Heat and Technology
Vol. 32, n. 1-2, 2014

IMPACT OF THE LIQUID FILM COMPOSITION OF THE WATER EVAPORATION BY FREE CONVECTION

Abdulmajeed S. Al-Ghamdi

Mechanical 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
Email: asaalghamdi@uqu.edu.sa

ABSTRACT

This paper concerns a numerical analysis of the evaporation of binary liquid mixture by free convection into air and superheated steam inside a vertical channel. The first plate is externally insulated and wetted by an extremely thin water film while the second one (y=d) is dry and isothermal. The effects of inlet liquid composition on the distribution of the velocity, temperature, concentration profiles and the axial variation of the water evaporation rate are analyzed. As was found in former work, this study shows that from a certain value of the inlet liquid concentration 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.

1. 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 binary liquid has also received considerable attention in many theoretical and experimental studies [1-6]. Two cases were considered: one where the channel wall is soaked with a liquid and another where a liquid film flows along this wall.

Cherif et al [1] considered thin binary liquid film evaporation by mixed convection falling on one of the two parallels plates' channel. 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 [2] presented a numerical analysis of the heat and mass transfer in a binary thin film flowing on an inclined plane. The most interesting results are obtained in forced convection, particularly in the case of ethylene glycol-water mixture. In fact, results obtained show that it is possible to increase the accumulated evaporation rate when the molar fraction of ethylene glycol is less than 40%. In addition, even if the heat transfer coefficient decreases generally when the ethylene glycol composition in the mixture increases, it was found that it is possible to stabilise perhaps to increase the heat transfer coefficient. W .W [3] studied the heat and mass transfers in two-component film evaporation in a vertical tube. Z. Ziobrowski et al. [4] presented a theoretical and experimental study of evaporation of a binary liquid film (water–isopropanol mixture) in the presence of the stagnant inert gas. They presented a comparison of experimental and calculated data of evaporation of a binary liquid film (water–isopropanol) in the presence of the stagnant inert gas. They showed a small effect of diffusion resistances in the liquid phase on the total mass flux and on the selectivity. A. Nasr et al. [5] presented a numerical study of 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 (the less volatile component) is less than 40%. In fact, they showed that, when the inlet liquid concentration of ethylene glycol is less than 40%, it is possible to evaporate in the same conditions more water than if the film at the entry was pure water only. This result has been explained by the fact that an increase of the inlet liquid concentration of ethylene glycol has two antagonistic effects on the accumulated evaporation rates of water and of liquid mixture. Hoke et al. [6] 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. Belhadj Mohamed and Orfi [7] presents a numerical analysis of coupled heat and mass transfer by mixed convection during water/ammonia binary liquid film evaporation inside vertical channels. They showed that the evaporation rates for the ammonia are found to be higher than those of water.

2. ANALYSIS

The present work deals with a numerical analysis of evaporation of water-ethylene glycol into hot humid air by natural convection induced by the thermal and mass buoyancy forces in a finite vertical channel (Fig. 1). The studied channel is made up of two parallel plates. The first plate is externally insulated (q=0) and wetted by an extremely thin water-ethylene glycol film while the second one (y=d) is dry and isothermal. The imposed temperature is maintained at T_w=100°C for all computations. For natural convection case, the moist air in the ambient is driven into the channel by the resultant forces of thermal and solutal buoyancies.

