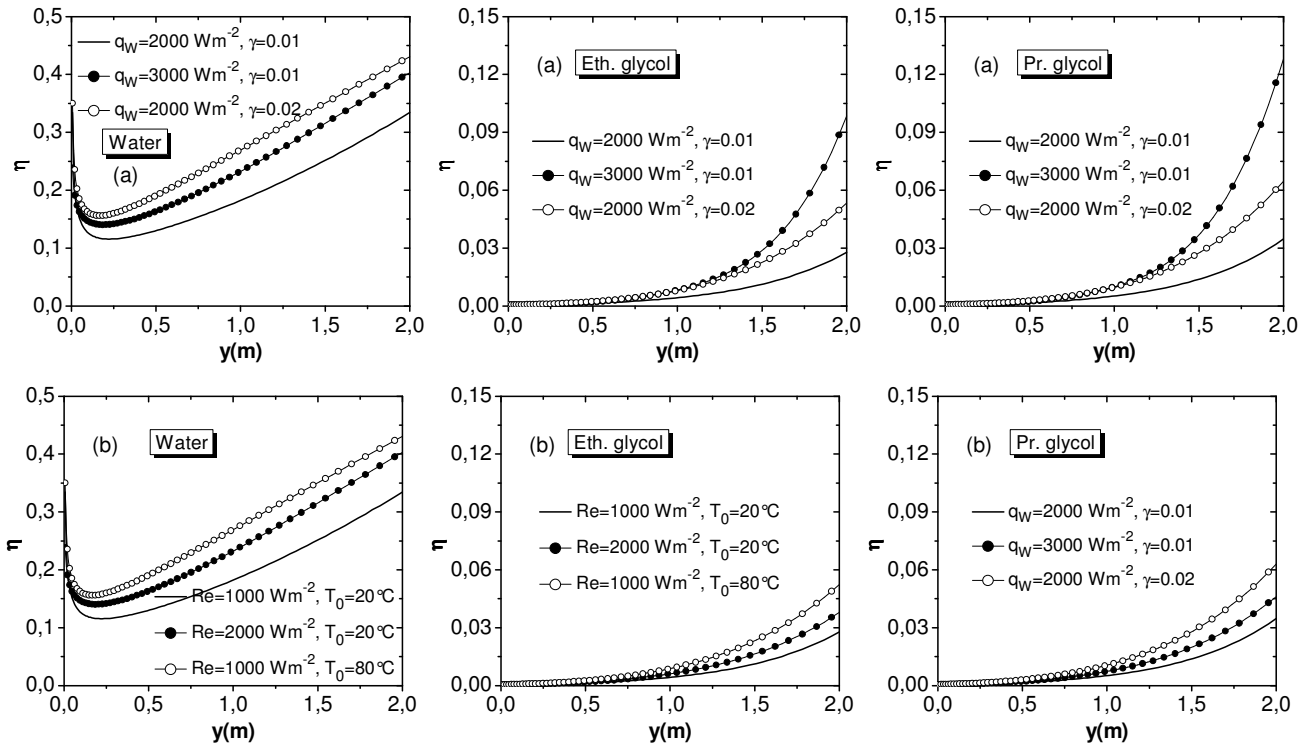


Fig.8: Comparing profiles of thermal efficiency of evaporation of Water, Ethylene glycol and Propylene glycol for: (a) $Re = 1000$, $T_0 = 20^\circ C$, (b) $q_w = 2000 Wm^{-2}$, $\gamma = 0.01$.

