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Film condensation on horizontal tube with wall suction effects†

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Abstract

This study performs a theoretical investigation into the problem of two-dimensional steady filmwise condensation flow on a horizontal tube with suction effects at the tube surface. An effective suction function is introduced to model the effect of the wall suction on the thickness of the liquid condensate film. The local condensate film thickness and the local Nusselt number are then derived using a simple series numerical method. The results show that the Nusselt number varies as a function of the Jakob number *Ja*, the Rayleigh number *Ra*, and the suction parameter *Sw*. It is found that the wall suction effect has a significant influence on the heat transfer performance. An analytical solution is derived for the mean Nusselt number for the case in which the wall suction effect is ignored. Finally, a closed-form correlation is presented for the mean Nusselt number subject to a wall suction effect.

***Keywords*:** Film condensation; Horizontal tube; Wall suction

1. Introduction

Condensation is a frequently encountered phenomenon in industrial applications and leads to the formation of a liquid layer on the cold surface. Condensation on horizontal tubes has many thermal engineering applications, including heat exchange systems, chemical engineering processes, and so forth.

The problem of laminar film condensation was originally analyzed by Nusselt [1] in 1916. In performing his analysis, Nusselt contended that a local balance existed between the viscous forces and the weight of the condensate film if three basic assumptions were satisfied, namely the condensate film was very thin, the convective and inertial effects were negligible, and the temperature within the condensate layer varied linearly with the film thickness. Since his seminal study, many other researchers have also investigated the laminar film condensation of quiescent vapors and have attempted to refine the original analysis by implementing more realistic assumptions. An excellent review of the related studies is presented by Merte in [2].

In condensation systems, the condensate flows as a result of the combined effects of gravity, vapor shear, pressure and surface tension forces, and may lead to the accumulation of liquid in certain regions of the surface depending on its profile. In practical engineering applications, the problem of laminar condensation is not restricted to vertical surfaces, and thus researchers have explored a variety of condensation systems, particularly those involving the flow of the condensate layer over horizontal cylinders [3]. Dhir and Lienhard [4] proposed a general integral method for predicting the heat transfer coefficient in non-circular cross-section condensation problems. Gaddis [5] used a series expansion method to solve the coupled boundary layer equations for laminar film condensation on a horizontal cylinder. Neglecting the inertial and convective effects in the condensate film, Honda and Fujii [6] formulated the problem of forced flow condensation on a horizontal cylinder as a con-

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jugate heat transfer problem. Yang and Chen [7] investigated the role of surface tension and ellipticity in laminar film condensation on a horizontal elliptical tube. The result showed that the mean heat transfer coefficient obtained using an elliptical tube orientated with its major axis in the vertical direction was greater than that obtained using a simple circular tube. More recently, Hu and Chen [8] analyzed the problem of turbulent film condensation on an inclined elliptical tube. The theoretical results showed that the heat transfer performance of the condensate film could be enhanced by increasing the vapor velocity. Furthermore, for forced-convection turbulent condensation, the use of a circular tube yielded a higher heat transfer coefficient than that obtained using an elliptical tube.

While many previous studies [9-12] have suggested that the heat transfer performance of a condensate film can be enhanced by applying a wall suction effect, the literature lacks a systematic investigation into the characteristics of this effect in condensation on a horizontal tube. Accordingly, the present study conducts a theoretical investigation into the problem of laminar film condensation on a horizontal tube with suction at the wall. The effects of wall suction on the condensate film thickness are modeled using an effective suction function, and analytical expressions are then derived for both the local Nusselt number and the condensate film thickness as a function of the Jakob number, the Rayleigh number and the suction parameter. In addition, an analytical formulation is presented for the mean Nusselt number for the case in which a wall suction effect is assumed not to exist. Finally, a closed-form correlation is derived for the mean Nusselt number subject to a wall suction effect.

