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RESEARCH ARTICLE

A SCIENTIFIC STUDY ON EARTHENWARE POTTERY WASTE AND ITS POTENTIAL USE

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ABSTRACT

The present study deals with the problem of transient film condensation on a vertical surface embedded in a thin porous medium with anisotropic permeability filled with pure saturated vapour. The principal axes of anisotropic permeability are oriented in a direction that non-coincident with the gravity force. On the basis of the flow permeability tensor due to the anisotropic properties and the Darcy-Brinkman'sflow model adopted by considering negligible macroscopic and microscopic inertialterms and boundary-layer approximations in the porousliquid film momentumequation, the energyequationissolvedanalyticallyusing the method of characteristics. The previous analyses have been extended to take into account the influence of the time variable which is involved only in the energy equation.Thus, the analytical solution of the governing equations of the problem is obtained and shown that the expressions of the dimensionless thickness of the liquid film and the Nusselt number didn't depend on anisotropic parameters in the transient regime, but the increasing of the anisotropic parameters improved the characteristic limit time of the transition from transient to steady state.

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INTRODUCTION

Most of the works on condensation phenomena have been directed to attack film condensation in a porous medium with Darcy's model in both steady (Cheng (1); Chui et al. (2); Nakayama and Koyama (3); Vovos and Poulikakos (4); Reeken et al. (5)) and transient problems (Cheng and Chui (6); Ebinuma and Nakayama (7); Masoud et al. (8)). Al-Nimr and Alkam (9) have studied steady film condensation on a vertical plate imbedded in a porous medium and have considered the Darcy-Brinkman's model by neglecting the macroscopic and microscopic inertial terms to obtain analytical solutions for the three following requests: liquid film thickness, condensate mass flow rate and convective heat transfer coefficient. In the same way, Masoud et al. (8) have adopted the Brinkman-extended Darcy model to found analytical solutions that describe the transient behaviour of the three latter requests. The current results show the effect of the permeability of the porous material on several issues including the velocity profiles, the film thickness and the time required to reach steady state conditions. Cheng and Chui (6) considered the problem of transient liquid film condensation on a vertical surface in an isotropic porous medium. They used the integral Kärman-Pholhausen method and the characteristics method to deduce the liquid film thickness and the local Nusselt number. In a previous paper, Sanya et al. (10) considered the problem of steady condensation of a liquid film along a vertical surface in a thin porous medium with large anisotropic permeability. The porous medium is assumed to be hydrodynamically anisotropic and the principal directions of the permeability are oriented in a direction that is oblique to the gravity vector. The results found showed that the anisotropic permeability properties have a strong influence on the liquid film thickness, condensate mass flow rate and surface heat transfer rate. In this paper, the problem of transient laminar liquid film condensation on a vertical surface embedded in a thin porous medium with anisotropic permeability, with its principal axes oriented in a direction that is oblique to the gravity vector, based on the classical analysis by Nusselt (11) is presented using the Brinkman-Darcy flow model. With the consideration of the anisotropic permeability, the flow permeability tensor adopted is the same with previous report given by Degan et al (12). The analysis aims to deduce the influence of the permeability anisotropy parameters of the porous medium on the thickness of the liquid film formed along the vertical surface studied, as well as on the heat transfer flow at the surface, for a transient regime.

Mathematical formulation

The physical model adopted is a vertical plate of low thickness (Figure 1), height L and inner surface temperature T_w, which is in direct contact with the porous medium with anisotropic permeability. The coordinate axes (Ox) and (Oy) are aligned respectively with the vertical and horizontal directions. The permeability along the two principal axes of the porous matrix are denoted by K_1 and K_2. The permeability anisotropy of the porous medium is characterised by the permeability ratio $K^* = K_1/K_2$ and the orientation angle φ defined between the horizontal direction and the main permeability axis K_2. Inside this porous medium flows a pure saturated vapour with a saturation temperature T_S higher than the surface temperature T_w. As the vapour flows through the porous medium, condensation of the vapour occurs on the wall leading to the formation of a thin liquid film with a thickness δ_L along the vertical surface. As a result, there are two areas: the porous medium saturated by the liquid film dropping on the wall and the saturated vapour in the rest of the porous space with anisotropic permeability. It is assumed that the porous medium has large permeability. This assumption is valid if the thermal storage of the porous domain is neglected (Masoud et al. [8]). In addition, the following assumptions are assumed as those of Cheng [1], namely that the liquid-vapour interface is quite distinct, the properties of the porous medium are such that those of the liquid film and vapour are constant, and the boundary layer approximations are applicable to the phenomenon near to the vertical surface.