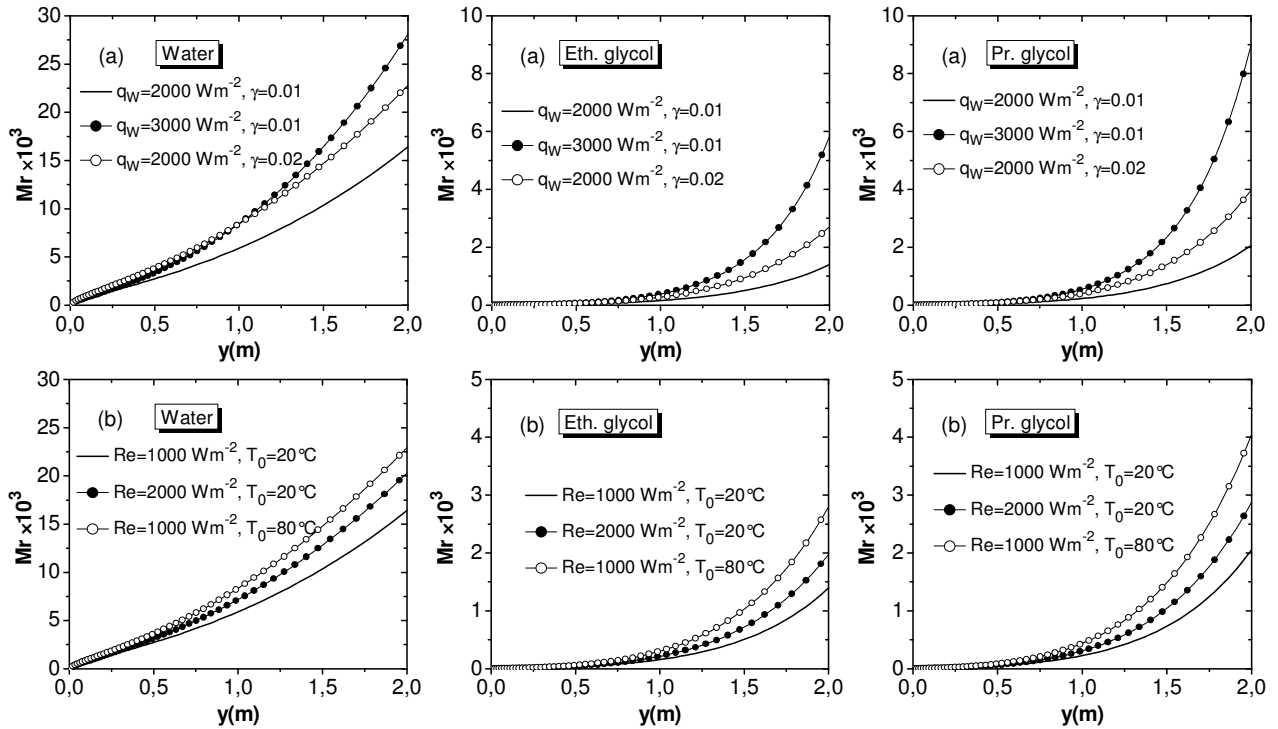


Fig.9: Comparing profiles of dimensionless accumulated mass evaporation rate along the channel of Water, Ethylene glycol and Propylene glycol for: (a) $Re = 1000$, $T_0 = 20^\circ C$, (b) $q_w = 2000 Wm^{-2}$, $\gamma = 0.01$.

V. CONCLUSION

In this work, we have presented a numerical study on heat transfer and mass during the evaporation of water, ethylene glycol and propylene glycol in a vertical channel in the presence of a gaseous flow of air sec. The effect of input parameters on heat transfer and mass along the canal was highlighted. Based on the results, one can cite the following conclusions:

- In the case in large Reynolds number and large flow imposed to the wall film, the heat transfer and evaporative mass is greater.
- The increase of gas flow rate (Reynolds number) and inlet liquid temperature of the gas tends to improve slightly evaporation.
- The component nature of liquid film plays an important role on evaporation. The most volatile element has a greater rate of evaporation.
- Water evaporates in more intense way in comparison to glycols film. A small proportion of this fluid absorbs a significant amount of energy supplied from the wall (about 50%) in comparison to propylene glycol (about 13%) and ethylene glycol (about 10%) using the same flow parameter

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