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The influence of physical and geometrical parameters on the dimensionless thickness of liquid film

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Abstract

The study of condensation in porous media is subject of growing interest because of its importance in many areas of technology such as heat exchanges, fuel cells, geothermal, energy storage etc...It also finds its application in some technological problems with a two-phase zone, called mushy zone, represented by a saturated porous medium and a binary fluid. It is particularly well developed in these recent years and has been the subject of numerous studies both experimental and numerical. A numerical study of the forced condensation of pure saturated steam and convection to a vertical wall covered with a porous material is shown. Transfers in the porous medium and the liquid film are respectively described by the Darcy-Brinkman model and the classical equations of the boundary layer. The dimensionless equations are solved by an implicit finite difference method and the iterative Gauss-Seidel. The thickness of the condensate film is determined from the equation of heat balance at the vapor-liquid interface and an iterative procedure based on Quasi Linearized Newton method. We analyze the influence of Prandtl, Jacob and Froude numbers and dimensionless thermal conductivity on the dimensionless thickness of liquid film.

Keywords: Condensation; Implicit Finite Difference; Thin Film; Darcy-Brinkman Model; Vertical Wall

1. Introduction

The study of condensation in porous media is a subject of growing interest due to its importance in many technological areas such as heat exchangers, fuel cells, geothermal, energy storage, etc... It also finds its application in some technological problems having a diphasic zone, called mushy zone, represented by a saturated porous medium and a binary fluid. Numerous studies have been carried out using: numerical experimentation (numerical simulation) and / or practical (laboratory experiment), and theoretical developments.

Ndiaye, M. and al [1] presented a numerical study of thin film condensation in forced convection of saturated vapor on a vertical wall covered with a porous material the study of forced convection in a porous medium has aroused and still arouses today the interest of many scientists and industrialists. A considerable amount of work has been undertaken following the discovery of the phenomenon. Solving a standard problem of forced convection in porous media comes down to predicting the temperature and velocity fields as well as the intensity of the flow as a function of the various parameters of the problem. A numerical study of the condensation in forced convection of a pure and saturated vapor on a vertical wall covered with a porous material is presented. The transfers in the porous medium and the liquid film are described respectively by the Darcy-Brinkman model and the classical boundary layer equations. The dimensionless equations are solved by an implicit finite difference method and the iterative Gauss-Seidel method. Our study makes it possible to

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examine and highlight the role of parameters such as: the Froude number and the thickness of the porous layer on the speed and the temperature in the porous medium. Given the objective of our study, the presentation of velocity and temperature profiles is limited in the porous medium. The results show that the Froude number does not influence the thermal field. The temperature increases with an increase in the thickness of the dimensionless porous layer. The decrease in the Froude number leads to an increase in the hydrodynamic field.

Ndiaye, M. and al [2] have analyzed the effects of Prandtl and Jacob numbers and dimensionless thermal conductivity on the hydrodynamic field.

In this present study we have analyzed the effects of the Prandtl and Jacob numbers and the dimensionless thermal conductivity on the velocity profiles in the media (porous and liquid). The transfers in the porous medium and the liquid film are described respectively by the improved Wooding model and the classical boundary layer equations. The mesh of the digital domain is considered uniform in the transverse and longitudinal directions. The terms of advection and diffusion are discretized respectively with a back-offset and a center scheme. The systems of coupled algebraic equations thus obtained are solved numerically thanks to an iterative method of relaxation line by line of the Gauss-Seidel type. The results obtained show that the parameters relating to the thermal problem (the dimensionless thermal conductivity, the numbers of Prandtl (Pr) and Jacob (Ja)) have no influence on the dimensionless speed although the thermal and hydrodynamic problems are coupled via the heat balance equation.

Ndiaye, M. and al [3] have analyzed the effect of Physical and Geometrical Parameters on Nuselt Number. The results of this study show that the Nusselt number decreases with the increase of the dimensionless thermal conductivity and the Prandtl, Froude numbers. The increased Reynolds, Jacob numbers and the dimensionless thickness of porous layer leads to an increase the Nusselt number.