Thus, the governing equations of the problem, in compact form, are deduced, namely the following continuity (1), momentum (2) which is deduced from the work of Sanya et al. [10] and energy (3) equations:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho\vec{V}) = 0 \tag{1}$$

$$\vec{V} = \frac{\bar{\bar{K}}}{\mu}\left(-\vec{\nabla}P + \rho\vec{g} + \mu_e \nabla^2\vec{V}\right) \tag{2}$$

$$\frac{\partial T}{\partial t} + \vec{V}.\vec{\nabla}T = \alpha_c \nabla^2 T \tag{3}$$

Where P is the pressure in the porous medium, ρ the density of the fluid, $\vec{g}$ the gravitational acceleration vector, μ the dynamic viscosity of the fluid, μ_e the effective dynamic viscosity due to the presence of the porous domain, $\vec{V}$ the velocity vector of the fluid in the porous medium, α is the thermal diffusivity of the fluid and $\bar{\bar{K}}$ the second-order permeability tensor defined in the cartesian coordinates by Sanya et al [10] :

The writing of equations (1), (2) and (3) in the region of the liquid film become in primitive form:

$$\frac{\partial u_L}{\partial x} + \frac{\partial v_L}{\partial y} = 0 \tag{4}$$

$$u_L = \frac{C}{A}\frac{sinh\left(\sqrt{A}\delta_L\right)}{cosh\left(\sqrt{A}\delta_L\right)} sinh\left(\sqrt{A}y\right) - \frac{C}{A} cosh\left(\sqrt{A}y\right) + \frac{C}{A} \tag{5}$$

$$\frac{\partial T}{\partial t} + u_L\frac{\partial T}{\partial x} + v_L\frac{\partial T}{\partial y} = \alpha_c\frac{\partial^2 T}{\partial y^2} \tag{6}$$

Where the equation (5) is obtained from the previous study by Sanya et al. [10] and the ratio of the heat capacities and the thermal diffusivity of the liquid in porous medium are defined as follows:

$$\sigma = \frac{(\rho c_p)_c}{(\rho c_p)_L} \text{ and } \alpha_c = \frac{k_c}{(\rho c_p)_L} \tag{7a, b}$$

Where $(\rho c_p)_c$ and k_c are the heat capacity and the thermal conductivity of the fluid-filled porous medium defined by Cheng and Chui [6] as $(\rho c_p)_c = (1-\emptyset)(\rho c_p)_p + \emptyset(\rho c_p)_L$ and $k_c = (1-\emptyset)k_p + \emptyset k_L$ where $\emptyset$ is the porosity and the subscripts « p » and « L » denote the quantities associated with the porous medium and the saturated liquid, respectivily.
The parameters A and C are such that :

$$A = a\frac{\mu_L}{\mu_{L,e}K_1} \quad and \quad C = \frac{g}{\mu_{L,e}}(\rho_v - \rho_L) \tag{8}$$

In addition, the initial and boundary conditions associated with the preceding governing equations are as follows:

- Initial condition: $T(x,y,0) = T_S$ (at $t = 0$) (9)
- Boundary condition at the vertical surface:
- $u_L(0) = 0$ (10a)
- $T(x,0,t) = T_W$; $t > 0$ (10b)
- Boundary condition at liquid-vapour interface:
- $y = \delta_L$: $\frac{\partial u_L(\delta_L)}{\partial y} = 0$ (11a)
- $T(x,\delta_L,t) = T_S$; $t > 0$ (11b)
- $$y = \delta_L: \quad \begin{cases} \dot{m}h_{fg} = k_c\left(\frac{\partial T}{\partial y}\right)_{y=\delta_L} \\ \dot{m} = \frac{\partial}{\partial x}\int_0^{\delta_L}\rho_L u_L dy + \rho_L\frac{\partial \delta_L}{\partial t} \end{cases} \tag{11c}$$

