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Key words: surface tension, laminar film condensation, porous medium.

ABSTRACT

The problem of steady filmwise condensation on a finite-size horizontal plate embedded in a porous medium is studied for the case in which a cold plate faces upwards with a dry saturation vapor. Due to the effects of surface tension forces, there is a two-phase zone lying between the liquid film and the vapor zone. As in classical filmwise condensation problems, it is assumed that; (a) the inertia within the liquid film is negligible, and (b) the properties of porous medium, dry vapor, and condensate are constant. A dimensionless parameter Bo_c is introduced to characterize liquid flow due to surface tension forces. The mean Nusselt number \overline{Nu} can be enhanced by increasing the surface tension parameter Bo_c . Without considering the surface tension effects, a closed form correlation for the Nusselt number is also obtained in the present study.

INTRODUCTION

Heat transfer in a porous medium with phase change has received increasing attention due to its wide range of heat transfer applications. For example, the problems of the horizontal two-phase flow in a porous medium involving phase change have important applications in heat pipe design, geothermal energy utilization and thermal enhancement of oil recovery. When there exists a two-phase flow in a porous medium, it is known that Darcy's law is applicable to both the liquid and the vapor phases.

The classical analysis of laminar film condensation on vertical or inclined surfaces was first performed by Nusselt [15]. In that analysis, the condensate film was assumed to be thin; convective and inertial effects were negligible. Within the condensate film, the temperature profile is linear. After the publication of Nusselt's work in 1916, many other researchers had extended the analyses by removing the overly restricted

assumptions [2, 8, 9, 17, 19], a review for these analyses can be found in Merte's work [12]. The earliest attempt to consider the condensation heat transfer rate on a horizontal surface was experimentally done by Popov [16] in 1951. Gerstmann and Griffith [5] then investigated the condensation on the underside of a horizontal plate both theoretically and experimentally. The case of the upper side condensation of a horizontal plate was first studied by Leppert and Nimmo [10] and Nimmo and Leppert [14]. However, they left one point in argument. The film condensation thickness at the plate edge is either assumed or specified by the particular boundary condition. Shigechi *et al.* [18] obtained the condensate thickness and heat transfer results on a horizontal plate by adjusting the inclined angle of the vapor-liquid interface at the plate edge. Yang and Chen [22] used the concept of minimum mechanical energy [1] to search the boundary condition at the horizontal plate edge.

The problem of a downward condensate flowing along a cool vertical or inclined surface in the presence of a porous medium has been extensively studied [3, 4, 6]. Recently, Wang *et al.* [21] reveal that the condensation heat transfer coefficient can be enhanced by increasing values of the wave number and amplitude of the horizontal wavy surface. Most of the previous theoretical investigations do not consider the effect of surface tension forces. In many of these problems, the effective pore radii are small, thereby accentuating the significance of surface tension effects. Udell [20] investigated the heat and mass transfer characteristics of a sand-water-system by including surface tension forces. Majumdar and Tien [11] studied the effect of surface tension on film condensation on a vertical wall.

The problem of laminar film condensation on a horizontal plate in a porous medium is investigated in the present study with the consideration of surface tension effects. In order to achieve the goal of finding the effects of surface tension forces, the present study used the concepts of the thermodynamics of the two-phase zone to analyze the liquid flow driven by the surface tension forces. Beside, the concept of minimum

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mechanical energy is applied to obtain the minimum film thickness at the plate edge. The dimensionless heat transfer coefficient can thus be properly solved for different values of Darcy number Da , Jakob number Ja , effective Rayleigh number Ra , effective Prandtl number Pr_e and the surface tension parameter Bo_c .

ANALYSIS

Consider a finite-size horizontal flat plate with wall temperature T_w embedded in a porous medium filled with a dry vapor. The vapor is pure and at a uniform temperature T_{sat} . If the wall temperature T_w is lower than the saturation temperature T_{sat} , and the liquid wets the plate surface ideally, a film of condensate will be formed on the plate surface. Adjacent to this film, there will be a region where the vapor and the liquid will co-exist to form a two-phase zone. Beyond this region a vapor zone will exist. A schematic diagram of the physical model and coordinate system is shown in Figure 1.

Under steady-state conditions, the liquid film boundary layer will be established with maximum depth existing at the center of plate and gradually decreasing to minimum depth at the plate edge. The analysis of film condensation about a horizontal flat plate in a porous medium with surface tension effects is developed under the following assumptions.

