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Filmwise Condensation from a Flowing Vapor onto Isothermal, Axisymmetric Bodies

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A model is developed for the study of laminar, filmwise condensation from flowing vapors onto isothermal, axisymmetric bodies. The method extends and combines earlier theoretical work, and relies upon earlier experimental studies. However, it is unique in as much as it geometrically generalizes these ideas, and removes a previously imposed assumption. Although the simplifications (in particular the asymptotic shear stress approximation) render the model slightly less accurate than numerical solutions of the coupled two-phase conservation equations, the results appear to be accurate within a few percent, and it is much simpler and easier to apply. A planar geometry (the cylinder in crossflow) is used to verify the analysis, and then it is applied to a cone at a zero angle of attack, and a sphere in a uniform flow. These have not previously appeared in the literature.

Nomenclature

c_p = specific heat at constant pressure, J/kgK
D^* = dimensionless pressure gradient parameter, $\partial S^*/\partial x^*$
G^* = dimensionless gravity component (see Fig. 1), $g(x^*)/g$
Gr_c = modified Grashof number, $\rho(\rho - \rho_v)L^3 g/\mu^2$
g = acceleration due to gravity, m/s²
h = heat transfer coefficient, W/m²K
Ja = Jakob number, $c_p \Delta T/\lambda$
j = mass flux of condensation, kg/m²s
j^* = dimensionless condensate mass flux, $j/\rho U_\infty$
k = thermal conductivity, W/mK
L = characteristic length (see Fig. 1), m
Nu = Nusselt number, hL/k
Pr = Prandtl number, $c_p \mu/k$
R^* = dimensionless axisymmetric radius, $r(x^*)/L$
$\tilde{R}e$ = two-phase Reynolds number, $\rho U_\infty L/\mu$
r = axisymmetric radius (see Fig. 1), m
S^* = dimensionless velocity parameter, $U_{eg}(x^*)/U_\infty$
T = temperature, K
U = velocity within the vapor, m/s
u = streamwise velocity within the condensate layer, m/s
u^* = dimensionless velocity within the condensate layer, u/U_∞
x = streamwise boundary-layer coordinate (see Fig. 1), m
x^* = dimensionless streamwise coordinate, x/L
y = transverse boundary-layer coordinate (see Fig. 1), m
y^* = dimensionless transverse coordinate, $y/L\sqrt{\tilde{R}e}$
γ = density ratio, ρ_v/ρ
ΔT = driving temperature difference $(T_{sat} - T_{sur})$, K
δ = condensate-layer thickness (see Fig. 1), m
δ^* = dimensionless condensate-layer thickness, $\delta/L\sqrt{\tilde{R}e}$
λ = latent heat of condensation, J/kg
μ = dynamic viscosity, Ns/m²
ρ = mass density, kg/m³
τ = shear stress, N/m²

Subscripts

crit = at the x^* position where a singularity occurs
eg = at the edge of the vapor boundary layer
lv = at the liquid vapor interface
sat = at saturation
sur = at the surface
v = in the vapor
∞ = in the freestream

(*Note:* when not subscripted, a property is taken as that of the liquid phase.)

Introduction

CONDENSATION from quiescent pure vapors onto isothermal axisymmetric bodies is often modeled using the analysis of Dhir and Lienhard.[1] This approach is largely based on Nusselt's work,[2,3] which when modified according to Bromley[4] and Rohsenow[5] is appropriate for Pr greater than unity, and Ja less than unity.[6,7] The Dhir and Lienhard model tacitly assumes a zero initial condensate-layer thickness, and this influences heat transfer predictions for some geometries.[8] Furthermore, the model cannot be employed when there is a vapor flow.

Condensation from flowing vapors and the effects of vapor shear have been studied by many investigators.[9–16] This complex situation prompted numerical solution of the coupled conservation equations for two-phase systems.[17–19] In this context, a particularly relevant numerical study was that of Denny and Mills.[20] In that report, the authors applied the asymptotic shear model of Shekriladze and Gomelauri[14] to condensation on a circular cylinder. They developed an explicit solution, and compared the results to numerical solutions of the coupled boundary-layer equations. For that geometry, they demonstrated that the asymptotic shear approximation yields results very close to the boundary-layer solutions (within 1 or 2%). Denny and Mills found that for their conditions, pressure gradient effects were negligible; however, the study was limited to "normal" (terrestrial) gravity. In a more recent study, Rose[21] found that pressure gradient effects can be important during condensation onto circular cylinders, and he developed a simple model to study such effects. Rose's approach has recently found utility in predicting heat transfer from a flowing vapor to circular cylinders.[22] The technique has also been extended for evaluating the effects of saturation state variation during condensation from flowing vapors onto circular cylinders.[23]

