

# Numerical Study of Thin Film Condensation in Forced Convection on an Inclined Wall Covered with a Porous Material

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## Abstract

The present work presents a study of forced convection condensation of a laminar film of a pure and saturated vapor on a porous plate inclined to the vertical. The Darcy-Brinkman-Forchheimer model is used to write the flow in the porous medium, while the classical boundary layer equations have been exploited in the pure liquid and in the porous medium taking into account inertia and enthalpy convection terms. The problem has been solved numerically. The results are mainly presented in the form of velocity and temperature profiles. The obtained results have been compared with the numerical results of Chaynane *et al.* [1]. The effects of different influential parameters such as: inclination ( $\phi$ ), effective viscosity ( $Re_K$ ), and dimensionless thermal conductivity  $\lambda^*$  on the flow and heat transfers are outlined.

## Keywords

Condensation, Implicit Finite Difference, Thin film, Porous Material, Darcy-Brinkman-Forchheimer Inclined Wall

## 1. Introduction

The study of convection in a porous medium is the object of much covetousness both at the scientific and industrial levels. Indeed, many actors are interested in this field during these last years because of its importance in some important

technological problems such as phase change. Condensation in porous media is a subject of growing interest because of its diverse and important technical applications in heat exchangers, in the cooling of electronic equipment, energy storage, etc... Today numerical simulation is more and more used by scientists because it is the least expensive even if it is still confronted with data storage problems. Several numerical and experimental publications were consulted during our research. Among them, there are the following.

Chaynane R. *et al.* [1] presented an analytical and numerical study of film condensation on a wall inclined from the vertical and covered with a material. The Darcy-Brinkman model is used to write the flow in the porous medium, while the classical boundary layer equations have been exploited in the pure liquid taking into account inertia and enthalpy convection terms. The problem has been solved both analytically and numerically. The results are essentially presented in the form of the dimensionless thickness of the liquid film, the velocity and temperature profiles, and the coefficients of heat exchange represented by the Nusselt number. The effects of different influents such as: inclination ( $\varphi$ ), effective viscosity (Reynolds number  $Re_K$ ), the dimensionless thickness of the porous substrate  $H$ , and dimensionless thermal conductivity,  $K^*$  on the flow and heat transfers are illustrated.

Asbik M. *et al.* [2] have analytically studied the laminar thin film condensation of a pure and saturated vapor flowing in forced convection over a vertical porous plate. The transfers in the porous medium and the pure liquid are respectively described by the Darcy-Brinkman model and the classical boundary layer equations. Thermal dispersion is considered in the heat equation for heat transfer in the porous layer. The analysis of the velocity, temperature, and local Nusselt number profiles shows the influence of thermal dispersion on the condensate flow and heat transfer. The results show that the increase in the thermal dispersion coefficient leads to a considerable increase in heat exchange.

The comparison of the results deduced from the analytical expressions with those obtained by solving the conservation equations of momentum and heat using a numerical method leads to a quantitatively satisfactory agreement. The difference is less than 10%.

Asbik M. *et al.* [3] were interested in the analytical study of a condensation film deposited by forced convection on a vertical surface covered with a porous layer. A forced convection condensation problem in a porous thin film is considered. The flow in the region is described by the Darcy-Brinkman-Forchheimer (DBF) model, while the classical boundary layer equations without inertia and enthalpy terms are used in the pure condensate region. In order to solve this problem, an analytical method is proposed. Then, analytical solutions for the flow velocity, temperature distributions and local Nusselt number are obtained. The results are presented mainly in the form of velocity and temperature profiles in the porous layer.

A comparison of the Darcy-Brinkman-Forchheimer model and the Darcy-Brinkman model is performed. The effects of effective viscosity (Reynolds number), per-

meability (Darcy number), and thickness of the  $H$  dimensionless porous liner on the flow and heat transfer enhancement are also illustrated.