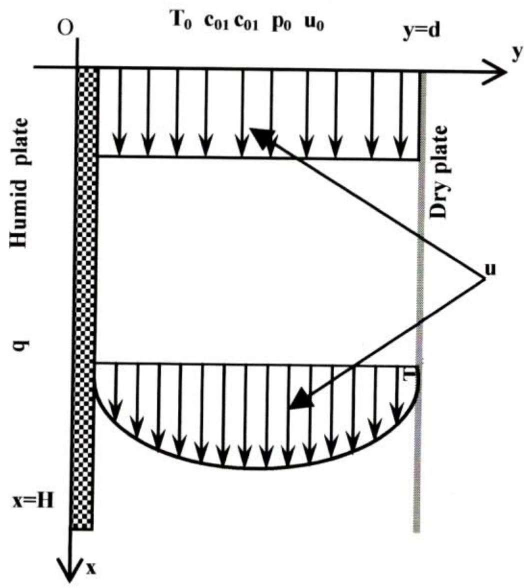


Fig .1. Physical description of the system

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

- the liquid film is assumed to be extremely thin. Under this assumption, transport in the liquid film can be replaced by approximate boundary conditions for gas flow.
- the boundary layer approximations are generally used to study the downward flow in the channel induced by natural convection.
- the viscous dissipation and the pressure work are negligible.
- the Dufour and Soret effects are negligible.
- the thermal radiation is negligible.
- vapor mixture is an ideal gas.
- liquid mixture is ideal.
- transfers in the two phases are permanent and the vapour is laminar and bi-dimensional.

The heat and mass transfer for the laminar forced convection induced by the combined thermal and mass buoyancy forces, with the usual boundary layer approximation, can be described by the following governing equations [1, 2, 8-12] :

Continuity equation

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

momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{dP}{dx}+\beta g(T-T_0)+\sum_{i=1}^{2}e\beta^{*}g(C_i-C_0) + (1/\rho)\frac{\partial}{\partial y}(\mu\frac{\partial u}{\partial y}) \tag{2}$$

Energy equation

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

Species diffusion equations

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

$\left(\beta g(T-T_0)+\sum_{i=1}^{2}\beta^{*}g(C_i-C_0)\right)$ represents the momentum transfer caused by the combined buoyancy forces. The thermo-physical properties of gas mixture are considered as variable with temperature and composition.

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 composition. The correlations used in this study were given in [1] for viscosity, mass heat capacity and mass diffusion coefficients and in [1, 2] for thermal conductivity.

In this study of steady forced channel flow, the overall mass balance described by the following equation should be satisfied at every axial location:

$$\int_{\delta}^{d}\rho u(x,y)dy=d\rho_0 u_0+\int_{0}^{x}\rho v(x,0)dx \tag{5}$$

Boundary conditions

* At x=0 :

- $u=u_0, T=T_0, c_1=c_{01}, c_2=c_{02}$

For the free convection case, one must add:

$P(x=0)=-\frac{1}{2}\rho u_0^2$ and $P(x=H)=0$;

* At y=0 (isolated plate):

- $u=0$
- the transverse velocity of gas is deduced by assuming that the air–ethylene glycol-water interface is semi-permeable:

$$v(x,0)=-\frac{1}{1-c_1(x,0)-c_2(x,0)}\left[D_{1m}\left(\frac{\partial c_1}{\partial y}\right)_{y=0}+D_{2m}\left(\frac{\partial c_2}{\partial y}\right)_{y=0}\right]$$

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

$$-\lambda\frac{\partial T}{\partial y}-\frac{\rho L_v}{1-c_1(x,0)-c_2(x,0)}\left[D_{1m}\left(\frac{\partial c_1}{\partial y}\right)_{y=0}+D_{2m}\left(\frac{\partial c_2}{\partial y}\right)_{y=0}\right]=0$$

• According to Daltons law and by assuming the interface to be at thermodynamic equilibrium and the air–vapour mixture is an ideal gas mixture, the concentration of vapour can be evaluated by:

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

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

$P^*_{vsj}=P^*_{vsj}(X_{Li},T)=X_{Li}\,P_{vsj}(T)\,(i=1,2)$ and

$$X_{Li}=C_{Li}\frac{M}{M_i}\ \ with\ \frac{1}{M}=\frac{C_{L1}}{M_1}+\frac{C_{L2}}{M_2}$$