The purpose now is to present a generalization and combination of the models of Dhir and Lienhard[1] and Rose.[21]

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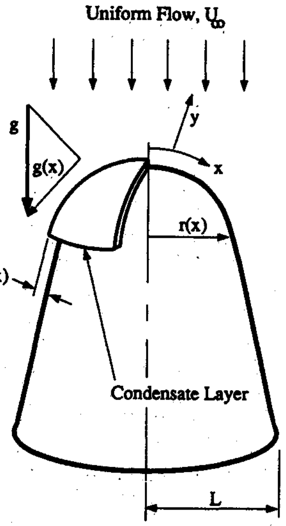

Fig. 1 The physical system.

The extended model will be applicable to condensation from flowing, pure vapors onto axisymmetric bodies. In particular, it will account for pressure gradient and vapor shear effects in a general fashion, accommodate a nonuniform gravitational field, and be amendable to any physically relevant initial condition. After developing the model, it will be applied to two example cases that have not previously appeared in the literature.

Analysis

The physical situation to be analyzed is illustrated in Fig. 1. A saturated pure vapor flows with a freestream velocity U_∞, past an isothermal axisymmetric body. The axisymmetric radius r is taken as a function of the streamwise coordinate x. Although the gravitational field need not be uniform, it is assumed to be symmetrical. If the temperature of the surface of the body T_{sur} is below the saturation temperature T_{sat}, the surface is assumed to be such that a liquid film forms over the entire body. The usual Nusselt assumptions are employed,[1-7] and the conservation equations may be simplified, and written

$$j = \frac{\rho}{r(x)}\frac{d}{dx}\int_0^\delta r(x)u\,dy \tag{1}$$

$$\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) + (\rho - \rho_v)g(x) + \rho_v U_{eg}\frac{dU_{eg}}{dx} = 0 \tag{2}$$

with $u = 0$ at $y = 0$ and $\mu(\partial u/\partial y) = \tau_{lv}$ at $y = \delta$, and

$$j = k\Delta T/\delta\lambda \tag{3}$$

The conservation of mass is given in integral form by Eq. (1). The momentum equation, Eq. (2), reflects a balance of viscous, gravitational, and pressure gradient effects through the first, second, and third terms, respectively. Vapor shear enters the model through a boundary condition imposed upon the momentum equation. The energy equation, Eq. (3), is a balance between the heat release at the liquid/vapor interface through condensation, and that conducted through the condensate layer to the surface of the axisymmetric body.

The boundary condition at the liquid/vapor interface, i.e., the vapor shear, remains to be modeled. This could be accomplished by numerical solution of the two-phase conservation equations; however, the usefulness, simplicity, and generality, of this study would likely be vitiated through such an approach. A good approximation, for high condensation rates, is given by[14]

$$\tau_{lv} = jU_{eg} \tag{4}$$

This approximation has limitations, and other models are available[24,25]; however, Eq. (4) is useful in its simplicity, and is known to yield good results.[20,21]

Before proceeding, it is convenient to introduce a set of dimensionless variables, and transform the governing equations. Equations (1–3) may be rewritten, using the definitions given in the nomenclature and assuming constant thermophysical properties, to yield

$$j^* = \frac{1}{R^*\sqrt{\tilde{R}e}}\frac{d}{dx}\int_0^{\delta^*} R^*u^*\,dy^* \tag{5}$$

$$\frac{\partial^2 u^*}{\partial y^{*2}} + \frac{Gr_c G^*}{\tilde{R}e^2} + \gamma D^* = 0 \tag{6}$$