Ndiaye, G. and al [4] were interested the influence of Prandtl number on thin film condensation in forced convection in an inclined wall covered with a porous material.

The numerical study of thin film type condensation in forced convection of a saturated pure vapor in an inclined wall covered with a porous material is presented. The generalized Darcy-Brinkman-Forchheimer (DBF) model is used to describe the flow in the porous medium while the classical boundary layer equations have been exploited in the case of a pure liquid. The dimensionless equations are solved by an implicit finite difference method and the iterative Gauss-Seidel method. The objective of this study is to examine the influence of the Prandtl number on the hydrodynamic and thermal fields but also on the local Nusselt number and on the boundary layer thickness. For $Pr \leq 0.7$ (low) the velocity and the longitudinal temperature increase with the Prandtl number. On the other hand, when $Pr \geq 2$ (high) the Prandtl number no longer influences the velocity and the longitudinal temperature. The local Nusselt number increases as the Prandtl number increases and the thickness of the hydrodynamic boundary layer increases as the Prandtl number decreases.

Asbik M. and al [5-8] were interested in an analytical and numerical study of condensation in forced convection laminar film on a vertical porous layer. These authors showed significant contribution of the porous substrate and the effect of thermal dispersion on a flat wall causing an increase in the transfer rate.

Chaynane R. and al. [9] have analyzed their side effect on the inclination of the condensation in a forced convection laminar pure saturated steam on a porous plate film. The Darcy- Brinkman model is used to describe the flow in the porous medium, while the classical equations of the boundary layer have been exploited in the pure liquid neglecting the inertia terms and convection enthalpy. The problem was solved by analytical and numerical means. Results are mainly presented as the dimensionless thickness of the liquid film, profiles of velocity, temperature and heat transfer coefficients represented by the Nusselt number. The results obtained were compared with those of experimental Renken and al. The effects of various influencing parameters such as the angle, the effective viscosity, Reynolds number, the dimensionless thickness of the porous substrate and the dimensionless thermal conductivity on the dimensionless flow and heat transfer are analyzed.

However, these authors in their studies have neglected the effects of inertia in the equations of Darcy-Brinkman.

We propose in the present work to study numerically the forced convection along a vertical plane wall covered with a homogeneous porous material saturated by a pure liquid by adopting approximations full Darcy-Brinkman model for the porous medium and those of thermal and hydrodynamic boundary layers for the pure liquid.

2. Mathematical formulation

2.1. Physical Model and Assumptions

We consider the phenomenon of thin film condensation on a vertical plate, covered with a thick porous material H, permeability K and porosity ε (Figure 1). The vertical flat plate of length L is positioned in a flow of saturated steam and pure, longitudinal velocity U_0. The vapor condenses on the wall of the plate maintained at lower than the saturation vapor temperature Ts. The film of condensate flows under the influence of gravity and viscous drag forces.

Our field of study includes three (3) areas. The area (1) is the porous medium saturated with the liquid, the zone (2) corresponds to the liquid film whilst the region (3) is on the saturated vapor see figure 1. To study the transfers, we assume that:

The flow is laminar and two-dimensional and the regime is permanent;

- The porous matrix is homogeneous and isotropic and is in local equilibrium with the condensate that is in the form of a thin film;
- The thermo-physical properties of fluids and those of the porous matrix are assumed to be constant;
- Forces are negligible viscous dissipation;
- Saturating fluid, the porous medium is Newtonian and incompressible;
- The dynamic and kinematic viscosity, the actual porous material is equal to those of the film of the condensate;
- The liquid-vapor interface is in thermodynamic equilibrium and the shear stress is assumed to be negligible.