Renken K. J. *et al.* [4]-[10] were the first to show numerically via a finite-difference scheme the effect of the porous layer thickness on the transfers by studying laminar thin film condensation on a vertical surface with a porous coating. Their model simulates two-dimensional condensation inside a highly permeable, thinly conductive porous layer. The local volume averaging technique is used to establish the energy equation. The Darcy-Forchheimer model is employed to describe the flow field in the porous layer while the classical boundary layer equations are used in the pure condensate region. They also developed experiments on forced convection condensation in thin and porous coatings. This study presents the results of forced convection heat transfer experiments of condensation on plates with a thin porous coating. The composite system consists of a porous, thin, highly conductive, and permeable material bonded to a cold surface in isothermal condensation that runs parallel to the saturated vapor flow, were interested in studying forced convective condensation on a thin porous layer led plate. The system consists of a relatively thin permeable highly conductive composite placed parallel to the vapor flow. The pores have thicknesses ranging from 0 to 254 micrometers which are used as a passive technique for heat transfer enhancement. The use of a thin porous layer on isothermal surfaces under the condition of forced convection shows that the thinner the porous layer the more heat transfer is increased. Thus, the experiments demonstrated the advantages of using a thin porous coating in a forced convection heat transfer environment.

Ndiaye M. *et al.* [11] [12] [13] [14] [15] proposed a numerical model for the study of pure saturated vapor condensation of thin-film type in forced convection on a wall covered with a porous material. They analyzed the influences of Prandtl, Froude, Reynolds, and Jacob number, the dimensionless thickness of the porous layer, and the thermal conductivity ratio on the transfers in the porous medium and in the liquid phase. They had also retained that the effects of inertia could no longer be ignored in the porous medium as soon as the Reynolds number is higher than 7.

Louahlia *et al.* [16] have provided a numerical study of condensation by forced convection of R134a between two vertical plates. The physical model is based on the solution of the boundary layer equations taking into account the parameters often neglected in theoretical studies of condensation, namely the pressure gradient, the inertia and enthalpy convection terms, and the variation of the physical properties. Their computational results are compared with experimental values. The effects of turbulence, gravity, steam velocity, pressure forces, and tangential stresses are also analyzed.

Ma X. H. *et al.* [17] presented a numerical study of film condensation on a vertical porous plate coated with a porous/fluid composite system based on the dispersion effect.

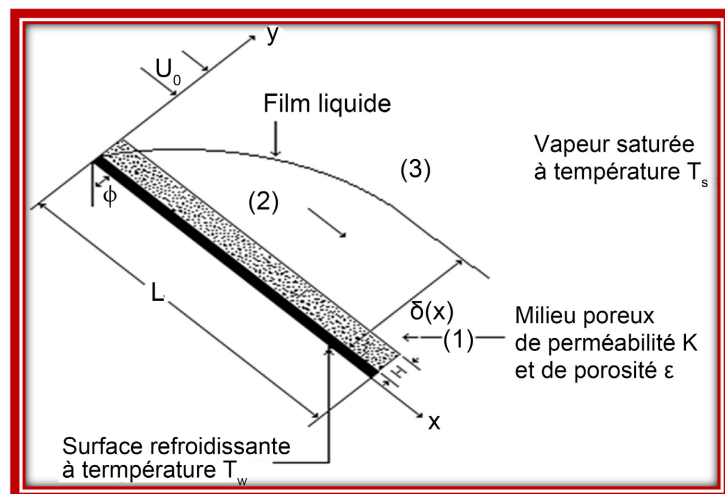
The mathematical model improves the corresponding conventional conditions

by considering the stress forces at the porous coating/fluid interface. Numerical results show the effects of the thickness of the porous medium, the effective thermal conductivity, the permeability of the condensate film thickness, and the local Nusselt numbers.