1. The flow is steady and laminar.
2. The inertia within the film is negligible (a creeping film flow is assumed).
3. The wall temperature and vapor temperature are uniform and are kept constant.
4. The kinetic energy of the film flow is negligible.
5. Darcy's law is applicable to the liquid film in the porous medium.
6. The properties of porous medium, dry vapor, and condensate are kept constant.

Under the aforementioned assumptions, the governing equations in the liquid film with boundary layer simplifications are given as

Continuity equation:

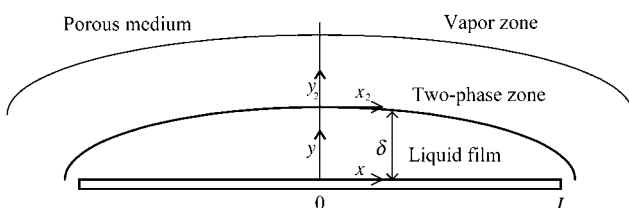


Fig. 1. Condensate film flow on a finite-size horizontal plate with porous medium.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

The momentum equation along x -direction:

$$0 = -\frac{\partial P}{\partial x} - \frac{\mu_e}{K} u \quad (2)$$

The momentum equation along y -direction:

$$0 = -\frac{\partial P}{\partial y} - \rho g \quad (3)$$

Energy equation:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_e \frac{\partial^2 T}{\partial y^2} \quad (4)$$

where K is the intrinsic permeability of the porous medium, u and v are the Darcian velocity components in the x - and y -directions, respectively, P is the pressure of liquid, δ is the liquid film thickness, and μ_e and α_e are the effective dynamic viscosity and the effective thermal diffusivity of a porous medium saturated with liquid, respectively.

The static pressure P can be obtained by integrating Eq. (3) with the use of boundary condition $P = P_{sat}$ at the interface of the two-phase zone with the liquid film ($y = \delta$) gives,

$$P = P_{sat} + \rho g(\delta - y) \quad (5)$$

Substituting Eq. (5) into Eq. (2) yields

$$u = -\frac{\rho g K}{\mu_e} \frac{d\delta}{dx} \quad (6)$$

At the interface of the two-phase zone with the liquid film, the mass continuity equation is given as

$$\left. \frac{\partial u_2}{\partial x} \right|_{y_2=0} + \left. \frac{\partial v_2}{\partial y_2} \right|_{y_2=0} = 0 \quad (7)$$

where subscript 2 represent the properties in the two-phase zone and $y_2 = 0$ corresponds to the interface of the two-phase zone with the liquid film.

At this interface, the no slip condition can be written as

$$u_2|_{y_2=0} = u|_{y=\delta} \quad (8a)$$

or

$$\begin{aligned} \left. \frac{\partial u_2}{\partial x} \right|_{y_2=0} &= \left. \frac{\partial u}{\partial x} \right|_{y=\delta} \\ &= -\frac{\rho g K}{\mu_e} \frac{d^2 \delta}{dx^2} \end{aligned} \quad (8b)$$

Using the concepts of capillary pressure [20], the velocity in the two-phase zone can be written in the following form.

$$u_2 = \frac{K K_{r1}}{\mu_e} \frac{\partial P_c}{\partial x} \quad (9)$$

$$v_2 = \frac{K K_{r1}}{\mu_e} \frac{\partial P_c}{\partial y_2} \quad (10)$$

where

$$K_{r1} = s^3 \quad (11a)$$

$$P_c = \frac{\sigma}{\sqrt{K/\epsilon}} f(s) \quad (11b)$$

$$f(s) = 1.417(1 - s) - 2.120(1 - s)^2 + 1.263(1 - s)^3 \quad (11c)$$

s is the dimensionless saturation and $s = 1$ at $y_2 = 0$ (11d)

Substituting Eqs. (11a)-(11d) into Eq. (10), the capillary suction velocity of the two-phase zone v_2 can be expressed as

$$v_2 = \frac{K}{\mu_e} s^3 \left(\frac{\sigma}{\sqrt{K/\epsilon}} f' \frac{\partial s}{\partial y_2} \right) \quad (12)$$

Substituting Eqs. (8b) and (12) into Eq. (7), Eq. (7) is transformed into the following form.