2. Analysis

Consider a pure quiescent vapor in a saturated state with a uniform temperature T_{sat} condensing on a horizontal, clean, permeable tube with a radius R and a constant temperature T_w. If the temperature of the saturated vapor is higher than that of the wall, the resulting condensation wets the tube surface ideally and forms a thin condensate layer on the surface of the tube. Under steady-state conditions, the thickness of the liquid film boundary layer, δ, has a minimum value at the top of the tube and increases gradually as the liquid flows downward over the tube surface. Fig. 1 presents a schematic illustration of the physical model and coordinate system, in which the curvilinear coordinates (x, y) are aligned along the tube wall surface and the surface normal, respectively.

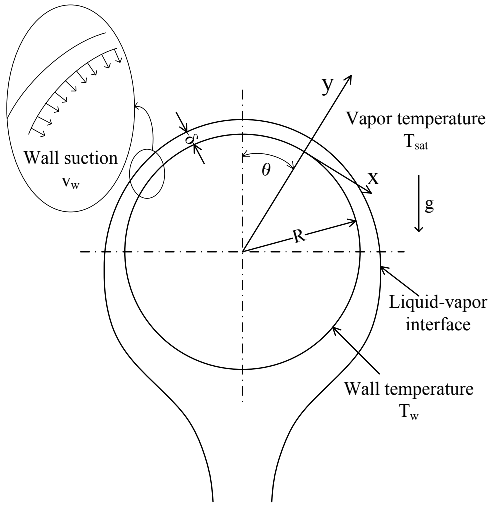

Fig. 1. Schematic illustration of film condensation on horizontal tube with suction at the wall.

In analyzing the heat transfer characteristics of the condensate film, the following analysis adopts the same set of assumptions as those used by Rohsenow in [13]. Consequently, the governing equations for the liquid film subject to boundary layer simplifications are formulated as follows:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equation in x-direction

$$0=\mu\frac{\partial^2 u}{\partial y^2}+(\rho-\rho_v)g\sin\theta \tag{2}$$

Energy equation

$$0=\alpha\frac{\partial^2 T}{\partial y^2} \tag{3}$$

where u and v are the velocity components in the x- and y-directions, respectively, α and μ are the thermal diffusivity and dynamic viscosity of the liquid condensate, respectively, and ρ and ρ_v are the liquid density and vapor density, respectively. The boundary conditions are given as follows:

At the tube surface, i.e. $y = 0$

$$v=v_w \text{ and } T=T_w \tag{4}$$

where v_w is the wall suction velocity.

At the liquid-vapor interface, i.e. $y=\delta$

$$T=T_{sat} \tag{5}$$

Integrating the momentum equation given in Eq. (2) with the boundary conditions given in Eqs. (4) and (5), the velocity distribution equation can be derived as

$$u=\frac{(\rho-\rho_v)g\sin\theta}{\mu}\left(\delta y-\frac{1}{2}y^2\right) \tag{6}$$

Integrating the energy equation given in Eq. (3) with the boundary conditions given in Eqs. (4) and (5) yields the following linear temperature relationship:

$$T=T_w+\Delta T\frac{y}{\delta} \tag{7}$$

where $\Delta T=T_{sat}-T_w$.

According to the first law of thermodynamics, Fourier's conduction law and Nusselt's classical analysis method, an energy balance exists on each element of the liquid film with height δ and width dx:

$$\begin{aligned}&\frac{d}{dx}\left\{\int_0^\delta \rho u\left(h_{fg}+Cp\left(T_{sat}-T\right)\right)dy\right\}dx\\&+\rho\left(h_{fg}+Cp\Delta T\right)v_w dx=k\frac{\partial T}{\partial y}dx,\end{aligned} \tag{8}$$

where k is the effective thermal conductivity of the liquid-saturated porous medium.

The right hand side of Eq. (8) represents the energy transferred from the liquid film to the tube surface. Meanwhile, the first term on the left hand side of the equation expresses the net energy flux across the liquid film (from x to $x+dx$), while the second term expresses the net energy sucked out of the condensate layer by the permeable tube.