Ndiaye P. T. *et al.* [18] [19] were interested in the influences of Reynolds number and Prandtl number on the longitudinal velocity and temperature in the porous medium and in the pure liquid and the rate of heat transfer (local Nusselt number). In their study, it is denoted that the increase in Reynolds number and Prandtl number leads to an increase of the longitudinal velocity and temperature. The tangents of the velocity curves at the porous interface on the medial side are smaller than those obtained on the liquid side with low Reynolds number and Prandtl number. It is also noted that increasing the Reynolds and Prandtl numbers improves the heat exchange at the media interface. They also examined and demonstrated the influence of Jacob's number on the velocity and temperature profiles in porous media and pure liquid, liquid film thickness, local Nusselt number and inlet lengths. It has been noticed that the Jacob number is a very determining parameter on the transfers and condensation. The higher Jacob's number, the slower the flow, and therefore the more condensation is favored and the thickness of the liquid film increases. This increase in the thickness of the liquid film leads to a greater thermal resistance; therefore, a decrease in heat exchange and local Nusselt number is observed. An exponential decrease of the inlet length is noted and it is strong when the Jacob number is between  $Ja = 1E-8$  and  $Ja = 2E-8$ : a high sensitivity to condensation can be observed, in conclusion.

## 2. The Physical Model

We consider a saturated porous medium confined on a vertical plate, of thickness  $H$ , permeability  $K$  and porosity  $\varepsilon$  (**Figure 1**). This flat plate tilted by an angle  $\phi$  of length  $L$  is placed in a pure, saturated vapor flow of longitudinal velocity



**Figure 1.** Physical model geometry and coordinate system.

$u_0$ . The vapor condenses on the wall of the plate held at temperature  $T_w$  lower than the saturation temperature  $T_s$  of the vapor. The condensate film flows under the effect of gravity and viscous frictional forces. There are three zones: Zone (1) is the porous medium saturated by the liquid. The zone (2) corresponds to the liquid film while the zone (3) is relative to the saturating vapor. Let  $(x, y)$  and  $(u, v)$  respectively the Cartesian coordinates and the components of the velocity in the porous medium and the liquid in the reference frame associated with the model.

For the rest of our study, we have taken the following simplifying assumptions:

- 1) The porous substrate is isotropic and homogeneous.
- 2) The fluid saturating the porous medium is Newtonian and incompressible.
- 3) The flow generated is laminar and two-dimensional.
- 4) The work, induced by viscous and pressure forces, is negligible.
- 5) The thermo-physical properties of the fluids and those of the porous matrix are assumed constant.
- 6) The Darcy-Brinkman-Forchheimer model is used to describe the flow in the porous layer.
- 7) The inertia and enthalpy convection terms are taken into account in both phases.
- 8) The effective dynamic and kinematic viscosities of the porous material are equal to those of the condensate film.
- 9) Condensation occurs as a thin film.
- 10) The porous matrix is in local equilibrium with the condensate.
- 11) The liquid-vapor interface is in thermodynamic equilibrium and the shear stress is assumed to be negligible.
- 12) The vapor and the film are separated by a distinct boundary.
- 13) The flow is considered of Bernoulli type in the pure vapor phase.

## 2.1. Equations

The equations characterizing our model are defined as follows:

In the porous medium.

**Porous layer**  $0 < \eta < 1$

The system of equations defining the motion is then written in the dimensionless form.

**Continuity equation**

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

Equation of the following momentum balance  $X$ .

$$u_p^* \frac{\partial u_p^*}{\partial X} + \frac{v_p^*}{H^*} \frac{\partial u_p^*}{\partial \eta} = -\frac{\varepsilon^2}{Re_K} u_p^* + \frac{\varepsilon^2}{Fr_K} \cos \phi \left( \frac{\rho_l - \rho_v}{\rho_l} \right) + \frac{1}{(H^*)^2} \frac{\varepsilon^2}{Re_K} \frac{\partial^2 u_p^*}{\partial \eta^2} - \varepsilon^2 b (u_p^*)^2 \quad (2)$$

Heat equation

$$u_p^* \frac{\partial \theta_p}{\partial X} + \frac{v_p^*}{H^*} \frac{\partial \theta_p}{\partial \eta} = \frac{1}{(H^*)^2} \frac{1}{\lambda^* Pr_{eff} \cdot Re_K} \frac{\partial^2 \theta_p}{\partial \eta^2} \quad (3)$$

Pure liquid  $1 < \eta < 2$ .