$$\begin{aligned} & -\frac{\rho g K}{\mu_e} \frac{d^2 \delta}{dx^2} + \frac{K}{\mu_e} \frac{\sigma}{\sqrt{K/\epsilon}} \left[s^3 f'' \left(\frac{\partial s}{\partial y_2} \right)^2 \right. \\ & \left. + 3s^2 f' \left(\frac{\partial s}{\partial y_2} \right)^2 + f' s^3 \frac{\partial^2 s}{\partial y_2^2} \right] \Bigg|_{y_2=0} = 0 \end{aligned} \quad (13)$$

According to the results Majumdar and Tein [11], the saturation profiles near the interface of the two-phase are almost linear. It can be expressed as at

$$\frac{\partial^2 s}{\partial y_2^2} = 0 \text{ at } y_2 = 0 \quad (14)$$

Eq. (13) can thus be written as

$$\frac{\partial s}{\partial y_2} \Bigg|_{y_2=0} = - \sqrt{\frac{-1}{(s^3 f'' + 3s^2 f')}} \frac{\sqrt{K/\epsilon}}{\sigma} \times \rho g \frac{d^2 \delta}{dx^2} \quad (15)$$

Substituting Eq. (15) into Eq. (12), the velocity of the liquid which leaves the liquid film into the two-phase zone via the surface tension forces can thus be solved as follows

$$v_2 \Big|_{y_2=0} = \frac{K}{\mu_e} \left(\left(\frac{s^3 f'}{s^3 f'' + 3s^2 f'} \right) \sqrt{\frac{-\rho g \sigma}{\sqrt{K/\epsilon}} \times \frac{d^2 \delta}{dx^2}} \right) \Bigg|_{y_2=0} \quad (16)$$

Using Nusselt's classical analysis method, the overall energy balance in the liquid film can be written as

$$\begin{aligned} & \frac{d}{dx} \left\{ \int_0^\delta \rho u (h_{fg} + Cp(T_s - T)) dy \right\} dx \\ & + \rho h_{fg} v_2 \Big|_{y_2=0} dx = \frac{k_e \Delta T}{\delta} dx \end{aligned} \quad (17)$$

where k_e is the effective thermal conductivity of a porous medium saturated with liquid.

The right hand side of Eq. (17) represents the energy transfer from liquid film to solid plate, the first term of the left hand side as the net energy flux across the liquid film (from x to $x + dx$), and the second term of the left hand side as the net energy transferred into the two-phase zone. Substituting Eqs. (6) and (16) into Eq. (17), yields

$$\begin{aligned} & \delta \frac{d}{dx} \left(\delta \frac{d\delta}{dx} \right) - \delta \left(\frac{h_{fg}}{h_{fg} + \frac{1}{2} Cp \Delta T} \right) \left(\left(\frac{s^3 f'}{s^3 f'' + 3s^2 f'} \right) \right. \\ & \left. \sqrt{\frac{-\sigma}{\rho g \sqrt{K/\epsilon}} \times \frac{d^2 \delta}{dx^2}} \right) \Bigg|_{y_2=0} \\ & = \frac{-k_e \Delta T \mu_e}{\rho^2 g K \left(h_{fg} + \frac{1}{2} Cp \Delta T \right)} \end{aligned} \quad (18)$$

Eq. (18) can be simplified by defining the following dimensionless parameters

$$Ja = \frac{Cp \Delta T}{h_{fg} + \frac{1}{2} Cp \Delta T} \quad (19a)$$

$$Ra = \frac{\rho^2 g \text{Pr}_e L^3}{\mu_e^2} \quad (19b)$$

$$Pr_e = \frac{\mu_e Cp}{k_e} \tag{19c}$$

$$Da = \frac{K}{L^2} \tag{19d}$$

$$Bo_c = \frac{\sigma\sqrt{\epsilon}}{\rho g K} = \frac{1}{Bo} \tag{19e}$$

The Bo_c number is a ratio of surface tension force and gravity force. If the Bo_c number becomes larger (a smaller Bond number), then the surface tension forces are dominated and hence the contribution of the two-phase zone to the total liquid flow. Eq. (18) can be rewritten as:

$$\delta \frac{d}{dx} \left(\delta \frac{d\delta}{dx} \right) - \delta \left(1 - \frac{1}{2} Ja \right) \left(\frac{s^3 f'}{s^3 f' + 3s^2 f'} \right) \Bigg|_{y_2=0} \times \sqrt{\left(-Bo_c \sqrt{K} \frac{d^2 \delta}{dx^2} \right)} = \frac{-Ja}{Ra_e} \frac{L}{Da} \tag{20}$$

with the following boundary conditions:

$$\frac{d\delta}{dx} = 0 \text{ at } x = 0 \tag{21}$$

$$\delta = \delta_{\min} \text{ at } x = L \tag{22}$$

With these boundary conditions, we still cannot solve Eq. (20), since δ_{\min} is unknown.