Substituting Eqs. (6) and (7) into Eq. (8) and applying the correlation $dx=Rd\theta$ yields

$$\begin{aligned}&\frac{\rho(\rho-\rho_v)g\left(h_{fg}+\frac{3}{8}Cp\Delta T\right)}{3\mu}\frac{d}{Rd\theta}\left\{\delta^3\sin\theta\right\}\\&+\rho\left(h_{fg}+Cp\Delta T\right)v_w=k\frac{\Delta T}{\delta}\end{aligned} \tag{9}$$

For analytical convenience, let the following dimensionless parameters be defined:

$$\begin{aligned}&Ja=\frac{Cp\Delta T}{h_{fg}+\frac{3}{8}Cp\Delta T}\ ,\ Pr=\frac{\mu Cp}{k},\\&Ra=\frac{\rho(\rho\text{-}\rho_v)gPrR^3}{\mu^2}\ ,\ Re_w=\frac{\rho v_w R}{\mu},\\&Sw=\left(1+\frac{5}{8}Ja\right)Re_w\frac{Pr}{Ra}\end{aligned} \tag{10}$$

where R is the tube radius, Ja is the Jakob number, Pr is the Prandtl number, Ra is the Rayleigh number, Re_w is the suction Reynolds number, and Sw is the suction parameter.

Substituting the dimensionless parameters give in Eq. (10) into Eq. (9) yields

$$\delta\frac{d}{d\theta}\left(\delta^3\sin\theta\right)+3SwR^3\delta=3\frac{Ja}{Ra}R^4 \tag{11}$$

Introducing the dimensionless liquid film thickness parameter, $\delta^*=\delta/R$, Eq. (11) can be rewritten as

$$\delta^*\frac{d}{d\theta}\left(\delta^{*3}\sin\theta\right)+3Sw\delta^*=3\frac{Ja}{Ra} \tag{12}$$

Eq. (12) shows that the dimensionless local liquid film thickness, δ^*, depends on the Jakob number Ja, the Rayleigh number Ra, and the suction parameter Sw. The corresponding boundary conditions are given as

$$\frac{d\delta^*}{d\theta}=0 \quad \text{at} \quad \theta=0° \tag{13a}$$

$$\delta^*\big|_{\theta=180°}\to\infty \quad \text{at} \quad \theta=180° \tag{13b}$$

However, even with these boundary conditions, it is difficult to solve δ^* directly since $\delta^*\big|_{\theta=180°}$ does not have a finite value. Thus, an effective suction function, f, is introduced to represent the influence of the wall suction effect on the thickness of the condensate layer:

$$\frac{\delta^*}{\delta^*\big|_{Sw=0}}=1-f \quad \text{or} \quad \delta^*=(1-f)\times\delta^*\big|_{Sw=0} \tag{14}$$

where $\left.\delta^*\right|_{Sw=0}$ is the dimensionless local liquid film thickness in the absence of wall suction, i.e. Sw=0.

For the case of Sw=0 (i.e. f=0), Eq. (12) can be rewritten as

$$\left.\delta^*\right|_{Sw=0}\frac{d}{d\theta}\left(\left(\left.\delta^*\right|_{Sw=0}\right)^3\sin\theta\right)=3\frac{Ja}{Ra} \tag{15}$$

Using the separation of variables method, the analytical solution of the dimensionless local liquid film thickness can be derived as follows:

$$\left.\delta^*\right|_{Sw=0}=\sin^{-1/3}\theta\left(4\int_0^\theta\sin^{1/3}\theta d\theta\right)^{1/4}\left(\frac{Ja}{Ra}\right)^{1/4} \tag{16}$$

The distribution of $\left.\delta^*(\theta)\right|_{Sw=0}$ along the tube surface can be derived by using a simple numerical integration method [14(a)] to calculate the value of $\int_0^\theta\sin^{1/3}\theta d\theta$.