Scale analysis

Based on the work of Bejan [13] and designating as L and δ_L respectively the orders of magnitude on the x and y axes, in the liquid boundary layer region where $\delta_L \ll L$, equations (4), (5) and (6) obey the following orders of magnitude:

$$\frac{u_L}{LRa_L} \sim \frac{v_L}{\delta_L} \tag{12}$$

$$\frac{u_L}{{\delta_L}^2},\ a\frac{\mu_L}{\mu_{L,e}K_1}u_L \sim \frac{g}{\mu_{L,e}}(\rho_v - \rho_L) \tag{13}$$

$$\left(\sigma\frac{\Delta T_L}{t}\delta_L\right),\left(u_L\frac{\Delta T_L}{LRa_L}\delta_L\right),(v_L\Delta T_L) \sim \left(\frac{h_{fg}}{c_{pL}}\frac{u_L}{LRa_L}\delta_L\right),\left(\frac{h_{fg}}{c_{pL}}\frac{\delta_L}{t}\right),\left(\alpha_c\frac{\Delta T_L}{\delta_L}\right) \tag{14}$$

In equation (14), ΔT_L is such that:

$$\Delta T_L = (T_W - T_S) \tag{15}$$

Considering the orders of magnitude of equations (12) to (14), the following results are obtained for δ_L, u_L, v_L and t :

$$\delta_L \sim L \tag{16}$$

$$u_L \sim \frac{\alpha_c}{L}Ra_L \tag{17}$$

$$v_L \sim \frac{\alpha_c}{L} \tag{18}$$

$$t \sim \frac{\sigma L^2}{\alpha_c} \tag{19}$$

The Rayleigh number is defined from equation (17)as :

$$Ra_L = \frac{K_1 g L}{\mu_L \alpha_c}(\rho_L - \rho_v) \tag{20}$$

Taking into account the orders of magnitude LRa_L, L, $\alpha_c Ra_L/L$, α_c/L, ΔT_L, $\sigma L^2/\alpha_c$ respectively for the x and y axes, the x and y components of velocity, temperature and time, the governing equations (4), (5) and (8) take the following dimensionless form:

$$\frac{\partial U_L}{\partial X} + \frac{\partial V_L}{\partial Y} = 0 \tag{21}$$

$$U_L = \frac{1}{a}\{tanh(\beta\Delta_L)sinh(\beta Y) - cosh(\beta Y) + 1\} \quad (22)$$

$$\int_0^{\Delta_L} \frac{\partial\theta_L}{\partial\tau} dY + \int_0^{\Delta_L} \frac{\partial(U_L\theta_L)}{\partial X} dY = \left(\frac{\partial\theta_L}{\partial Y}\right)_{Y=\Delta_L} - \left(\frac{\partial\theta_L}{\partial Y}\right)_{Y=0} \quad (23)$$

Where Δ_L is the dimensionless thickness of the liquid film and β a parameter defined as:

$$\Delta_L = \frac{\delta_L}{L} \quad (24a)$$

$$\beta = L\sqrt{A} \quad (24b)$$

Where :

$$\left(\frac{\partial\theta_L}{\partial Y}\right)_{Y=\Delta_L} = -\frac{1}{Ja}\left\{\frac{\partial}{\partial X}\int_0^{\Delta_L} U_L\, dY + \frac{1}{\sigma}\frac{\partial\Delta_L}{\partial\tau}\right\} \quad (25)$$

Equation (23) can be solved under the following dimensionless boundary conditions:

$$\tau = 0, \quad \theta_L(X, Y, 0) = 0 \quad (26)$$

$$Y = 0, \quad \theta_L(X, 0, \tau) = 1 \quad (27)$$

$$Y = \Delta_L, \quad \theta_L(X, \Delta_L, \tau) = 0 \quad (28)$$

With the following temperature profile that satisfies the boundary condition (26b), defined by Cheng et Chui [6] as:

$$\theta_L(\eta) = 1 - \lambda\eta + (\lambda - 1)\eta^2$$

Where η represents the variable defined as follows:

$$\eta = \frac{Y}{\Delta_L}$$

For the thin porous medium with large anisotropic permeability, when $K_1 \to 0$ (that is to say $A \to \infty$), the equation (22) implies the following equation (29) similar to that obtained for Darcy's model by Degan et al [14] using scale analysis:

$$U_L = \frac{1}{a} \quad (29)$$

Substituting equations (27), (28) and (29) in equation (23), the following equationis obtained:

$$\frac{\lambda}{\Delta_L} = \left[\frac{4-\lambda}{6} + \frac{1}{\sigma Ja}\right]\frac{\partial\Delta_L}{\partial\tau} + \frac{1}{a}\left\{\frac{4-\lambda}{6} + \frac{1}{Ja}\right\}\frac{\partial\Delta_L}{\partial X} \quad (30)$$