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 vapour in the mixture given by [1]:

$$p_{vs,1}=10^{17.443-[2975/T+3.68\log(T)]}\times 10^5$$

$$P_{vs,2}=6894.8\exp[16.44-10978.8/(9T/5-49)]$$

* y = d (the isothermal plate):

$$\bullet\ u=0;\ v=0;\ T=T_w$$

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

$$\frac{\partial c_i}{\partial y}=0\ ;\ i=1,2$$

The equation giving interfacial transverse velocity is expressed as :

$$v(x,0)=\frac{1}{\rho L_V}\left.\frac{\partial T}{\partial y}\right|_{y=0}$$

In order to describe the mass and energy magnitude transported between the channel walls and moist air, the following dimensionless coefficients are used :

- The average evaporated mass flux of species i is given by:

$$\dot{m}_i=\rho v(x,0)c_i(x,0)-\rho D_{im}\left(\frac{\partial c_i}{\partial y}\right)_{y=0}$$

- The average evaporated mass flux of species i is given by:

$$\overline{\dot{m}}_i=\frac{1}{H}\int_0^H \dot{m}_i dx$$

- The average evaporated mass flux of mixture is given by:

$$\overline{\dot{m}}=\overline{\dot{m}}_1+\overline{\dot{m}}_2$$

3. SOLUTION METHOD

The presented system of equations (1–5) is solved numerically using finite difference method. The flow area is divided into a regular mesh placed in axial and transverse direction and a (51,31) grid is retained in actual computations. The procedure has been tested by comparing the present result of interface temperature Tp to those of Cherif et al [1]. Figure 2 shows a good agreement between our result and those obtained by Cherif et al [1].

4. RESULTS AND DISCUSSION

All the above cases are based on a vertical channel with length of 1 m and width of 0.015m. Moreover, the dry wall temperature is always kept at T_w=373.15 K which is less than ambient gas temperature so that the thermal buoyancy force acts in the downward direction. In this section attention was paid to the evaporation of binary liquid mixture by natural convection driven by the simultaneous presence of combined buoyancy effects of heat and mass diffusion. Development of the axial velocity, the temperature and the concentration profiles at the section exit (x=H) is plotted in Figure.3. Figure.3.a shows that the axial velocity profiles at the section exit (x=H) decreases when one increases the liquid composition of ethylene glycol. This result can be justified by the fact that when one increases the liquid composition, the total evaporating mass flow decreases (water is more volatile that ethylene glycol). Consequently, according to (eq.5), when the total evaporating mass flow decreases, the axial velocity decreases. Figure.3.b shows that the temperature at the section exit (x=H) increases when one increases the liquid composition of ethylene glycol, this result can be justified by the fact the water is more volatile that the ethylene glycol. Figure.3.c shows that the concentration of water vapor at the section exit (x=H) increases when one increases the inlet liquid concentration of ethylene glycol until a value from which it starts to decrease. It is shown from Fig.3.d that the concentration of vapor ethylene glycol at the section exit (x=H) (x=H) increases with an increase of the inlet 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 illustrates the effects of the inlet liquid concentration of ethylene glycol on the temperature and water vapour concentration at the interface. Figure.4.a shows that when one increases the inlet liquid concentration of ethylene glycol, the temperature interfacial increases also, this result can be justified by the fact that the water is more volatile that the ethylene glycol. Figure.4.b shows that from a certain value of the inlet liquid concentration of ethylene glycol, the water vapour concentration at the interface can increase. Fig.5.a gives the effect of liquid composition of ethylene glycol on the interfacial relative heat fluxes. According to the imposed thermal boundary conditions, the figure.5 shows that the sensible and latent heat fluxes are symmetrical along the humid zone. Fig.5.a shows that an increase on the inlet liquid concentration of ethylene glycol induces an increase of the latent and sensible heat fluxes. Fig.5.b shows that it is possible to increase the evaporation rate from a certain value of the inlet liquid concentration of ethylene glycol. This result can be explained by the fact that an increase of the inlet liquid concentration of ethylene glycol has two antagonistic effects on the water evaporation rate. For the first effect, it is generally obvious that an increase of the inlet liquid concentration of ethylene glycol (the less volatile component) induces an increase of the ethylene glycol evaporation and a decrease of the water evaporation. Whereas the second effect can be attributed that an increase of the inlet liquid concentration of ethylene glycol induces an increase of the interfacial temperature (see Fig. 3.b) and consequently the water evaporation rate increase. When the second effect overcomes the first effect, the water evaporation rate increases with the inlet liquid concentration of ethylene glycol.