Continuity equation

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

Equation of the following momentum balance  $X$ .

$$\begin{aligned} u_l^* \left( \frac{\partial u_l^*}{\partial X} - \frac{\eta-1}{\delta^* - H^*} \frac{d\delta^*}{dX} \frac{\partial u_l^*}{\partial \eta} \right) + \frac{v_l^*}{\delta^* - H^*} \frac{\partial u_l^*}{\partial \eta} \\ = \frac{1}{(\delta^* - H^*)^2} \frac{1}{\nu^* \cdot Re_K} \frac{\partial^2 u_l^*}{\partial \eta^2} + \left( \frac{\cos \phi}{Fr_K} \right) \left( \frac{\rho_l - \rho_v}{\rho_l} \right) \end{aligned} \quad (5)$$

Heat equation

$$\begin{aligned} u_l^* \left( \frac{\partial \theta_l}{\partial X} - \frac{\eta-1}{\delta^* - H^*} \frac{d\delta^*}{dX} \frac{\partial \theta_l}{\partial \eta} \right) + \frac{v_l^*}{\delta^* - H^*} \frac{\partial \theta_l}{\partial \eta} \\ = \frac{1}{(\delta^* - H^*)^2} \frac{1}{Pr \cdot Re_K} \frac{\partial^2 \theta_l}{\partial \eta^2} \end{aligned} \quad (6)$$

## 2.2. Boundary and Interface Conditions

The basic equations described above are solved taking into account the boundary conditions specific to our problem. These are the following:

At the wall  $\eta = 0$ .

$$u_p^*(X, 0) = v_p^*(X, 0) = 0 \quad (7)$$

$$\theta_p(X, 0) = 0 \quad (8)$$

At the interface porous layer/pure liquid  $\eta = 1$ .

Continuity of velocities and dimensionless temperatures

$$u_p^*(X, 1) = u_l^*(X, 1) \quad (9)$$

$$\theta_p(X, 1) = \theta_l \quad (10)$$

Continuity of dimensionless constraints

$$\mu_{eff}^* \cdot \frac{\partial u_p^*}{\partial x} \Big|_{y=H} = \mu_l^* \cdot \frac{\partial u_l^*}{\partial x} \Big|_{y=H} \quad (11)$$

$$\frac{1}{H^*} \frac{\partial u_p^*}{\partial \eta} = \frac{\mu^*}{\delta^* - H^*} \frac{\partial u_l^*}{\partial \eta} \quad (12)$$

We have installed.

Continuity of dimensionless flows

$$\frac{1}{H^*} \frac{\partial \theta_p}{\partial \eta} = \frac{\lambda^*}{\delta^* - H^*} \frac{\partial \theta_l}{\partial \eta} \quad (13)$$

At the liquid/vapor interface  $\eta = 2$ .

$$\theta_l(X, 2) = 1 \quad (14)$$

$$\left. \frac{\partial u_l^*}{\partial \eta} \right|_{\eta=2} = 0 \quad (15)$$

Entry requirements  $X = 0$ .

$$\theta_p(0, \eta) = 1 \quad (16)$$

$$u_p^*(0, \eta) = 1 \quad (17)$$

$$v_p^*(0, \eta) = 0 \quad (18)$$

### 2.3. Mass and Heat Balance Equations

Since the dimensionless velocity and temperature depend on the thickness of the liquid film  $\delta^*$ , the dimensionless heat and mass balances are expressed by the following relationship respectively:

$Pe_{eff} = \lambda^* \cdot Pr \cdot Re_K$  is the modified Peclet number.