$u^* = 0$ at $y^* = 0$, $(\partial u^*/\partial y^*) = \sqrt{\tilde{R}e}j^*S^*$ at $y^* = \delta^*$, and

$$j^* = \frac{Ja}{\delta^* Pr\sqrt{\tilde{R}e}} \tag{7}$$

Notice that Eq. (4) has been used to express the boundary condition. R^* is an axisymmetric radius, G^* a gravitational acceleration, S^* a vapor velocity, and D^* is a pressure gradient. These dimensionless parameters are all taken as functions of the dimensionless axisymmetric coordinate x^*, and describe the body shape, gravitational field, and vapor flow. The momentum equation, Eq. (6), may be integrated applying the boundary conditions to yield the general velocity profile within the condensate layer:

$$u^*(x,y^*) = y^*\left(j^*S^*\sqrt{\tilde{R}e} + \frac{Gr_c G^*\delta^*}{\tilde{R}e^2} + \gamma D^*\delta^*\right) - \frac{y^{*2}}{2}\left(\frac{Gr_c G^*}{\tilde{R}e^2} + \gamma D^*\right) \tag{8}$$

This may be substituted into Eq. (5), which is in turn integrated and combined with Eq. (7) to eliminate j^*. The resulting differential equation describes the evolution of the condensate layer. After rearranging and simplifying, it may be written as

$$\frac{d\delta^*}{dx^*} = \frac{1 - \dfrac{R^{*\prime}}{R^*}\dfrac{\delta^{*4}}{3}\left(\Pi_1 G^* + \Pi_2 D^* + \dfrac{3S^*}{2\delta^{*2}}\right) - \dfrac{\delta^{*4}}{3}\left(\Pi_1 G^{*\prime} + \Pi_2 D^{*\prime} + \dfrac{3S^{*\prime}}{2\delta^{*2}}\right)}{\delta^*\left(\Pi_1 G^*\delta^{*2} + \Pi_2 D^*\delta^{*2} + \dfrac{S^*}{2}\right)} \tag{9}$$

where

$$\Pi_1 = \frac{PrGr_c}{Ja\tilde{R}e^2} \quad \text{and} \quad \Pi_2 = \gamma\frac{Pr}{Ja} \tag{10}$$

and the prime denotes a derivative with respect to x^*.

Equation (9) may be subjected to any physically relevant initial condition. The most obvious being either $\delta^* = 0$ or $d\delta^*/dx^* = 0$ at $x^* = 0$. The first condition is easily implemented, whereas implementing the second (symmetry) condition requires solving for the roots of the numerator of Eq. (9) as $x^* \to 0$. The second inital condition will likely be appropriate when $R^*(x^* = 0) = 0$ and $G^*(x^* = 0) = 0$. This may also hold when R^* is a constant approaching infinity (see cylinder example). However, if $R^*(x^* = 0) = 0$ but $G^*(x^* = 0) \neq 0$, or if $R^*(x^* = 0) = A$, where $0 < A < \infty$, then the second condition is likely inapplicable, because the geometry may involve a corner where the condensate layer begins (see cone example).

In terms of heat transfer, interpreting the results of this model is straightforward. Employing the usual idea of a heat transfer coefficient

$$\frac{Nu}{\sqrt{\tilde{R}e}} = \frac{1}{\delta^*} \tag{11}$$

Integrating this over a particular area (and neglecting saturation state variation) yields an average Nusselt number, given by

$$\frac{\overline{Nu}}{\sqrt{\tilde{R}e}} = \frac{\displaystyle\int_{x1}^{x2} \frac{R^*(x^*)}{\delta^*}\,\mathrm{d}x^*}{\displaystyle\int_{x1}^{x2} R^*(x^*)\,\mathrm{d}x^*} \tag{12}$$

The foregoing analytical development assumes that the condensate layer does not separate from the axisymmetric body. However, it is certainly conceivable that separation of the condensate layer may occur in a highly adverse pressure gradient environment. A separation criterion may be established by using Eq. (8) to determine where $\partial u^*/\partial y^* = 0$ @ $y^* = 0$. This yields

$$S^* + \Pi_1 G^*\delta^{*2} + \Pi_2 D^*\delta^{*2} \leq 0 \tag{13}$$

as the condition for separation for the condensate layer.

Another difficulty may occur, because Eq. (9) may exhibit a singularity. This will happen when the denominator of Eq. (9) vanishes, i.e.

$$\frac{S^*}{2} + \Pi_1 G^*\delta^{*2} + \Pi_2 D^*\delta^{*2} = 0 \tag{14}$$

It is obvious that for G^* and $S^* > 0$ the condition of Eq. (14) always occurs prior to condition of Eq. (13), i.e., the singularity is encountered prior to condensate-layer separation.