5. CONCLUSION

The evaporation of a binary liquid mixture into air and superheated steam by natural convection in a vertical channel has been numerically studied. One plate of the channel is wetted by a binary liquid film and externally insulated. The second is dry and isothermal. The gas is a mixture of three components: dry air, water vapor and ethylene glycol vapor. The effect of the inlet liquid concentration of ethylene glycol on the heat and mass transfer and on the mixture and water evaporation rates has been analyzed. It is shown that from a certain value of the inlet liquid concentration 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.

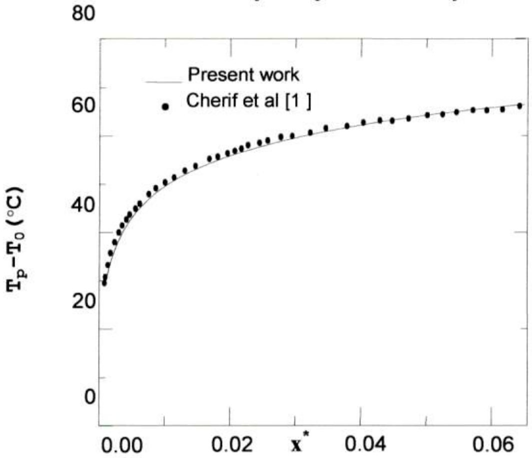
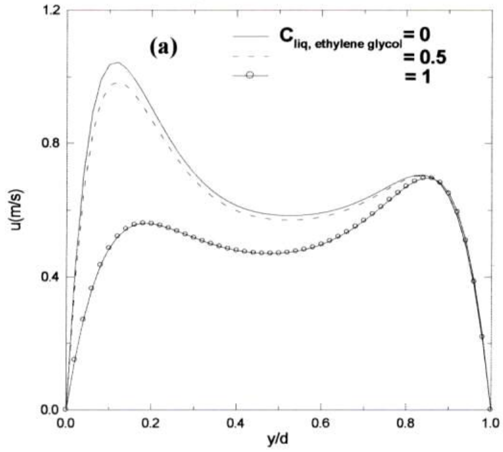


Figure. 2: Axial evolution of the interface temperature.