Substituting Eq. (14) into Eq. (12) yields

$$\begin{aligned}&3\left(\left.\delta^*\right|_{Sw=0}\right)^4\sin\theta(1-f)^3\frac{df}{d\theta}+\left.\delta^*\right|_{Sw=0}\\&\frac{d}{d\theta}\left(\left(\left.\delta^*\right|_{Sw=0}\right)^3\sin\theta\right)\left(f^4-4f^3+6f^2-4f\right)\\&+3\left.\delta^*\right|_{Sw=0}(1-f)\times Sw=0\end{aligned} \tag{17}$$

Eq. (17) is a first-order differential equation of the effective suction function f with respect to θ. By setting θ =0, the following polynomial equation with respect to the initial boundary condition, $f(0)$, can be derived:

$$Af^4(0)+Bf^3(0)+Cf^2(0)+Df(0)+E=0 \tag{18}$$

where

$$A=\left(\left.\delta^*(\theta=0)\right|_{Sw=0}\right)^4$$
$$B=-4A$$
$$C=6A$$
$$D=-4A-3\left(\left.\delta^*(\theta=0)\right|_{Sw=0}\right)\times Sw$$
$$E=3\left(\left.\delta^*(\theta=0)\right|_{Sw=0}\right)\times Sw$$

From Eq. (14), it can be seen that although the dimensionless liquid film thickness is reduced as a result of the wall suction effect ($\delta^*\le\left.\delta^*\right|_{Sw=0}$ or $f\ge0$), it cannot attain a negative value($\delta^*\ge0$ or $f\le1$). In other words, $f(0)$ falls within the range $0\le f(0)\le1$. (Note that the exact value of $f(0)$ can be derived using the bisection method [14(b)].)

Substituting the derived value of $f(0)$ into Eq. (17), the variation of f in the θ direction can be calculated using a forward difference shooting method [14(c)].

The dimensionless local liquid film thickness, $\delta^*(\theta)$, can then be derived in accordance with

$$\begin{aligned}\delta^*(\theta)&=(1-f)\times\left.\delta^*\right|_{Sw=0}\\&=(1-f)\sin^{-1/3}\theta\left(4\int_0^\theta\sin^{1/3}\theta d\theta\right)^{1/4}\left(\frac{Ja}{Ra}\right)^{1/4}\end{aligned} \tag{19}$$

Let the local Nusselt number be defined as

$$Nu_\theta=\frac{\mathrm{h}_\theta\mathrm{D}}{\mathrm{k}} \tag{20}$$

where

$$h_\theta=\frac{k}{\delta}$$

Substituting h_θ into Eq. (20), the local Nusselt number can be rewritten as

$$\begin{aligned}Nu_\theta&=\frac{2}{\delta^*(\theta)}\\&=2\left(\frac{Ra}{Ja}\right)^{1/4}\frac{\sin^{1/3}\theta\left(4\int_0^\theta\sin^{1/3}\theta d\theta\right)^{-1/4}}{(1-f)}\end{aligned} \tag{21}$$

Meanwhile, the mean Nusselt number is defined as

$$\begin{aligned}\overline{\mathrm{Nu}}&=\frac{1}{\pi}\int_0^\pi Nu_\theta d\theta\\&=\frac{2}{\pi}\left(\frac{Ra}{Ja}\right)^{1/4}\int_0^\pi\frac{\sin^{1/3}\theta\left(4\int_0^\theta\sin^{1/3}\theta d\theta\right)^{-1/4}}{(1-f)}d\theta\end{aligned} \tag{22}$$

For the particular case of Sw=0, the local Nusselt number can be derived by substituting f=0 into Eq. (21):

$$\left.Nu_\theta\right|_{Sw=0}=2\left(\frac{Ra}{Ja}\right)^{1/4}\sin^{1/3}\theta\left(4\int_0^\theta\sin^{1/3}\theta d\theta\right)^{-1/4} \tag{23}$$

Similarly, the mean Nusselt number for the case of Sw=0 can be derived by substituting f=0 into Eq. (22):

$$\overline{Nu}\Big|_{Sw=0} = \frac{2}{\pi}\left(\frac{Ra}{Ja}\right)^{1/4} \int_0^{\pi} \sin^{1/3}\theta \left(4\int_0^{\theta} \sin^{1/3}\theta d\theta\right)^{-1/4} d\theta \tag{24}$$

3. Results & discussions

For the case where the effects of wall suction are ignored, i.e., the suction Reynolds number Re_w is set to zero, an explicit formulation for the mean Nusselt number can be obtained by solving the integration term $\int_0^{\pi} \sin^{1/3}\theta \left(4\int_0^{\theta} \sin^{1/3}\theta d\theta\right)^{-1/4} d\theta$ in Eq. (24) using a simple numerical integration method [14(a)], yielding

$$\overline{Nu}\Big|_{Sw=0} = 1.224 \times \left(\frac{Ra}{Ja}\right)^{1/4} \tag{25}$$