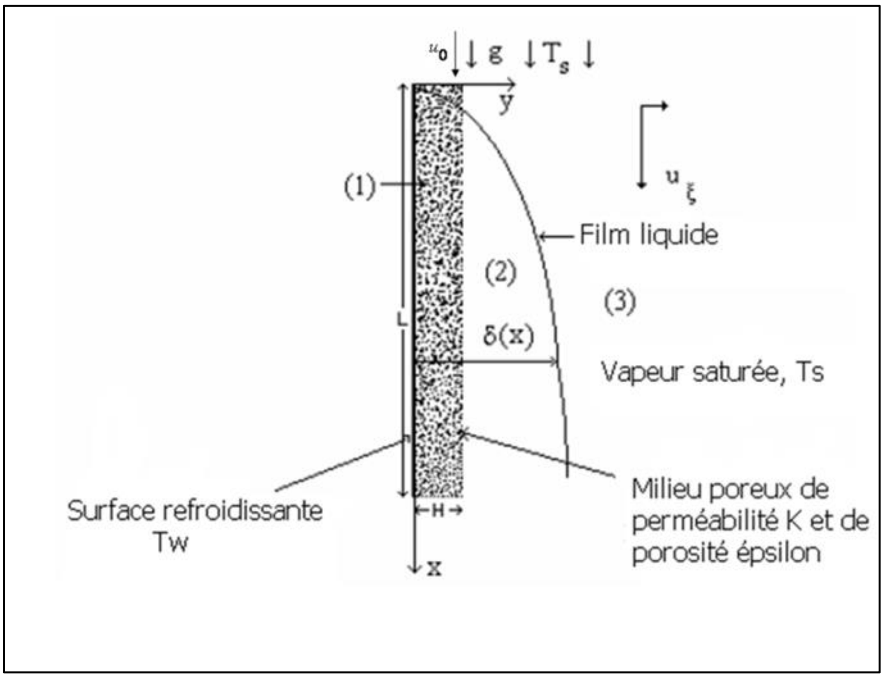

Figure 1 Geometry of the physical model and coordinate system

2.2. Solution procedure

The equations governing the transfers in the areas (1) and (2) defined above as well as the boundary conditions associated with them have been dimensionless using the following parameters and variables (Abik M. and al [6]):

$$H^* = \frac{H}{\sqrt{K}} \qquad \mu^* = \frac{\mu_{eff}}{\mu_l} \qquad x^* = \frac{x}{\sqrt{K}} \qquad y^* = \frac{y}{\sqrt{K}} \qquad L^* = \frac{L}{\sqrt{K}} \qquad \text{(1.a-b-c-d-e)}$$

$$\theta_\xi = \frac{T_\xi - T_W}{T_S - T_W} \qquad u^* = \frac{u_\xi}{u_r} \qquad u_r = \frac{K}{\nu_{eff}} g \qquad \lambda^* = \frac{\lambda_l}{\lambda_{eff}} \qquad \delta^* = \frac{\delta}{\sqrt{K}} \qquad \text{(2.a-b-c-d-e)}$$

In order to reduce the physical area having a curvilinear interface (vapor / liquid interface) in a rectangular area, we perform the following change of variable:

$$X = x^* \quad ; \quad \eta = coef.\frac{y^*}{H^*} + (1 - coef).\left\{1 + \frac{y^* - H^*}{\delta^* - H^*}\right\} \qquad \text{(3.a-b)}$$

coef with a coefficient equal to 1 if we are in the porous layer and 0 in the pure liquid.

So the plan (x^*, y^*) is transformed into a rectangular domain (X, η) and interfaces porous medium / liquid and liquid / vapor saturated environment are respectively parameterized by the coordinate lines $\eta = 1$ and $\eta = 2$.