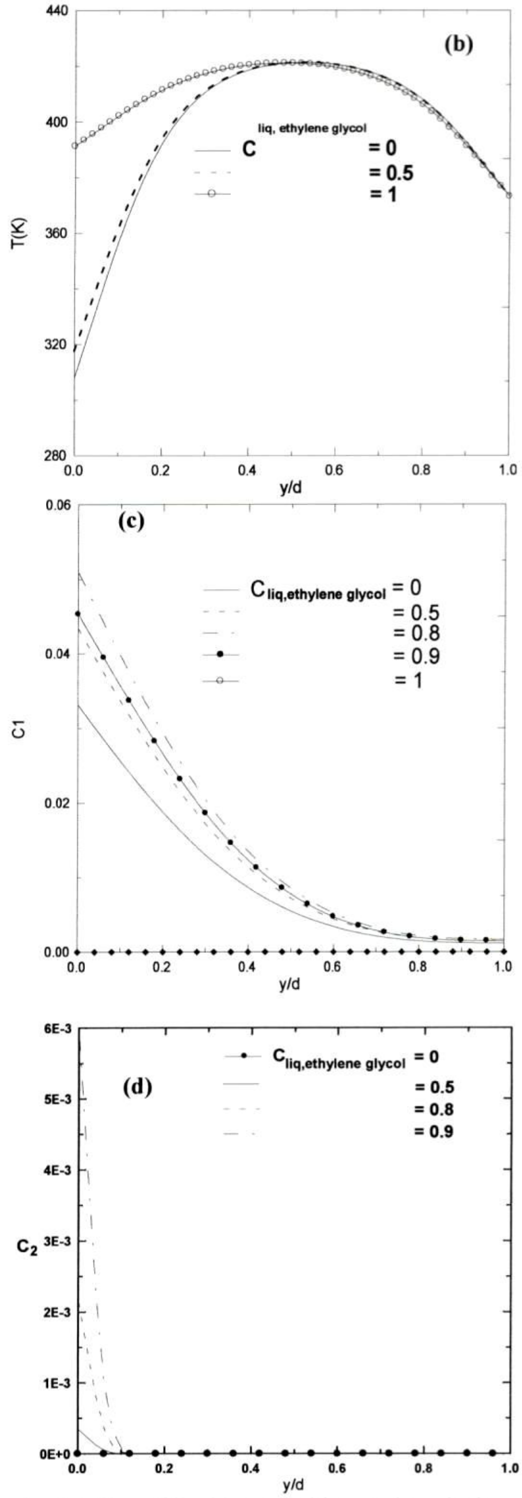


Fig.3: Effect of liquid composition on the velocity, temperature, concentration of water vapour: $C_{01}=C_{02}=0$, $T_w=100°C$, $T_0=150°C$, d=0.05m

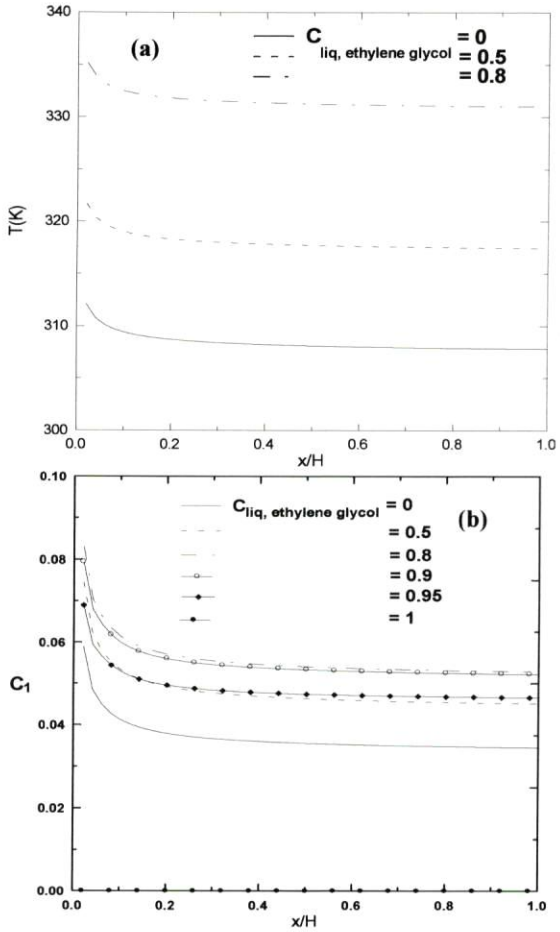
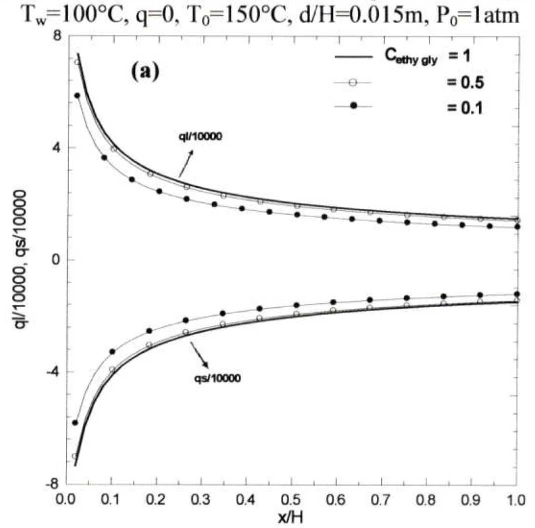