With the mass flow equation which is given by:

$$H^* \int_0^1 u_p^* d\eta + (\delta^* - H^*) \int_1^2 u_l^* d\eta = \frac{\rho_v}{\rho_l} u_0^* \delta^* \quad (19)$$

$$Ja = \frac{C_{pL}(T_s - T_w)}{h_{fg}} \quad (20)$$

Represents the number of Jacob that compares the sensible and latent heat.

$$Fr_K = \frac{(u_r)^2}{g\sqrt{K}} \quad (21)$$

The Froude number which characterizes the ratio between the forces of inertia and gravity.

$$Re_K = \frac{u_r \sqrt{K}}{\nu_{eff}} \quad (22)$$

The Reynolds number which compares the effects of inertia and viscosity. It is the most important characteristic number in Fluid Mechanics.

$$Pr = \frac{\nu_l}{\alpha_l} \quad (23)$$

The number of Prandtl.

$$Pr_{eff} = \frac{\nu_{eff}}{\alpha_l} \quad (24)$$

The Prandtl number calculated on the basis of the effective viscosity.

### 2.4. Numerical Resolution

The boundary layer equations are solved according to the implicit scheme. In this scheme, the partial derivative at nodes  $(i, j)$  of cell  $(i, j)$ . The uniform mesh is

not rectangular and the progression is geometric. The domain mesh of the real problem is converted into a numerical mesh of the next rectangular domain. The transfer equations are discretized by a finite difference method. The advection and diffusion terms are discretized with a backward decentered and centered scheme respectively in order to make the main diagonals of the matrices as dominant as possible. The coupled algebraic equations are solved numerically by a line of iterative Gauss-Seidel relaxation method. Résultats et discussions.

To validate our model, we compared the results of R. Chaynane *et al.* [1] with those of our computational code in which, for the liquid medium, the inertial and enthalpic convection terms were considered and the tilt angle  $\Phi$  with respect to the vertical is zero. We observe that the correspondence is acceptable as we will see later.

We show in this study the influence of parameters such as: tilt ( $\phi$ ), effective viscosity  $Re_K$  and dimensionless thermal conductivity  $\lambda^*$  on the flow and heat transfers.

$$\varepsilon = 0.4; Pr = 2; v^* = 1; H^* = 2.10^{-2}; Fr_K = 10^{-2}; Ja = 10^{-5}$$

The mesh sensitivity study led us to choose  $\Delta X = 0.05$  and  $\Delta \eta = 0.02$ . The convergence criterion in the iterative process is set to  $10^{-6}$ .

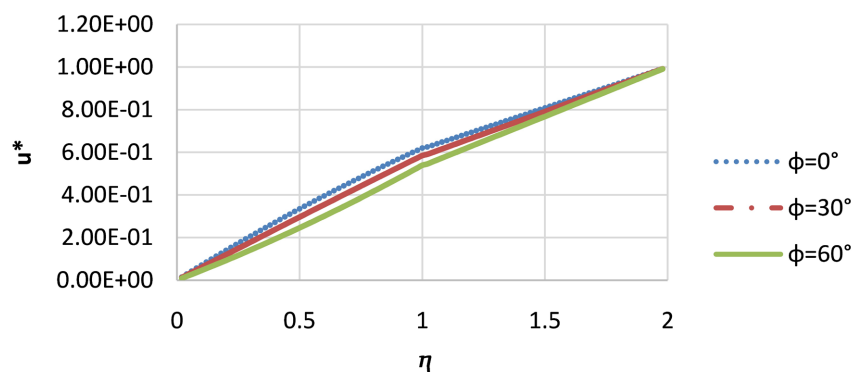
**Figure 2** below shows the variation of the longitudinal velocity for different values of the angle.

**Figure 3** below shows the temperature variation for different values of the angle.

The longitudinal velocity increases when the angle of inclination with respect to the vertical is low. Their profiles are similar to those of R. Chaynane *et al.* [1]. The velocity in the porous substance is linear and undergoes a slight variation at the porous medium/pure liquid interface due to the increase in buoyancy forces.