Equation (30) can be solved under the following dimensionless boundary conditions:

$$\tau = 0, \quad \Delta_L(X, 0) = 0 \quad (31a)$$

$$\tau \geq 0, \quad \Delta_L(0, \tau) = 0 \quad (31b)$$

Equation **(30)** is a partial differential equation of the hyperbolic type which will be solved by the method of characteristics through the following system of differential equations:

$$\frac{\lambda_2}{\left[\frac{4-\lambda_2}{6} + \frac{1}{\sigma Ja}\right]} d\tau = \Delta_L d\Delta_L = \frac{a\lambda_4}{\left[\frac{4-\lambda_4}{6} + \frac{1}{Ja}\right]} dX \quad (32)$$

The values of λ_2 and $\lambda_4$are given by the parameter λ in the case of steady state and transient regimes respectively. This parameter λ is obtained using equation (25). Equation (32) has the following characteristic:

$$dX = \frac{\lambda_2}{a\lambda_4}\frac{\left[\frac{4-\lambda_4}{6} + \frac{1}{Ja}\right]}{\left[\frac{4-\lambda_2}{6} + \frac{1}{\sigma Ja}\right]} d\tau \quad (33)$$

Parameter Δ_L can then be deduced from the following relationships:

•For transient film condensation:

$$\left[\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right]\Delta_L d\Delta_L=\lambda_2 d\tau \tag{34}$$

•For steady film condensation:

$$\left[\frac{4-\lambda_4}{6}+\frac{1}{Ja}\right]\Delta_L d\Delta_L=a\lambda_4 dX \tag{35}$$

By integrating equation (34) with condition (31a), the equation (36) is obtained in the case of transient regime:

$$\Delta_L=\left\{\frac{2\lambda_2}{\left(\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right)}\right\}^{1/2}\tau^{1/2} \tag{36}$$

Then the final result is as follows:

$$\frac{\delta_L}{x}\sqrt{Ra_{x,L}}=\left\{\frac{2\lambda_2}{\left(\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right)}\right\}^{1/2}\left(\frac{\tau}{X}\right)^{1/2} \tag{37}$$

The parameter λ_2 is determined by introducing equation (35) into (25), and is obtained in the following form similar to that of Cheng and Chui [6]:

$$\lambda_2=\frac{3(\sigma Ja+2)-\sqrt{9(\sigma Ja+2)^2-4\sigma Ja(2\sigma Ja+3)}}{\sigma Ja} \tag{38}$$

Similarly, by solving equation (35) subject to condition (31b), expression (39) is found in steady state:

$$\Delta_L=\left\{\frac{2a\lambda_4}{\left(\frac{4-\lambda_4}{6}+\frac{1}{Ja}\right)}\right\}^{1/2}X^{1/2} \tag{39}$$

This gives, otherwise, the following expression (40):

$$\frac{\delta_L}{x}\sqrt{Ra_{x,L}}=\left\{\frac{2a\lambda_4}{\left(\frac{4-\lambda_4}{6}+\frac{1}{Ja}\right)}\right\}^{1/2} \tag{40}$$

Where the parameter λ_4 is given by expression (41), introducing equation (39) into (25), and is consistent with that of Cheng and Chui[6]:

$$\lambda_4=\frac{3(Ja+2)-\sqrt{9(Ja+2)^2-4Ja(2Ja+3)}}{Ja} \tag{41}$$

Thus, the expression of Δ_L changes according to equations (36) and (39) along the boundary characteristic line given by the equation (42):

$$\tau_C=a\frac{\lambda_4}{\lambda_2}\frac{\left[\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right]}{\left[\frac{4-\lambda_4}{6}+\frac{1}{Ja}\right]}X \tag{42}$$