Obviously, the film thickness at the plate edge cannot be zero, in fact, it should be established by the application of a minimum mechanical energy principle [1, 22]. The principle states that a fluid flowing across a hydrostatic pressure gradient and off the plate will adjust itself so that the rate of mechanical energy within the fluid will be minimal with respect to the boundary layer at the plate edge. The minimum (critical) thickness can thus be calculated by setting the derivative of mechanical energy with respect to δ equal to zero for the steady flow rate;

$$\left[\frac{\partial}{\partial \delta} \int_0^\delta \left(\frac{u^2}{2} + gy + \frac{P}{\rho} \right) \rho u dy \right] \Bigg|_{m_c} = 0 \tag{23}$$

where m_c is the critical value of mass flow out of the plate edge.

Substituting Eqs. (5) and (6) into Eq. (23) yields the new boundary condition

$$\frac{d\delta}{dx} \Bigg|_L = - \left(\frac{\mu_e^2}{\rho^2 g K^2} \delta_{\min} \right)^{1/2} \tag{24}$$

By introducing the normalized variables of $x^* = x / \sqrt{K}$, $\delta^* = \delta / \sqrt{K}$, for Eq. (20), which can be written as

$$\delta^* \frac{d}{dx^*} \left(\delta^* \frac{d\delta^*}{dx^*} \right) - \left(1 - \frac{1}{2} Ja \right) \left(\frac{s^3 f'}{s^3 f' + 3s^2 f'} \right) \Bigg|_{y_2=0} \times \delta^* \sqrt{\left(-Bo_c \frac{d^2 \delta^*}{dx^{*2}} \right)} = \frac{-Ja}{Ra Da^{3/2}} \tag{25}$$

Eq. (21) becomes at

$$\frac{d\delta^*}{dx^*} = 0 \text{ at } x^* = 0 \tag{26a}$$

and Eq. (24) becomes

$$\frac{d\delta^*}{dx^*} \Bigg|_{x_L^*} = - \left(\frac{Pr_e}{Ra Da^{3/2} \delta_{\min}^*} \right)^{-1/2} \tag{26b}$$

From Eqs. (25) and (11c) and the corresponding boundary conditions Eqs. (26a) and (26b), we can obtain the dimensionless film thickness δ^* in terms of Ja , Ra , Pr_e , Bo_c , and Da .

Eq. (25) is solved numerically by using Runge-Kutta shooting method to obtain the dimensionless liquid film thickness. Since the slope of the dimensionless liquid film thickness is not flat at the plate edge, the progressively finer grid size toward the plate edge is used in the calculations.

The mean Nusselt number is also calculated as

$$\bar{Nu} = \frac{\bar{h}L}{K_e} \tag{27}$$

where

$$\bar{h} = \frac{1}{L} \int_0^L h(x) dx = \frac{1}{L} \int_0^L h \frac{k_e}{\delta} dx = \frac{1}{L} \int_0^{x_L^*} \frac{k_e}{\delta^*} dx^* \tag{28}$$

RESULTS AND DISCUSSION

At first, the effects of surface tension on the film condensation in a porous medium are neglected. In the other words, the surface tension parameter Bo_c is set to zero. Then Eq. (25) becomes

$$\delta^* \frac{d}{dx^*} \left(\delta^* \frac{d\delta^*}{dx^*} \right) = \frac{-Ja}{Ra_e Da^{3/2}} \tag{29}$$

The above equation and its corresponding boundary conditions can be solved by the same numerical procedures mentioned in the previous section, and the resulting δ^* value along x^* -direction can be obtained.