In both environments, the dimensionless equations of conservation of mass, momentum and heat are written:

Porous layer: $0 \le \eta \le 1$

$$\frac{\partial u_p^*}{\partial X} + \frac{1}{H^*}\frac{\partial v_p^*}{\partial \eta} = 0 \qquad \text{……….} \quad (1)$$

$$u_p^* \frac{\partial u_p^*}{\partial X} + \frac{v_p^*}{H^*}\frac{\partial u_p^*}{\partial \eta} = -\frac{\varepsilon^2}{R_{e_K}} u_p^* + \frac{\varepsilon^2}{R_{e_K}}\left(\frac{1}{H^{*2}}\frac{\partial^2 u_p^*}{\partial \eta^2}\right) + \frac{\varepsilon^2}{F_{r_K}} \qquad \text{……….} \quad (2)$$

$$u_p^* \frac{\partial \theta_p}{\partial X} + \frac{v_p^*}{H^*}\frac{\partial \theta_P}{\partial \eta} = \frac{1}{p_r R_{e_K} H^{*2}}\frac{\partial^2 \theta_P}{\partial \eta^2} \qquad \text{……….} \quad (3)$$

Pure liquid: $1 \prec \eta \prec 2$

$$\left(\delta^* - H^*\right)\frac{\partial u_l^*}{\partial X} - (\eta - 1)\frac{d\delta^*}{dX}\frac{\partial u_l^*}{\partial \eta} + \frac{\partial v_l^*}{\partial \eta} = 0 \qquad \text{……….} \quad (4)$$

$$u_l^*\left[\frac{\partial u_l^*}{\partial X} - \frac{\eta - 1}{\delta^* - H^*}\frac{d\delta^*}{dX}\frac{\partial u_l^*}{\partial \eta}\right] + \frac{v_l^*}{\delta^* - H^*}\frac{\partial u_l^*}{\partial \eta} = \frac{1}{\nu^*.R_{e_K}\left(\delta^* - H^*\right)^2}\frac{\partial^2 u_l^*}{\partial \eta^2} + \left(1 - \frac{\rho_v}{\rho_l}\right)\frac{\left(\delta^* - H^*\right)^2}{F_{r_K}} \qquad \text{……….} \quad (5)$$

$$u_l^*\left[\frac{\partial \theta_l}{\partial X} - \frac{\eta - 1}{\delta^* - H^*}\frac{d\delta^*}{dX}\frac{\partial \theta_l}{\partial \eta}\right] + \frac{v^*{}_l}{\delta^* - H^*}\frac{\partial \theta_l}{\partial \eta} = \frac{1}{R_{e_K} P_r \left(\delta^* - H^*\right)^2}\frac{\partial^2 \theta_l}{\partial \eta^2} \qquad \text{……….} \quad (6)$$

Boundary conditions:

in the wall $\eta = 0$

$$u_p^* = v_p^* = 0 \qquad \theta_p = 0 \qquad \text{(4.a-b)}$$

interface to the porous layer / pure liquid, $\eta = 1$

$$\theta_l = \theta_p \qquad u_l^* = u_p^* \qquad \text{(5.a-b)}$$

$$\frac{1}{H^*}\frac{\partial u_p^*}{\partial \eta} = \frac{1}{\left(\delta^* - H^*\right)}\frac{\partial u_l^*}{\partial \eta} \qquad \frac{1}{H^*}\frac{\partial \theta_p}{\partial \eta} = \frac{\lambda^*}{\left(\delta^* - H^*\right)}\frac{\partial \theta_l}{\partial \eta} \qquad \text{(6.a-b)}$$

at the vapor / liquid interface, $\eta = 2$

$$\theta_l = 1 \qquad \frac{\partial u_l^*}{\partial \eta} = 0 \qquad \text{(7.a-b)}$$

Since the dimensionless velocity and the temperature depend on the dimensionless thickness of the liquid film δ*, the heat balance is expressed respectively by the following relationship:

The heat and mass balance (7. 8) satisfy the following expressions:

$$\frac{Ja}{(Pe)_{eff}}\frac{1}{H^*}\frac{\partial \theta_p}{\partial \eta}/_{\eta=0} = \frac{d}{dx^*}\left[H^*\int_0^1\left\{1 + Ja\left(1-\theta_p\right)\right\}u_p^* d\eta\right] + \frac{d}{dx^*}\left[\int_1^2\left(\delta^* - H^*\right)\left\{1 + Ja\left(1-\theta_l\right)\right\}u_l^* d\eta\right] \quad \text{.......... (7)}$$

with $$(Pe)_{eff} = \lambda^* \Pr Re_K \quad \text{.......... (8.a)}$$

The mass flow rate:

$$H^*\int_0^1 u_p^* d\eta + \left(\delta^* - H^*\right)\int_1^2 u_l^* d\eta = \frac{\rho_v}{\rho_l}\delta^* \quad \text{.......... (8)}$$

Dimensionless numbers are defined by the following relations:

$$P_r = \frac{\mu_l C_{P_l}}{\lambda_l} \qquad Fr_K = \frac{u_0^2}{g\sqrt{K}} \qquad \text{(9.a-b)}$$

$$Re_K = \frac{u_0\sqrt{K}}{\nu_{eff}} \qquad Ja = \frac{C_{P_l}\left(T_S - T_w\right)}{h_{fg}} \qquad \text{(10.a-b)}$$

The equations are discretized transfer by an implicit finite difference method. The mesh of the digital domain is considered uniform in the transverse and longitudinal directions. The terms of advection and diffusion are discretized respectively with a rear and centered upwind scheme. The coupled algebraic equations are solved numerically obtained through an iterative relaxation method line by line Gauss-Seidel.

Thus, the discretization in the study area (porous medium and liquid) equations of continuity, energy and movement leads to the following algebraic equations:

$$b.Int^*(i,j) = ami.Int^*(i-1,j) + amj.Int^*(i,j-1) + apj.Int^*(i,j+1) + coef0 \quad \text{.......... (9)}$$

with 2≤ i ≤ im et 2 ≤ j ≤ jm-1

(i, j) and (Δx, Δη) respectively represent nodes and the step along x and η; im and jm are the maximum nodes along x and η.

For the equations of movement and heat:

$$b = \frac{coefx}{\Delta x} + \frac{coefe}{\Delta \eta} + 2 * \frac{coefe2}{\Delta \eta^2} \qquad ami = \frac{coefx}{\Delta x} \quad \text{……….} \quad (11.a\text{-}b)$$

$$amj = \frac{coefe}{\Delta \eta} + \frac{coefe2}{\Delta \eta^2} \qquad apj = \frac{coefe2}{\Delta \eta^2} \quad \text{……….} \quad (12.a\text{-}b)$$

For the continuity equation:

$$b = 1 \qquad amj = 1 \qquad apj = 0 \qquad ami = 0 \quad (13.a\text{-}b\text{-}c\text{-}d)$$

The thermal and dynamic conditions at the interface discretized:

$$u^*(i, j\_\text{int}) = H^* * u^*(i, j\_\text{int}+1) + rapp\_nu * (\delta^*(i) - H^*) * u^*(i, j\_\text{int}-1) / co\_\text{int} \quad \text{……….} \ (10)$$

$$\theta(i, j\_\text{int}) = rapp\_lambda * H^* * \theta(i, j\_\text{int}+1) + (\delta^*(i) - H^*) * \theta(i, j\_\text{int}-1) / co\_\text{int} \quad \text{……….} \ (11)$$

Approaching the integrals appearing in the equation of heat balance by Newton quadrature, we obtain after discretization:

$$\delta^*(i) = \delta^*(i-1) + R_\delta \quad \text{……….} \quad (12)$$

Coefficients that fall within the terms of the general equation are shown in the appendix.

Coupled algebraic systems thus obtained are solved numerically using an iterative relaxation method line by line Gauss - Seidel.