Equation (42) shows the limit time for the regime to move from the transient case to steady state case. From the expressions obtained for $\delta_L\sqrt{Ra_{x,L}}/x$, the corresponding temperature profile can now be deduced. By using equation (27), (28) and (36), the expression of the heat flux for the transient case can be deduced where $\tau < \tau_C$:

$$q_w = k(T_W - T_S)\,\lambda_2^{1/2}\left\{\frac{\left(\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right)}{2}\right\}^{1/2}\left(\frac{\sigma}{\alpha_c t}\right)^{1/2} \tag{43}$$

The local Nusselt number is given by the formula (46):

$$Nu_x = \frac{q_w\, x}{k(T_W - T_S)} \tag{44}$$

In other words, in the region $\tau < \tau_C$, the local Nusselt number is as follows:

$$\frac{Nu_x}{\sqrt{Ra_{x,L}}} = \lambda_2^{1/2}\left\{\frac{\left(\frac{4-\lambda_2}{6}+\frac{1}{\sigma Ja}\right)}{2}\right\}^{1/2}\left(\frac{\tau}{X}\right)^{-1/2} \tag{45}$$

Similarly, considering equations (27), (28) and (39), the expression of the heat flow for the steady state case can be obtained where $\tau > \tau_C$:

$$q_w = \frac{k(T_W - T_S)}{x}\,\lambda_4^{1/2}\left\{\frac{\left(\frac{4-\lambda_4}{6}+\frac{1}{Ja}\right)}{2a}Ra_{x,L}\right\}^{1/2} \tag{46}$$

Then, the expression (47) can be deduced:

$$\frac{Nu_x}{\sqrt{Ra_{x,L}}} = \lambda_4^{1/2}\left\{\frac{\frac{4-\lambda_4}{6}+\frac{1}{Ja}}{2a}\right\}^{1/2} \tag{47}$$

RESULTS AND DISCUSSION

Figure 2 illustrates the effect of the orientation angle of the main axes on the dimensionless thickness of the liquid film along a vertical surface as a function of time for $K^* = 3.0$, $Ja = 2.0$ and $\sigma = 1.0$. It can be noticed that the dimensionless thickness of the liquid film increases continuously with time in the transient state until it reaches a constant value corresponding to the steady state. This behaviour can be explained by the fact that the adimensional thickness of the liquid film is proportional to $\tau^{1/2}$ when $\tau < \tau_C$ (Eq. (37)) and is independent of time when $\tau > \tau_C$ (Eq. (40)). Another important observation in Figure2 can be made for isotropic properties when $\varphi = 0$ and the result of the dimensionless thickness of the liquid film is the same to that obtained analytically by Cheng and Chui[6]. In addition, the increasing of orientation angle of the main axes implies the increasing of the dimensionless thickness of the liquid film. The same remark can be noticed in Figure 3 illustrating the effect of the orientation angle of the main axes on the dimensionless thickness of the liquid film as a function of time for different values $K^* = 0.5$ and $K^* = 3.0$, for $Ja = 2.0$ and $\sigma = 1.0$. In fact, the dimensionless thickness of the liquid film increases as the orientation angle of the anisotropy permeability porous medium increases for $K^* = 3.0$. On the contrary, when $K^* = 0.5$, the opposite result is observed. It can also be proved when the parameters K^* and φ are held constant respectively to 1.0 and 0, in the equation (5), the velocity of the liquid film in the anisotropic porous medium u_L is the same to that found by Cheng and Chui [6] in the case of isotropic porous medium.

Figure 4 shows the variation of the **heat transfer rate** for different values of the orientation angle of the main axes for $K^* = 0.5$ and $K^* = 3.0$, $Ja = 2.5$ and $\sigma = 1.0$. With regard to the general trend, it can be seen that the local Nusselt number decreases over time, corresponding to the transient period $(\tau < \tau_C)$, and ends up maintaining a constant value from the limit time τ_C at which the steady state begins $(\tau > \tau_C)$. During this steady state, where the time variable no longer has any influence, the **heat transfer rate** decreases as the orientation angle of the main axes increases for $K^* = 3.0$, but increases as the orientation angle of the main axes increases for $K^* = 0.5$. The same behaviour is also observed in Figure 5 for an increase in the ratio of the anisotropic permeability coefficients of the porous medium. Moreover, in the steady regime, the time variable has no influence and the result found is qualitatively similar to that obtained analytically by Degan et al.[14] who have used the Darcy's flow model for the film condensation in the anisotropic permeability porous medium.