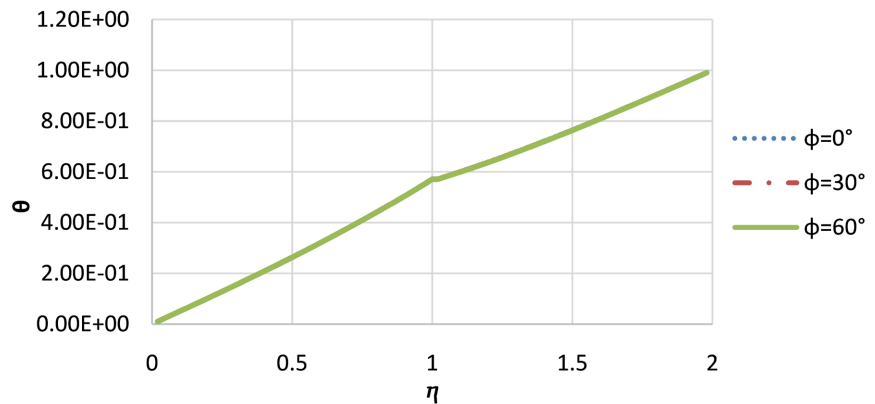
Contrary to R. Chaynane *et al.* [1], we note that the tilt angle does not influence the temperature profile. This means that the dynamic diffusion effects are negligible compared to the thermal diffusion effects.

**Figure 4** below shows the variation of the longitudinal velocity for different values of Reynolds number.

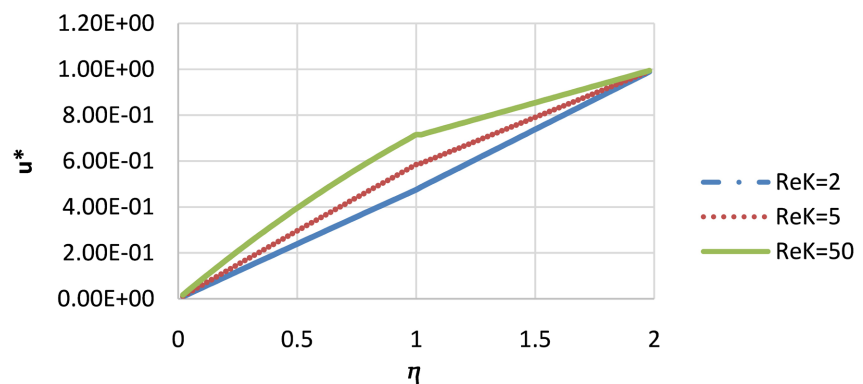


**Figure 2.** Variation of the longitudinal velocity as a function of the ordinate  $\eta$  for different values of  $\phi$  at the position  $X = 0.05$ .  $Re_K = 5$ ;  $\lambda^* = 5$ .





**Figure 3.** Variation of the temperature as a function of the ordinate  $\eta$  for different values of  $\varphi$  at the position  $X = 0.05$ .  $Re_K = 5$ ;  $\lambda^* = 5$ .



**Figure 4.** Variation of the longitudinal velocity as a function of the ordinate  $\eta$  for different values of  $Re_K$  at the position  $X = 0.05$ .  $\lambda^* = 5$ ;  $\varphi = 30^\circ$ .

**Figure 5** below shows the temperature variation for different values of Reynolds number.

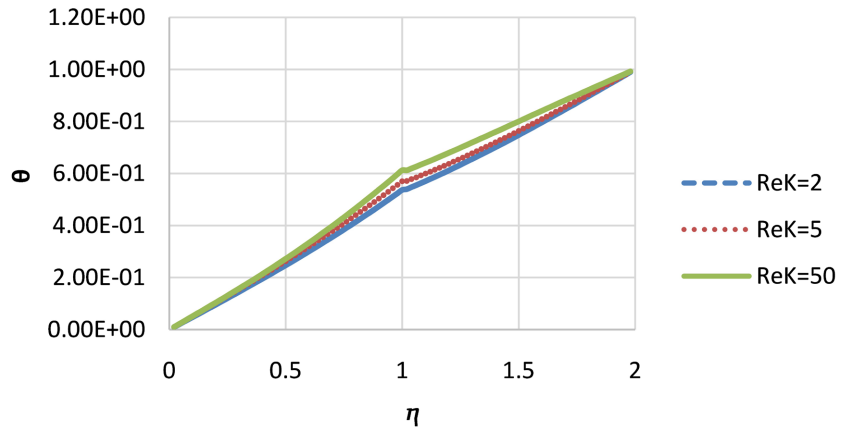
The longitudinal velocity increases proportionally to the Reynolds number, which corresponds to a low effective viscosity of the liquid. When the latter is less than or equal to 2 it becomes almost linear in both media and linear in the porous substance with a small variation at the interface porous medium/pure liquid when  $Re_K = 5$  which is contrary to the results of R. Chaynane *et al.* This can be explained by the fact that in these intervals the effects of inertia become negligible compared to the effects of effective viscosity and the medium is qualified as not very porous. When  $Re_K \geq 50$  the longitudinal velocity loses its linearity in the porous medium, the medium becomes quite porous and the velocity undergoes significant variations at the interface porous medium/pure liquid because of the predominance of inertia effects on the effects of viscosity at the time of the Darcy-Brinkman-Forcheimer approximation.