Yang and Chen [7] used a novel transformation method to investigate the problem of film condensation on a horizontal elliptical tube with no wall suction effect. However, the parameters defined in [7] differ from those used in the current analysis. Thus, to permit a direct comparison to be made between the two sets of results, the formulations presented in [7] must first be reformulated in terms of the current parameters. Having done so, it is found that the formulation for the mean Nusselt number in [7] has the form

$$\overline{Nu} = 1.225 \times \left(\frac{Ra}{Ja}\right)^{1/4} \tag{26}$$

Thus, it is evident that a good agreement exists between the current formulation for the mean Nusselt number in the absence of wall suction effects, i.e. Eq. (25), and that presented by Yang and Chen.

When the effects of wall suction are taken into account, Eqs. (18) and (19) show that the dimensionless liquid film thickness varies as a function of the Jakob number Ja, the Rayleigh number Ra , and the suction parameter Sw. In analyzing the characteristics of the condensation system shown in Fig. 1, the following analyses deliberately choose water-vapor as the working liquid since it is one of the most commonly used working liquids in practical engineering systems. The corresponding dimensional and dimensionless parameter values are summarized in Table 1 (reproduced from [15]).

Table 1. Physical parameters used in present analyses.

Symbol	Interpretation	Typical value
R	radius of tube	0.1 m
Ja	$\dfrac{Cp\Delta T}{h_{fg} + \frac{1}{2}Cp\Delta T}$	0.02
Ra	$\dfrac{\rho^2 g Pr R^3}{\mu^2}$	2×10^{11}

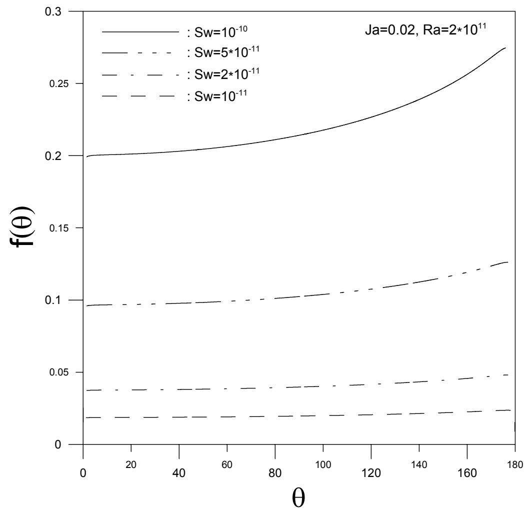

Fig. 2. Variation of f with θ as function of suction parameter Sw.

Fig. 2 illustrates the variation of the effective suction function f with θ as a function of the suction parameter Sw. Note that the remaining parameters are assigned the characteristic values shown in Table 1: Ja=0.02, and Ra=2×10^{11}. As shown, the effective suction function has a positive value and increases with both an increasing value of the suction parameter and an increasing value of θ. Fig. 3 shows the distributions of the dimensionless film thickness and local Nusselt number along the surface of the tube for the same suction parameter values as those considered in Fig. 2. In general, the results show that the dimensionless liquid film thickness decreases, while the local Nusselt number increases, with an increasing value of Sw. Furthermore, it can be seen that the dimensionless film thickness has a minimum value at the top of the tube ($\theta = 0^\circ$) and increases with increasing θ. This result is to be expected since the

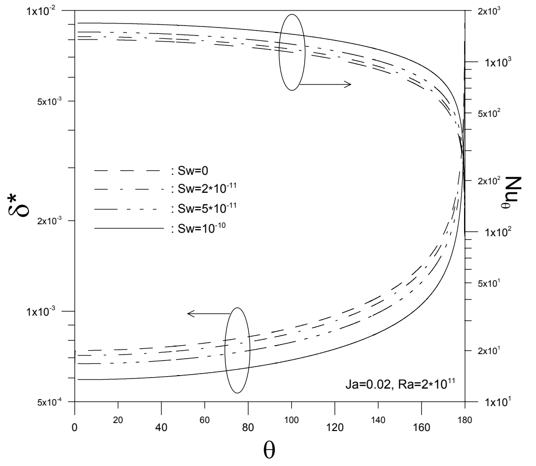

Fig. 3. Variation of δ^* and Nu with θ as function of suction parameter Sw.