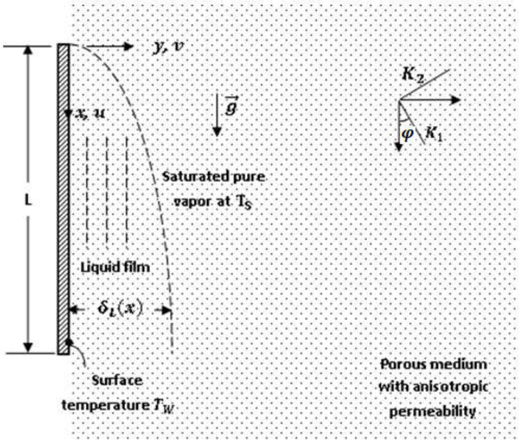

Figure 1. Physical situation and coordinate system

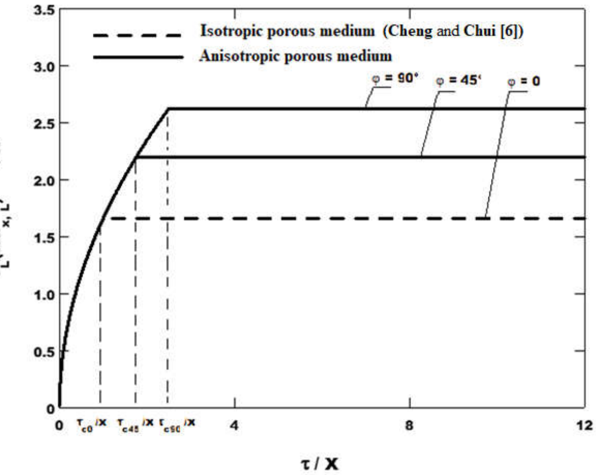

Figure 2. Effect of the orientation angle of the main axes on dimensionlessthickness of the liquid film as a function of time for K^*=3.0, Ja=2.0 and σ=1.0

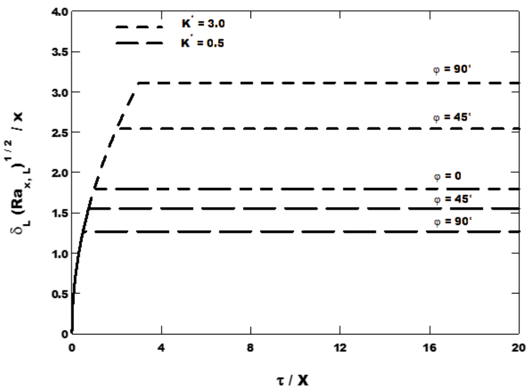

Figure 3. Effect of the orientation angle of the main axes on dimensionlessthickness of the liquid film as a function of time, Ja=2.0 and σ=1.0, for K^*=0.5 and K^*=3.0

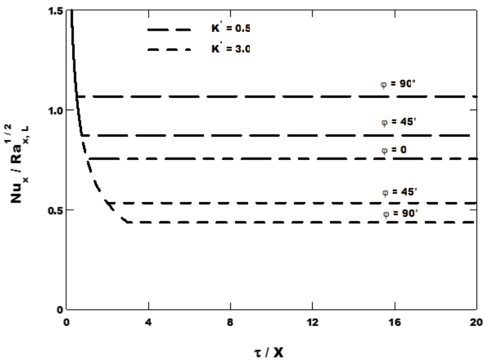

Figure 4. Effect of the orientation angle of the main axes on the local Nusseltnumber⟦Nu⟧_x⁄(⟦Ra⟧_(x,L)^(1⁄2)), Ja=2.5 and σ=1.0, for K^*=3.0 and K^*=0.5

