Numerical prediction of heat and mass transfer in vertical channel

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Abstract

The purpose of this work is to evaluate heat and mass transfer during the evaporation of a negligible thickness liquid film of acetone wetting the walls of a vertical or inclined channel, general conservation equations and the associated boundary conditions are discretized by means of the finite volume method and the pressure-velocity coupling is treated with SIMPLER algorithm. The study focuses on the analysis of the effect of the velocity and the relative humidity of the inlet air and the channel inclination angle, on the hydrodynamic thermal and mass behavior of the flow of moist air.

Keywords : *Mixed convection; Heat and mass transfer; Evaporation, vertical channel, wet wall, finite volumes method.*

1. Introduction

Heat and mass transfer coupled have been widely encountered in many practical applications. The processes such as distillation, film cooling, liquid film evaporator, cooling towers, cooling of microelectronic equipments. Due to such widespread applications, heat and mass transfer of air stream with liquid film evaporation associated with latent heat transfer has received considerable attention of researchers over the past decades considering several configurations.

Yan et Lin [1] investigated laminar natural heat and mass transfer in a vertical plate channel with pure liquid film evaporation. They show that the influence of the liquid is substantial near the interface. Ait Hammou et al. [2] studied numerically the effects of the inlet conditions on a downward laminar flow of humid air in a vertical channel with isothermal wetted walls. Cases of film evaporation and vapour condensation were considered. Lin et al. [3] and Yan [4] investigated the influences of the wetted wall on laminar mixed convection heat transfer in vertical ducts. In their studies, the liquid film on the wetted wall was assumed to be extremely thin so that it was regarded as a boundary condition for heat and mass transfer only. Ben Jabrallah et al. [5] who studied the effects of the flux density of heating, the temperature of the wall and the mass flow of the gas on evaporation by convection. Their results show that the heat and mass transfer can be intensified by decreasing the flow rate of the mass of feed and increasing the feed temperature due to increase the effective surface of the evaporation. Oulaid et al.[6,7] studied numerically the effect of buoyancy forces on the heat and mass transfer by mixed convection for laminar upward flow of humid air in a vertical and inclined channel consists of two flat plates. Their results show that buoyancy forces have significant effect on the thermal field and hydrodynamic mass fraction; these forces decelerate the flow near the walls and induce the flow reversal to deferent temperatures between the gas and the walls. Thus they reduce the heat and mass transfer.

An analysis has been developed for studying the evaporative cooling of liquid film falling inside a vertical insulated tube in turbulent gas stream is presented by Feddaoui et al [8].

The objective of the present study is to analyze the coupled heat and mass transfer processes in the gas stream in the evaporation of negligibly thin film of acetone along a vertical channel where the liquid film can be replaced by the approximate boundary conditions for the gas stream

2. Physical and mathematical model

Consider a negligible thickness liquid film of acetone wetting the walls of a vertical channel of length L and a half channel width b shown schematically in figure 1. The walls of the channel are maitenated at constant temperature T_w, the channel is traversed by a downward flow of mixture gas with a constant temperature T_0, a uniform relative humidity ϕ_0 and a uniform velocity profile U_0. The flow is assumed to be laminar. Radiation, viscous dissipation, and other secondary of Soret and Dufour effects are assumed negligible.

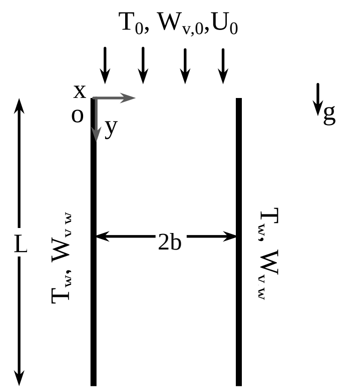


Figure 1 : Physical problem and boundary conditions.

2.1. General equations of conservation

Steady laminar mixed convection in the gas flow can be expressed by the boundary layer conservation equations of mass, axial-momentum, energy and concentration, this system can be written as follows:

$$\frac{\partial(\rho_m V_x)}{\partial x}+\frac{\partial(\rho_m V_y)}{\partial y}=0 \quad (1)$$

$$\frac{\partial \rho_m V_x V_x}{\partial x}+\frac{\partial \rho_m V_x V_y}{\partial y}=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial y}\left(\mu_m \frac{\partial V_y}{\partial y}\right)+\rho_m g \quad (2)$$

$$\frac{\partial \rho_m V_y V_x}{\partial x}+\frac{\partial \rho_m V_y V_y}{\partial y}=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial y}\left(\mu_m \frac{\partial V_y}{\partial y}\right) \quad (3)$$

$$\frac{\partial}{\partial x}(\rho_m V_x C_p T)+\frac{\partial}{\partial y}(\rho_m V_y C_p T)=\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\rho_m D_m (C_{pv}-C_{pa})\left(\frac{\partial T}{\partial y}\frac{\partial W}{\partial y}\right) \quad (4)$$

$$\frac{\partial \rho_m V_x W}{\partial x}+\frac{\partial \rho_m V_y W}{\partial y}=+\frac{\partial}{\partial y}\left(\rho_m D_{mv}\frac{\partial W}{\partial y}\right) \quad (5)$$

2.2. Boundary conditions

At the inlet of channel : $x = 0 \quad 0 < y < 2b$

$V_x = U_0 \quad V_y = 0 \quad T = T_0 \quad W = W_0$ (7)

at walls: $0 < x < L \quad y = 0\ ;\ y = 2b$

$V_x = 0 \quad V_y = V_e \quad T = T_w \quad W = W_w$ (8)

Where: $$V_e = -\frac{D_{mv}}{1-W_w}\frac{\partial W}{\partial y}\bigg|_{y=w} \quad (9)$$

3 Numerical method

The system of equations governing the flow, the heat and mass transfer as well as the associated boundary conditions are discretized by means of the finite volume method proposed by Patankar. [9]. The velocity-pressure coupling is treated with the SIMPLER algorithm [9].