3. Results and discussion

Our study allows examine the role and to identify parameters such as: Prandtl, Jacob and Froude numbers, the thickness of the porous layer and the dimensionless thermal conductivity on the profiles velocity, temperature longitudinal, and thickness of the liquid film in the areas (porous and liquid). Results from numerical simulations are related to: $H^* = 2.10^{-3}$; $Re_K = 45$; $\nu^* = 10^{-7}$; $\mu^* = 1$ ε = 0.4. The study of the sensitivity of the mesh led us to choose Δ η = 0.02 and Δ x = 0.004. The convergence criterion in the iterative process is set at 10^{-6}.

To validate our model, we compared the results of Asbik M. and al. [5-8] with those from our calculation code in which the inertia terms have been omitted. We note that the correspondence is acceptable as we see later.

The curves of Figures 2-5 show that the thickness of the hydrodynamic boundary layer is very sensitive to the Froude number (Figure. 2) increases as the thermal conductivity and decrease the Prandtl number (Figures. 3 and 4) and increases in the same meaning that the number of Jacob (Figure. 5). This means therefore that the variations in the thickness of the boundary layer depends much thermal parameters and in particular the number of Jacob. The more Jacob number is great plus the thickness of the liquid film increases as the condensation is favored.

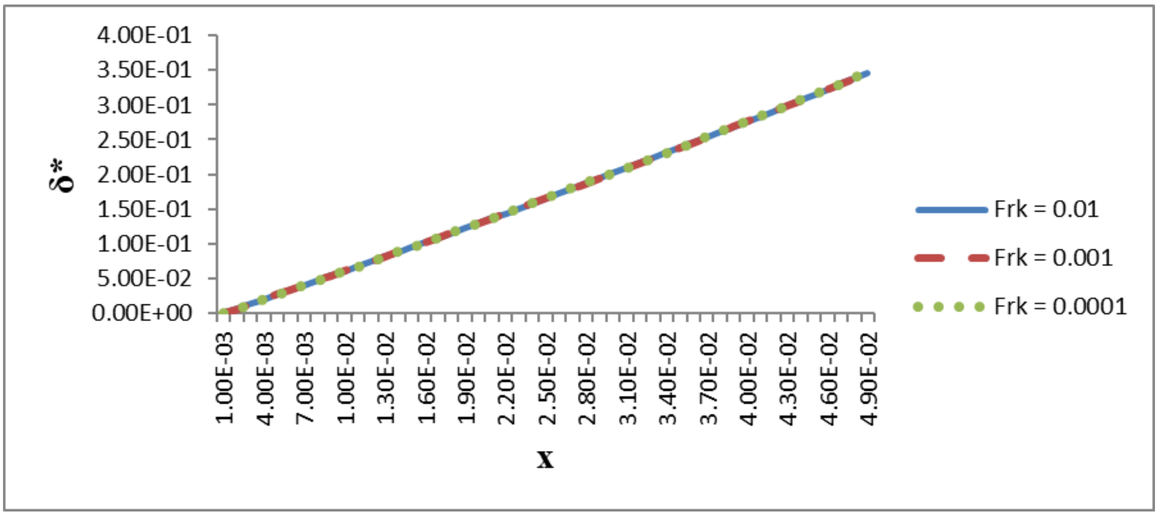

Figure 2 Variation of the thickness of the liquid film as a function of the abscissa x for different values of F_{r_K}