Fig.4: Effect of liquid composition film on the interfacial temperature, concentration of water vapour : $C_{01}=C_{02}=0$, $T_w=100°C$, $q=0$, $T_0=150°C$, $d/H=0.015m$, $P_0=1atm$



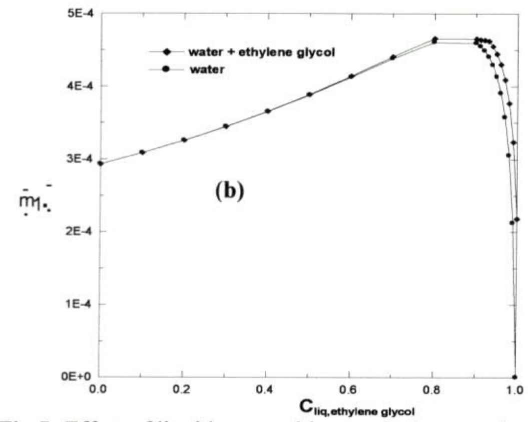


Fig.5: Effect of liquid composition on the latent and sensible heat fluxes and water evaporation rate: $C_{01}=0$, $C_{02}=0$, $T_w=100°C$, $q=0$, $T_0=150°C$, $d/H=0.05m$, $P_0=1atm$

6. REFERENCES

1. 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) 2399-2418.
2. Agunaoun , A. Il Idrissi, A. Daif, R. Barriol., Etude de l'évaporation en convection mixtes 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) 2197-2210.
3. J. W. Palen, Q. Wang, J.C. Chen., Falling film evaporation of binary mixtures. *Aiche Journal*, 40 (1994) 207-214.
4. Z. Ziobrowski, A. Rotkegel, R. Krupiczka, Evaporation of a binary liquid film in the presence of stagnant inert gas, Chemical and process Engineering Journal 30 (2009) 13-24.
5. A. Nasr, C. Debbissi Hfaiedh and S. Ben Nasrallah, Numerical study of evaporation by mixed convection of a binary liquid film. Energy (2011); 36: 2316-2327.
6. B. C. Hoke, Jr. Chen., Mass transfer in evaporating falling liquid film mixtures. *Aiche Journal*, 38 (1992) 781-787.
7. A. Belhadj Mohamed, J. Orfi, Evaporation of water/ammonia binary liquid film by mixed convection inside isothermal vertical plates. *Desalination and water treatment 51 (2013) 1966–1972.*
8. R. Vijay, Mhetar, John C. Slattery., The Stefan problem of a binary liquid mixture. *Chemical Engineering Sciences* 52 (1997) 1237-1242.
9. W. W. Baumann, F. Thiele., Heat and mass transfer in evaporating two-component liquid film flow. *Int. J. Heat Mass Transfer* 33 (1990) 267-273.
10. W. W. Baumann, F. Thiele., Heat and mass transfer in two-components film evaporation in vertical tube. *Int. J. Heat Mass Transfer* 4 (1986) 1843-1849.
11. A. Nasr, C. Debissi and S. Ben Nasrallah., Evaporation of a binary liquid film by free convection and inversion temperature. *International Journal of Heat and Technology,* (12), 133-140 (2010).
12. A. Nasr, C. Debissi and S. Ben Nasrallah., Evaporation of water by free convection inside two partially wetted heated vertical plates. *International Journal of Heat and Technology*, (27), 35-42 (2008).