4. Results and Discussion

The results presented for the case of evaporation in the presence of a laminar down air flow in a vertical channel with aspect ratio of γ = 1/100, L = 1.5 m length, and width b = 0,01 m. The channel walls are wetted by a thin film of acetone and maintained at a constant and uniform wall temperature (T_w = 20 °C).

Figure.2 presents the longitudinal velocity profiles for three different positions x = 0.01 m, x = 0.20 m and x = 1.50 m.

As we can see, the flow behavior of the air-acetone, where you notice the closest to the entrance region, the appearance of circulating cells near walls indicating an acceleration of the flow in these regions, while those at the center channel indicate that the flow is reversed because these cells having a negative value of the longitudinal velocity.

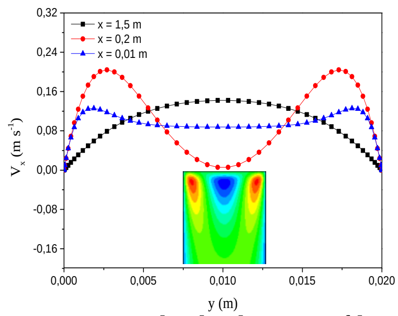
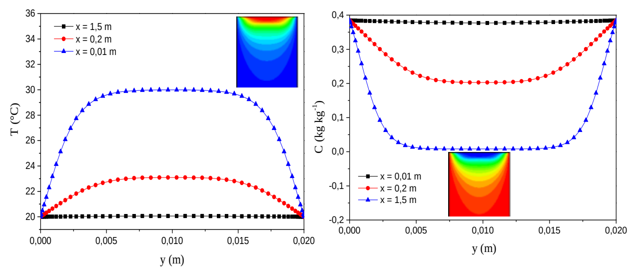


Figure 2 : Longitudinal velocity profiles ϕ_0 = 10 % ; T_0 = 30 °C ; T_w = 20 °C ; Re = 300 ; γ = 1/100.

Figure 3 illustrates the axial development of the temperature and concentration profiles, respectively in the gas stream, at different positions x = 0.01 m; x = 0.20 m and x= 1.50 m.



(a) (b)

Figure 3 : Temperature and concentration Profiles. ϕ_0 = 10 % ; T_0 = 30 °C ; T_w = 20 °C ; Re = 300 ; γ = 1/100.

Is clearly observed that the evolution of the temperature profile of the air-acetone shows more flattened isotherms in the entrance. We can see that the gas temperature decreases monotonically from the inlet temperature T_0 = 30 °C to attain T_w = 20 °C at the channel exit. This indicates that the direction of sensible heat transfer in the gas side is from the gas flow to the walls.

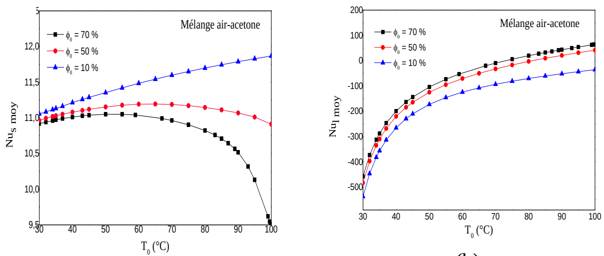
Consistent with the vaporization of the acetone film, the mass fraction of the acetone vapour shown in Figure.3(b) increases gradually as the gas moves downstream.

- **Combined effects of humidity and temperature**

In this section, we investigate the influence of humidity and air temperature at the entrance of the channel on the heat and mass transfer as well as the hydrodynamic behavior.
Figure 4 shows the evolution of the means sensible (a) and latent (b) Nusselt numbers depending on the inlet temperature for different air humidity values at the entrance.

By analyzing Figure 4 (a), we note that the average sensible Nusselt number remains positive. These positive values mean that the sensible heat exchange is always done from the air to the channel walls (air cooling) to the fact that these walls are kept at a temperature less than the air at the inlet. From this figure we also find that the means sensible Nusselt number increases with increasing temperature of air-acetone mixture, for humidity less than 50 %, such as increasing temperature increases the parietal temperature gradients which generates subsequently increased thermal transfer. However, they are decreasing for humidity more than 50 %.

For Figure 4 (b) reveals that the average latent Nusselt number has positive or negative values. Positive values correspond to a latent heat flux in the same direction as the flow sensible; thus condensing the steam contained in the air on the channel walls. By against the negative values correspond to a latent flux from walls of the channel to the gas flow; so there is evaporation of the film covering walls. It should be noted that the average latent Nusselt number decreases with increasing temperature and humidity at the inlet. We note also that condensation occurs for an input temperature higher than 80 °C and a relative humidity above 50 %.



(a) (b)

Figure 4 :Longitudinal evolution of the average sensible (a) and latent (b) Nusselt numbers Re = 300 ; $\gamma = 1/100$; $T_w = 20$ °C.

5. Conclusion

In this work, the hydrodynamic, thermal and solutal behavior of an evaporating thin liquid film of acetone flowing over a vertical channel is analysed, that the channel walls are wetted by thin acetone film and maintenated isothermal. The channel is traversed by laminair flow air at constant temperature and humidity at the entrance.
The major results are as follows:

- Condensation occurs when the vapor mass fraction at the inlet is higher than the corresponding saturation value at the wall temperature (for a temperature higher than 80 °C and humidity higher than 50 %). In the other case, evaporation takes place.
- Increasing of the inlet air temperature results in a small increase of the sensible Nusselt number for an humidity less than 50 % and a significant decrease in latent Nusselt number.

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