Ja =10^{-3}; Pr=2; $\lambda^*=2.9$

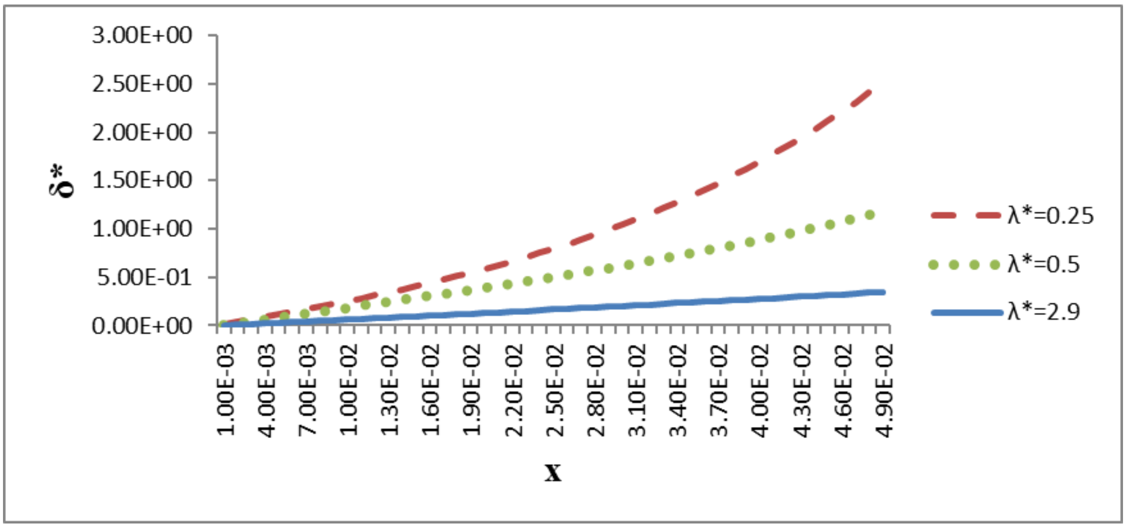

Figure 3 Variation of the thickness of the liquid film as a function of the abscissa x for different values of λ^*:

$F_{r_K} = 10^{-4}$; Ja=10^{-3}; Pr=2

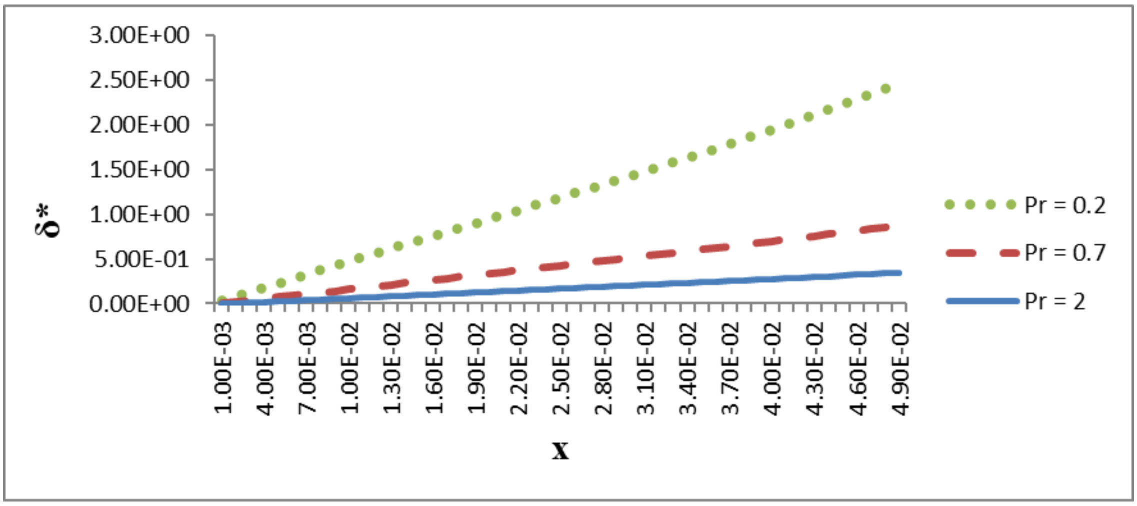

Figure 4 Variation of the thickness of the liquid film as a function of the abscissa x for different values of Pr:

$F_{r_K} = 10^{-4}$; **Ja =10^{-3};** λ^*=2.9

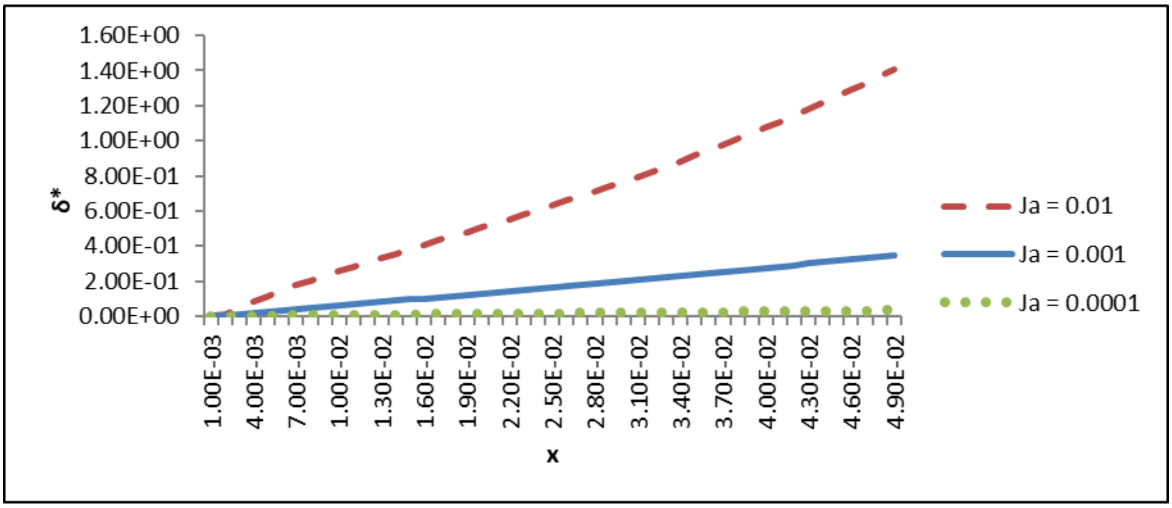

Figure 5 Variation of the thickness of the liquid film as a function of the abscissa x for different values of Ja:

$F_{r_K} = 10^{-4}$ **; Pr=2 ;** λ^*=2.9

Nomenclature

- Greek symbols:
- δ : Thickness of the condensate, m
- ε : Porosity
- θ : Temperature dimensionless
- λ : Thermal conductivity, W.m^{-1}.K^{-1}
- μ : Dynamic viscosity, kg.m^{-1}.s^{-1}
- ν : Kinematic viscosity, m^2.s^{-1}
- ρ : Density, kg/m^3
- *: Dimensionless quantity

Indices exhibitor:

eff: efficiency value

i: porous substrate interface / pure liquid

l: liquid

p: porous

s: saturation

v: steam

w: wall

Latin letters

- c_p : specific heat, J. kg-1 .K-1

- Fr_K : Froude number based on $\sqrt{K}$
- g: acceleration of gravity, m. s-2
- H: thickness of the porous layer, m
- h_{fg} : heat of evaporation, J.kg-1
- Ja: Jacob number
- K: hydraulic conductivity or permeability, m2
- L: length of the plate, m
- Pe: Peclet number
- Pr: Prandtl number
- R_{e_K} : Reynolds number based on $\sqrt{K}$
- T: temperature, K
- U_0 : velocity of free fluid (steam), m/s
- u: velocity along x, m/s
- u_r : velocity reference, m/s
- v: velocity along y, m/s
- x, y: cartesian coordinates along x and y, m

4. Conclusion

We studied in the forced condensation of pure saturated steam and coated on a vertical wall of porous material convection. The equations were solved using the method of finite differences implicit decentered rear for velocity and temperature profiles in the two media (porous and liquid). We analyzed the influence of the Prandtl, Jacob and Froude numbers and thermal conductivity on the dimensionless thickness of liquid film. The results show that the thickness of the hydrodynamic boundary layer is very sensitive to the Froude number increases as the thermal conductivity and decrease the Prandtl number and increases in the same meaning that the number of Jacob. This means therefore that the variations in the thickness of the boundary layer depends much thermal parameters and in particular the number of Jacob. The more Jacob number is great plus the thickness of the liquid film increases as the condensation is favored.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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