The temperature profile also increases with the Reynolds number. It is influenced by the velocity profile because the thermal diffusion becomes insignificant before the dynamic diffusion. However, we note small variations of the temperature at the level of the porous medium which become more and more signifi-

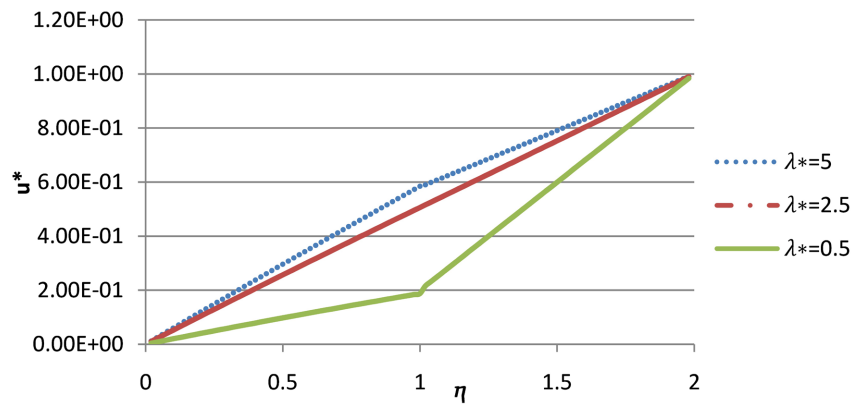
cant around the interface porous medium/pure liquid.

**Figure 6** below shows of the longitudinal velocity for different values of lambda addimensional.

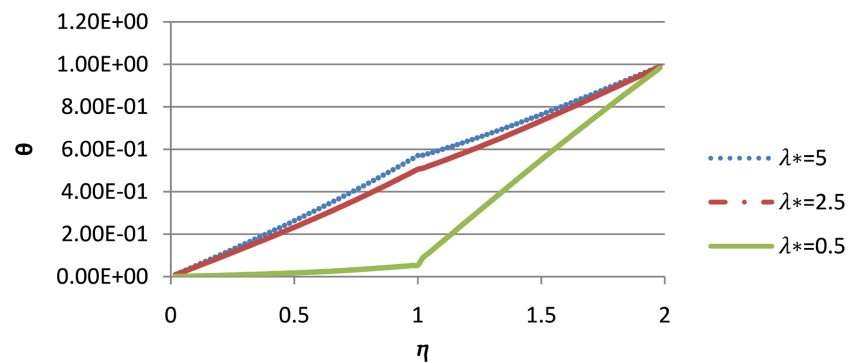
**Figure 7** below shows the temperature variation for different values of lambda adimensional.



**Figure 5.** Variation of the temperature as a function of the ordinate  $\eta$  for different values of  $Re_K$  at the position  $X = 0.05$ .  $\lambda^* = 5$ ;  $\phi = 30^\circ$ .



**Figure 6.** Variation of the longitudinal velocity as a function of the ordinate  $\eta$  for different values of  $\lambda^*$  at the position  $X = 0.005$ .  $Re_K = 5$ ;  $\phi = 30^\circ$ .