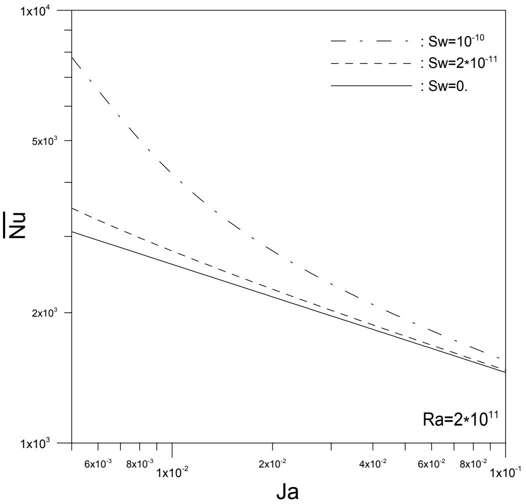

Fig. 4. Variation of $\overline{Nu}$ with Ja as function of suction parameter Sw for constant Ra=2×10^{11}.

current analysis considers the case of falling film condensation, and thus the effects of gravity minimize the film thickness on the upper surface of the horizontal tube (resulting in the maximum Nusselt number), but cause the film thickness to increase toward an infinite value at the lower surface of the tube (resulting in a Nusselt number close to zero).

Eq. (22) indicates that the mean Nusselt number, $\overline{Nu}$, is also a function of Ja, Ra, and Sw. Fig. 4 plots the mean Nusselt number, $\overline{Nu}$, against the Jakob number, Ja, as a function of the suction parameter, Sw, for a constant Rayleigh number of Ra=2×10^{11}. As expected, the results show that the mean Nusselt

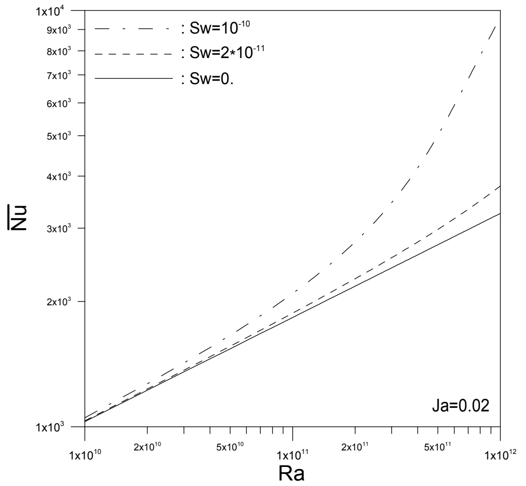

Fig. 5. Variation of $\overline{Nu}$ with Ra as function of suction parameter Sw for constant Ja=0.02.

number decreases with an increasing Jakob number. Furthermore, it is observed that the effect of Sw on the mean Nusselt number becomes more pronounced as the value of Ja is reduced. This result is reasonable since a lower value of Ja indicates a thinner liquid film, which in turn increases the rate at which heat is transferred from the condensate film under the effects of wall suction.

Fig. 5 illustrates the variation of $\overline{Nu}$ with Ra as a function of Sw at a constant value of Ja=0.02. As shown, the mean Nusselt number increases with an increasing Rayleigh number at all values of the suction parameter. From inspection, it is determined that for values of the suction parameter less than Sw=2x10^{-11}, $\overline{Nu}$ and Ra are related approximately linearly via the correlation $\overline{Nu} \propto Ra^{1/4}$. Moreover, it is observed that the wall suction effect becomes more significant with an increasing value of Ra. The physical reason for this is the same as that described above: A higher Rayleigh number indicates a thinner liquid film, and thus an enhanced rate of heat transfer occurs under the effects of wall suction.