Verification and Application

Verification: Application to Circular Cylinder

To verify the extension, the model is applied to a planar geometry in a fashion suggested by Dhir and Lienhard.[1] To model such geometries, one considers R^* to be a constant that approaches infinity. If it is further assumed that the vapor flow around the cylinder may be adequately modeled with potential flow theory, then the remaining parameters take the following form:

$$G^* = \sin(x^*) \qquad G^{*\prime} = \cos(x^*) \tag{15}$$

$$S^* = 2\sin(x^*) \qquad S^{*\prime} = 2\cos(x^*) \tag{16}$$

$$D^* = 4\sin(x^*)\cos(x^*) \qquad D^{*\prime} = 4[\cos^2(x^*) - \sin^2(x^*)] \tag{17}$$

Substituting Eqs. (15–17) into Eq. (9) yields

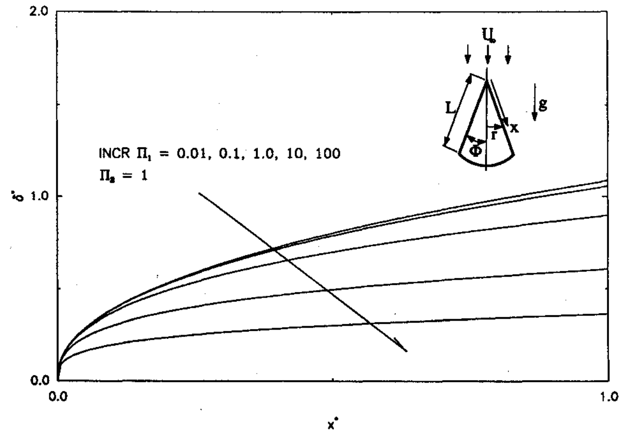

Fig. 2 Condensate-layer behavior on a cone in a uniform flow (Φ = 27.73).

Equation (18) is identical to the model developed by Rose[21] for this problem. Employing the general result offered by Eq. (9) yielded the same result with little effort. Numerically integrating Eq. (18) with a fourth-order Runge-Kutta also yielded the same results as previously published by Rose, along with the previously encountered singularities. However, it is worthwhile to note that on bodies of this type, i.e, where R^* is a constant approaching infinity, the form of Eq. (12) simplifies to

$$\frac{\overline{Nu}}{\sqrt{\tilde{R}e}} = \int_{x1}^{x2} \frac{1}{\delta^*}\,\mathrm{d}x^* \tag{19}$$

Cone at Zero Angle of Attack

The foregoing supports the generalization, and since the physics of this model are successful when applied to the circular cylinder, one has more confidence that they will likewise be appropriate for other geometries. With this in mind, the model is now applied to condensation from a flowing vapor onto a cone at a zero angle of attack. While certainly this case has fewer practical applications, it is possible that such a geometry may find use in pin-fins (where this analysis could serve as a first approximation), or more likely, this geometry may be encountered in flow through a nozzle or diffuser.

The geometry and gravitational field are simple to model for the cone, as shown in Fig. 2. Potential flow solutions are available,[26] and for a given cone half-angle these are employed to model the vapor flow around the cone. For a cone with a half-angle of Φ, the dimensionless geometry, gravity, and flow parameters take the following forms:

$$R^* = x^*\sin(\Phi) \qquad R^{*\prime} = \sin(\Phi) \tag{20}$$

$$G^* = \cos(\Phi) \qquad G^{*\prime} = 0 \tag{21}$$

$$S^* = x^{*n} \qquad S^{*\prime} = nx^{*(n-1)} \tag{22}$$

$$D^* = nx^{*(2n-1)} \qquad D^{*\prime} = (2n^2 - n)x^{*(2n-2)} \tag{23}$$

The velocity parameter n is given as a function of the cone half-angle Φ by White.[26] In the usual way, Eqs. (10–23) are substituted into Eq. (9), which is then numerically solved. However, notice that for this geometry $R^*(x^* = 0) = 0$, but $G^*(x^*)$ = a constant. The numerator of the evolution equa-

$$\frac{\mathrm{d}\delta^*}{\mathrm{d}x^*} = \frac{1 - \dfrac{\delta^{*4}}{3}\left(\Pi_1\cos(x^*) + 4\Pi_2[\cos^2(x^*) - \sin^2(x^*)] + \dfrac{1}{\delta^{*2}}\,3\cos(x^*)\right)}{\delta^{*3}\Pi_1\sin(x^*) + 4\delta^{*3}\Pi_2\cos(x^*)\sin(x^*) + \delta^*\sin(x^*)} \tag{18}$$