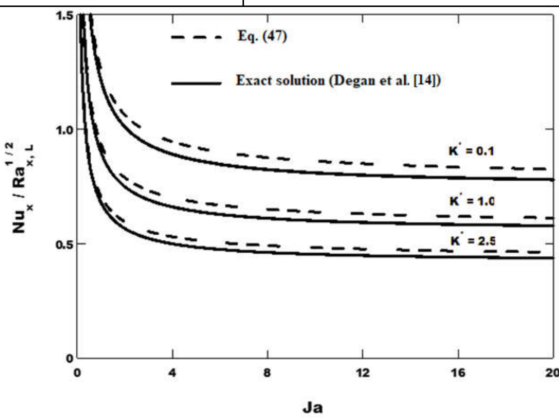

Figure 5 :Effect of the ratio of anisotropicpermeability coefficients of the main axes on the local Nusseltnumber⟦Nu⟧_x⁄(⟦Ra⟧_(x,L)^(1⁄2)) as a function of Jakob number Ja, for φ=45°.

Conclusion

Based on the Darcy-Brinkman's model and the energy equation showing the time variable, the boundary layer equations were formulated. The characteristics method was used to solve the equations in the transient regime and the results obtained lead to the following conclusions: The transient convective flow along a vertical plate bordering an anisotropic porous medium, due to liquid film condensation, has a singularity characterised by the transition that the convective flow undergoes from a regime where instabilities movements in the porous medium prevail to a regime characterised by stationary movements which take place from a limit **time** counted from the initial moment of heating of the surface by the initiation of the condensation phenomena. This time corresponds to the time from which the characteristic quantities of heat and mass transfer suddenly change from the transient one-dimensional conduction regime to a two-dimensional natural convection regime near to the vertical surface where a steady state regime now prevails.

The limiting time to reach the steady state increases with increasing the anisotropy ratio and the orientation angle of the main axes of the porous medium. The dimensionless thickness of the liquid boundary layer shows the same pattern as that obtained for the case of isotropic porous medium in the transient regime by previous work. The **heat transfer rate** depends on the time variable in the transient regime and the anisotropy permeability parameters in the steady state. Finaly, by considering negligible macroscopic and microscopic inertial terms in Darcy-Brinkman's flow model, the results found proved that for the thin porous medium with large anisotropic permeability (when) the Darcy's model can be used suintable for transient regime instead of Darcy-Brinkman's model which seems to be very complex to describe the liquid film condensation flow along the vertical surface.

Nomenclature

a, b, c	Anisotropy constants in permeability
c_P	Specific heat capacity of fluid at constant pressure ($J.kg^{-1}.K^{-1}$)
g	Gravitationalacceleration ($m.s^{-2}$)
Ja	Jakob number
$\overline{\overline{K}}$	Flow permeabilityanisotropictensor
K_1, K_2	Flow permeability along the principal axes x, yrespectivily(m^2)
K^*	Anisotropic permeability ratio, K_1/K_2
k_L	Effective thermal conductivity of the liquidfilmin porous medium ($W.m^{-1}.K^{-1}$)
L	Heightof the verticale surface (m)
Nu_x	Local Nusseltnumber
P	Pressure(Pa)
q	Local heattransfer ratetransmitted to the condensing surface
Ra_L	Rayleigh number
$Ra_{x,L}$	Local Rayleigh number
T	Temperature (K)
t	Time (s)
τ	Dimensionless time
τ_C	Time of the changing flow modefrom transient to steady state
V	Velocity of the liquid film in the porous medium ($m.s^{-1}$)
u_L, v_L	Velocity components in x, y directions ($m.s^{-1}$)
x, y	Cartesian coordinates (m)
Greek symbols	
α_c	Thermal diffusivity of the fluid-filled porous medium ($m^2.s^{-1}$)
δ_L	Liquidfilm thickness (m)
Δ	Dimensionless film thickness
η	Similarity variable
μ	Dynamic viscosity of the fluid ($kg.m^{-1}.s^{-1}$)
λ	Parameter defined in equations (38) and (41)
θ_L	Dimensionlesstemperatureprofile in the liquid film, $(T_L - T_S)/\Delta T_L$
ρ	Density of the fluid ($kg.m^{-3}$)
σ	Heatcapacity ratio, $\sigma = (\rho c_p)_c/(\rho c_p)_L$
φ	Orientation angle of main axes ($^\circ$)
Superscript	
*	Dimensionalquantities
Subscipts	
p	refers to porous medium
L	refers to liquidregion
s	refers tosaturation condition
w	refers to the vertical surface

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