Figure 2 shows that the calculated Nusselt number decreases when Ja/Ra increases. In fact, the relationship is almost linear and can be expressed as

$$\bar{Nu}/(Da^{0.32}Ra^{0.32}Ja^{-0.35}) = 1.231 - 0.02 (Ja / Pr) \tag{30}$$

for $Da < 10^{-2}$ and $Ja/Pr < 0.1$.

The maximum difference between the numerical results and the results of Eq. (30) is less than 2%. Beside, the constraint of $Da = K/L^2 < 10^{-2}$ in the above equation is usually satisfied for common porous materials, because the permeability K of many practically porous materials is at the order of (see Table 1.1 in reference [13] or Table 2.3 in reference [7]). For water vapor condensing on a smooth plate, the value of is much less than 0.1 and is about 0.0025 at one atmosphere. The resulting Nusselt number, Eq. (30), then becomes

$$\bar{Nu} = 1.23 (Da^{0.32}Ra^{0.32}Ja^{-0.35}) \tag{31}$$

Wang *et al.* [21] used a new transformation method to investigate the film condensation on a horizontal wavy plate in a porous medium but without the consideration of surface tension. Table 1 shows the comparison of Wang's results of wave number $n = 0$ (con-

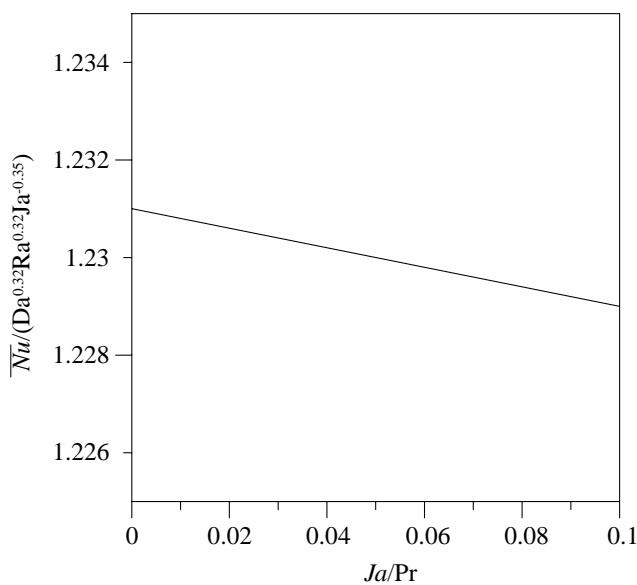


Fig. 2. Dimensionless heat transfer coefficient without surface tension effects.

densation on a flat plate) and the present study. It can be estimated that the maximum difference is lower than 1.6% between the solutions by Wang *et al.* [21] and those by the present study.

Figure 3 shows that the Nusselt number increases upon increasing Bo_c . A special dashed line is added in this figure to distinguish whether the effects of surface tension can be ignored or not. At the left side of the dashed line, the effects of surface tension are small and can be neglected. This is due to the small value of which means that the effect of surface tension is small, so that the Bo_c will be close to the resulting of Eq. (31). But at the right side of the dashed line, it is seen that the values of \bar{Nu} increase with Bo_c at different values of Pr , Da , Ja , and Ra . The physical reason underlying this is that higher values of Bo_c imply stronger surface tension forces, which result more liquid condensate into the two-phase zone. This creates a thinner liquid film and a sharper temperature gradient in the liquid film, which result in a higher heat transfer rate.

Figures 4(a) and 4(b) show the profile distribu-

Table 1. Comparison of the solutions by Wang *et al.* [21] and those by the present study

Parameters	\bar{Nu} (Wang <i>et al.</i>)	\bar{Nu} (Present study)
$Ja = 0.01, Ra = 10^5,$ $Da = 0.01, Pr = 7.$	55.7	56.2
$Ja = 0.1, Ra = 10^5,$ $Da = 0.01, Pr = 7.$	25.5	25.1