**Figure 7.** Variation of the temperature as a function of the ordinate  $\eta$  for different values of  $\lambda^*$  at the position  $X = 0.05$ .  $Re_K = 5$ ;  $\phi = 30^\circ$ .

Contrary to the work of R. Chaynane *et al.* [1], we note that the longitudinal velocity increases with the adimensional conductivity and is almost linear in both liquid/porous media if its value is between 2.5 and 5. This is due to the predominance of the liquid conductivity over the effective conductivity of the porous medium. However, when the adimensional conductivity is low ( $\lambda^* \leq 0.5$  liquid medium with low conductivity) we note a significant variation at the interface of the two media.

The conductivity ratio  $\lambda^*$  has a significant influence on the temperature distribution in the porous medium because it increases with it. At the same time, it favors heat transfer in the liquid phase due to the fact that large values of the dimensionless conductivity correspond to a highly conductive liquid phase. We note a strong variation of the temperature at the interface porous medium/liquid when the conductivity ratio becomes low ( $\lambda^* \leq 0.5$ ) then in this case most of the transfers are made in the liquid.

### 3. Conclusion

We have presented a numerical study of thin-film condensation in forced convection on a wall inclined to the vertical and covered with a porous material. The equations were solved using the off-center implicit finite difference method. We showed the hydrodynamic and thermal influences of parameters such as the tilt angle  $\Phi$ , the effective viscosity ( $Re_\lambda$ ), and the dimensionless thermal conductivity  $\lambda^*$ . Taking into account our simplifying assumptions, we compared our results with those of R. Chaynane *et al.* [1]. Thus, we were able to show that the angle influences the velocity profile of both media (liquid and porous) but not the temperature profile. We showed that small values of the effective viscosity will increase the flow velocity in both media and give linear appearances in the porous and liquid media with little variation at the interface. We have shown that when the liquid is too conductive ( $\lambda^*$  high), this favors an increase in velocity and temperature profiles.

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Nomenclature

- $\phi$ : Angle d'inclinaison: thermal diffusivity,  $\text{m}^2\cdot\text{s}^{-1}$   
 $\delta^*$ : Thickness of condensate, m  $\varepsilon$ : Porosity  
 $\eta$ : Dimensionless coordinate in the transverse direction  
 $\theta$ : Temperature dimensionless  
 $\lambda$ : Thermal conductivity,  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$   $\mu$ : Viscosité dynamique,  $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$   
 $\nu$ : Viscosité cinématique,  $\text{m}^2\cdot\text{s}^{-1}$   $\rho$ : Density,  $\text{kg}\cdot\text{m}^{-3}$
- Latines letters:
- $C_p$ : Specific heat,  $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$   $Da$ : Darcy's number  
 $F$ : Forchheimer coefficient  $Fr$ : Froude number  
 $g$ : Gravitational acceleration,  $\text{m}\cdot\text{s}^{-2}$   $H$ : Thickness of the porous layer, m  
 $h_{fg}$ : Enthalpy of evaporation,  $\text{J}\cdot\text{kg}^{-1}$   $Ja$ : Jacob number  
 $K$ : Hydraulic conductivity or permeability,  $\text{m}^2$   
 $L$ : Length of the plates of the channel, m  $Nu$ : local Nusselt number  
 $Pe$ : Peclet number  $Pr$ : Prandtl number  
 $Re$ : Reynolds number  $T$ : Temperature, K  
 $u$ : Velocity along  $x$ ,  $\text{m}\cdot\text{s}^{-1}$   $U_0$ : Velocity of the free fluid (at the entrance of the channel),  $\text{m}\cdot\text{s}^{-1}$   
 $v$ : Velocity along  $y$ ,  $\text{m}\cdot\text{s}^{-1}$   $x, y$ : Cartesian coordinates, m  
 $X$ : Dimensionless coordinate in the longitudinal direction
- Subscripts:
- $eff$ : Effective value int: Porous substrate/pure liquid interface  
 $l$ : Liquid p: Porous  
 $s$ : Saturation v: Steam (vapeur)  
 $w$ : Wall \* : Dimensionless quantity