The dot-dashed lines in Fig. 6 plot the variation of $\overline{Nu}\left(\frac{Ja}{Ra}\right)^{\frac{1}{4}}$ with Sw for three different values of Ra/Ja. Note that the Y-axis has a logarithmic scale and the dot-dashed lines are obtained from Eq. (22). It is observed that all three lines have an approximately linear characteristic. Applying a curve-fitting technique to the numerical data, the following closed-form correlation for the mean Nusselt number subject to wall suction effects is obtained:

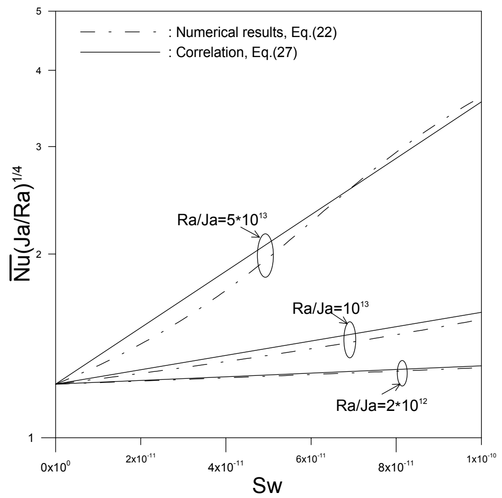

Fig. 6. Comparison of closed-form correlation results and numerical results for variation of $\overline{\text{Nu}}$ with *Sw*.

$$\overline{Nu} = 1.224 \times 10^{n} \times \left(\frac{Ra}{Ja}\right)^{1/4} \tag{27}$$

where n= $0.0105 \times Sw\left(\frac{Ra}{Ja}\right)^{0.85}$

The corresponding results are represented by the solid lines in Fig. 6. From inspection, the maximum difference between the numerical results and the closed-form correlation results is found to be less than 7%.

4. Conclusion

This study has analyzed the problem of laminar film condensation on a horizontal tube with suction at the wall. An effective suction function, f, has been introduced to model the effect of the wall suction on the thickness of the condensate film, thereby allowing both the local condensate film thickness and the local Nusselt number to be derived using simple numerical methods. Three major conclusions are warranted in the present study.

(1) The numerical results have shown that the thickness of the condensate film is reduced with an increasing wall suction effect and therefore gives rise to improved heat transfer performance.

(2) For the case where the wall suction effect is ignored, it has been shown that the analytical solution of the mean Nusselt number is given by $\overline{Nu}\big|_{Sw=0} = \frac{2}{\pi}\left(\frac{Ra}{Ja}\right)^{1/4} \int_0^{\pi} \sin^{1/3}\theta \left(4\int_0^{\theta} \sin^{1/3}\theta d\theta\right)^{-1/4} d\theta$.

(3) A closed-form correlation with the form $\overline{Nu} = 1.224 \times 10^{n} \times \left(\frac{Ra}{Ja}\right)^{1/4}$, where n= $0.0105 \times Sw\left(\frac{Ra}{Ja}\right)^{0.85}$, has been obtained for the mean Nusselt number subject to a wall suction effect.

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Nomenclature

Cp : Specific heat at constant pressure
f : Effective suction function defined in Eq. (13a)
g : Acceleration of gravity
h : Heat transfer coefficient
h_{fg} : Heat of vaporization
Ja : Jakob number defined in Eq. (10)
k : Thermal conductivity
K : Permeability of porous medium
Nu : Nusselt number defined in Eq. (19)
Pr : Prandtl number defined in Eq. (10)
R : Radius of circular tube
Ra : Rayleigh number defined in Eq. (10)
Re_w : Suction Reynolds number defined in Eq. (10)
Sw : Suction parameter. defined in Eq. (10)
T : Temperature
ΔT : Saturation temperature minus wall temperature
u : Velocity component in x-direction
v : Velocity component in y-direction

Greek symbols

δ : Condensate film thickness
μ : Liquid viscosity
ρ : Liquid density
α : Thermal diffusivity
θ : Angle measured from top of tube

Superscripts

$\overline{}$: Average quantity
* : Dimensionless variable

Subscripts

sat : saturation property
w : quantity at wall

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