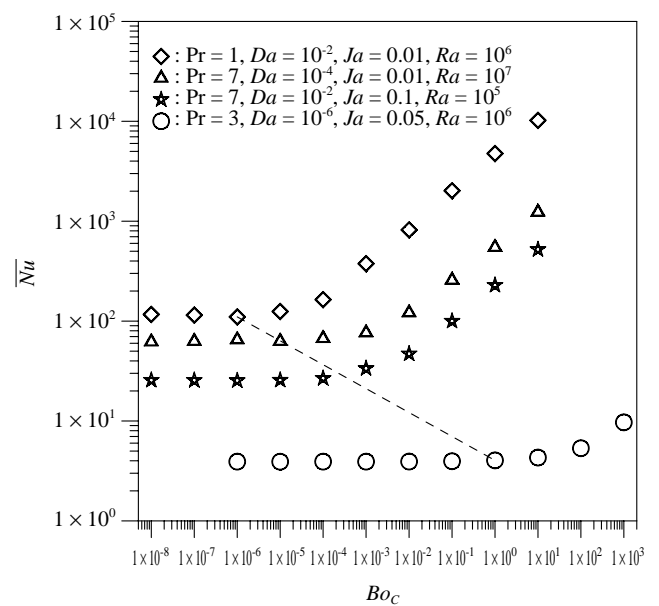


Fig. 3. Dimensionless heat transfer coefficient with surface tension effects.

tions of the dimensionless liquid film thickness ratio δ/δ_0 for $Pr = 0.7, Da = 10^{-4}, Ja = 0.01, Ra = 10^7$ and $Pr = 7, Da = 10^{-2}, Ja = 0.1, Ra = 10^5$, respectively. From these two figures we can see that an increase in Bo_c decreases the dimensionless liquid film thickness ratio δ/δ_0 . Besides, the difference of δ/δ_0 along the plate is the largest at the plate edge ($x^*/x_L^* = 1$) between any two different values of Bo_c . That is because the liquid

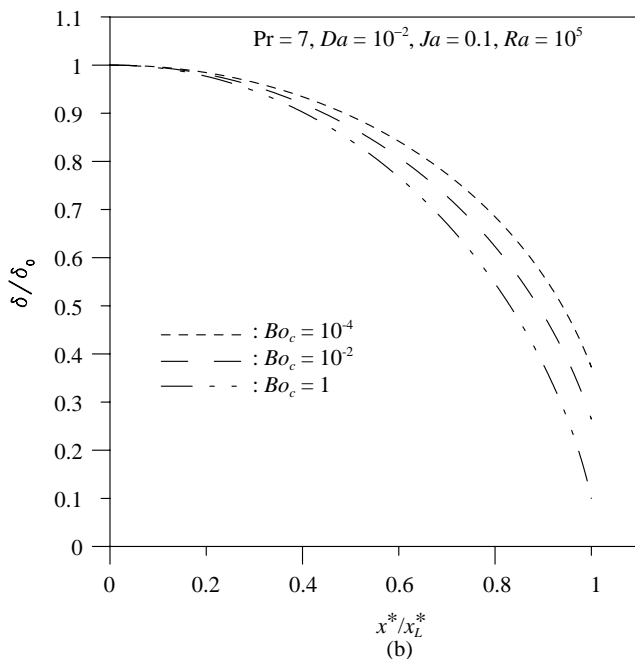
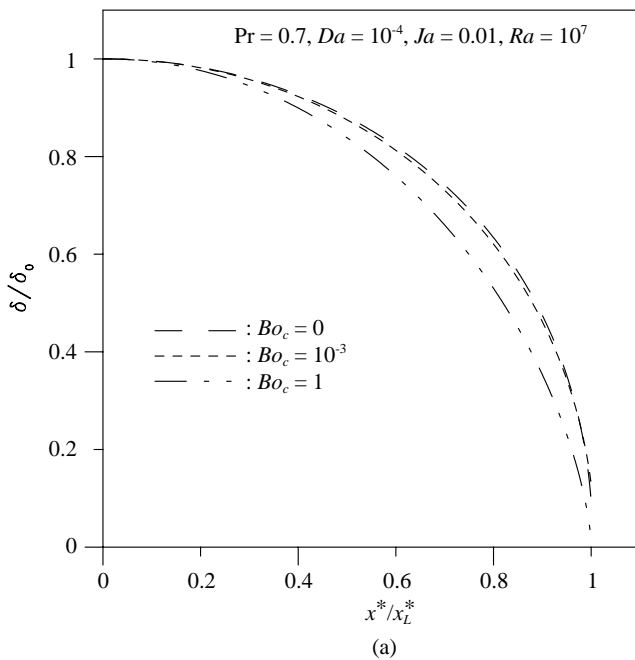


Fig. 4. Dimensionless liquid film thickness ratio for (a) $Pr = 0.7, Da = 10^{-4}, Ja = 0.01, Ra = 10^7$; (b) $Pr = 7, Da = 10^{-2}, Ja = 0.1, Ra = 10^5$.

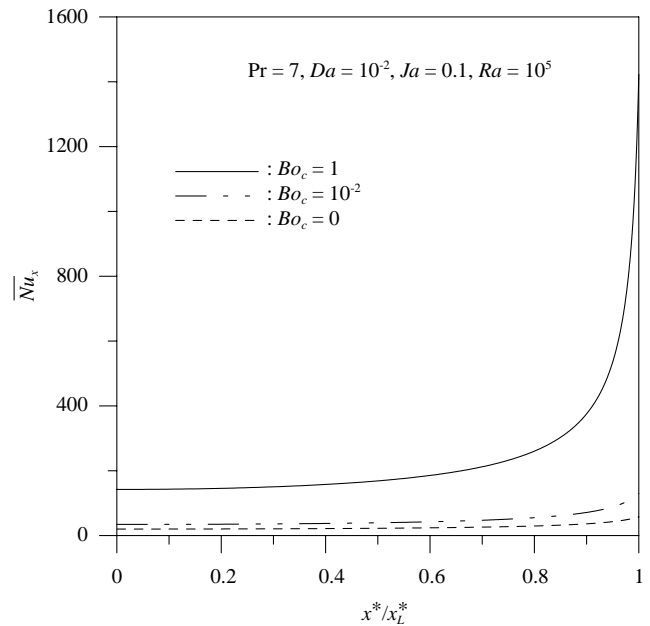


Fig. 5. The local Nusselt number distribution Nu_x with variation of Bo_c .

film thickness is decreased from the plate center to the plate edge. For the purpose of sucking the liquid condensate from the liquid film into the two-phase zone, the effects of surface tension will become relatively larger for a thinner liquid film thickness.

The influence of Bo_c on the local Nusselt number Nu_x for $Pr = 7, Da = 10^{-2}, Ja = 0.1, Ra = 10^5$ is displayed in Figure 5. From this figure, it can be seen that the value of increases from the plate center to the plate edge. That is because the liquid film thickness is decreased from the plate center to the plate edge, so that the local thermal resistance decreases as the liquid film becomes thinner. In addition, from this figure we also can see that the value of Nu_x increases with the increase of Bo_c . On the other hand, the effect of Bo_c on the Nu_x is maximum at the plate edge. The reason is the same as mentioned before since the liquid film thickness is minimum at the plate edge, the effects of surface tension will become larger for a thinner liquid film thickness.

CONCLUSION

The problem of laminar film condensation on a horizontal plate in a porous medium with surface tension effects is performed in the present study. With the presence of surface tension forces, there will be a two-phase zone just above the liquid film. A dimensionless parameter Bo_c is introduced to characterize liquid flow driven by the surface tension forces. The heat transfer performance can thus be enhanced by the capillary

suction of the two-phase zone, and it is observed that a higher value of Bo_c will induce a higher heat transfer performance and a lower liquid film thickness. A closed form correlation for the Nusselt number of the case without the consideration of surface tension forces is also be obtained in the present study.

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NOMENCLATURE

Bo_c	ratio of surface tension and gravity forces defined in Eq. (19e)
C_p	Specific heat at constant pressure
Da	Darcy number defined in Eq. (19d)
g	acceleration of gravity
h	heat transfer coefficient
h_{fg}	heat of vaporization
Ja	Jakob number defined in Eq. (19a)
k	thermal conductivity
K	permeability of the porous medium
L	half of plate width
	condensate mass flux
Nu	Nusselt number defined in Eq. (27)
P	pressure
Pr_e	effective Prandtl number
Ra	effective Rayleigh number
s	dimensionless saturation
T	temperature
ΔT	saturation temperature minus wall temperature
u, v	horizontal and vertical velocity component

Geek symbols

δ	condensate film thickness
δ_0	condensate film thickness at plate center
μ	liquid viscosity
ρ	liquid density
α	thermal diffusivity
σ	surface tension
ε	porosity

Superscripts

-	indicates average quantity
*	indicates dimensionless variable

Subscripts

2	properties in the two-phase zone
o	quantity at plate center
c	capillary
min	minimum quantity or quantity at plate edge
sat	saturation property

w	quantity at wall
e	effective property

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