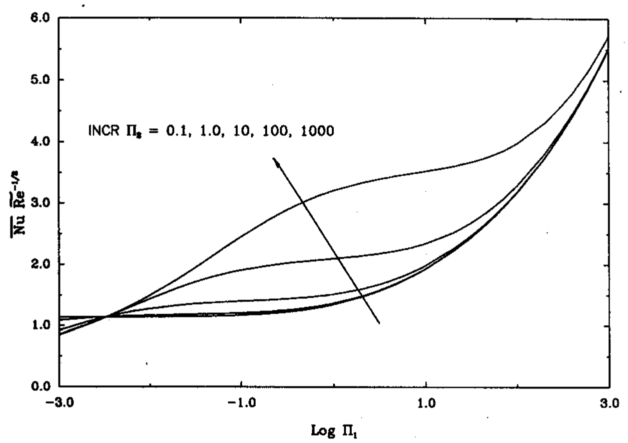

Fig. 3 Average Nusselt number behavior on a cone in a uniform flow.

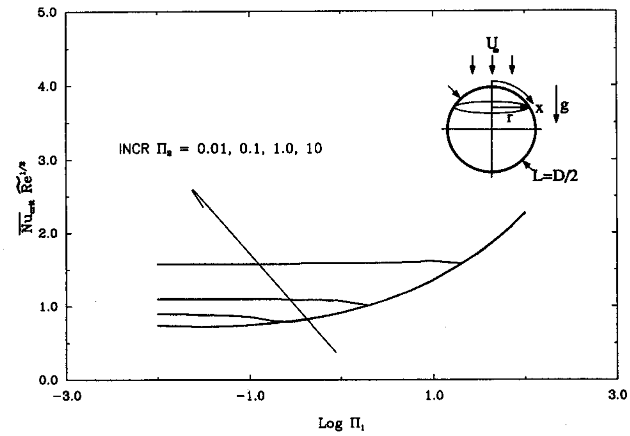

Fig. 4 Average Nusselt number behavior on a sphere in a uniform flow.

tion, Eq. (9), is singular at $x^* = 0$ if δ^* is finite. Therefore, the symmetry initial condition is not applicable (except for the $\Phi = 90$ deg case, i.e., axisymmetric stagnation, where $n = 1$ and $G^*(x^*) = 0$). The zero-condensate-layer-thickness initial condition is used in this case. To start the numerical integration the asymptotic expression for Eq. (9) as $x^* \to 0$ could be employed. This approach takes different forms for different cone geometries. However, it assumes validity of the model as $x^* \to 0$ (which is dubious). Another approach would be to specify a "contact angle," and begin the integration in this fashion. Since $R^* \to 0$ the choice makes very little difference in the average Nusselt number calculation, and in fact starting the integration with any of the methods discussed above produced differences of less than 1% in the final average Nusselt number value for several test cases.

For the geometry of the cone, a critical condition would occur if

$$x^*/2 + \Pi_1\cos(\Phi)\delta^{*2} + \Pi_2 n x^{(2n-1)}\delta^{*2} = 0 \tag{24}$$

This condition will not be met in $x^* > 0$ for cones with $\Phi <$ 90 deg, and predicted condensate-layer thicknesses reflect this for an example 27.73-deg half-angle cone ($n = 0.1$), as shown in Fig. 2. The favorable gravity component and pressure gradient in this flow ensure noncritical behavior of the condensate layer over the entire surface of the cone. The heat transfer results are summarized in Fig. 3. The numerical error was estimated to be less than 0.5%.

Sphere in Uniform Flow

Again, the sphere is not as common in application as the circular cylinder; however, it is used. For example, the Allihn condenser is essentially a series a spheres (of course the vapor flow is not uniform). An application in commercial cooking has been reported,[8] and Dhir has addressed the quiescent sphere.[27]

The case of a sphere in a uniform flow is cast into the form of Eq. (9) by making use of the potential flow solution (see also Fig. 4):

$$R^* = \sin(x^*) \qquad R^{*\prime} = \cos(x^*) \tag{25}$$

$$G^* = \sin(x^*) \qquad G^{*\prime} = \cos(x^*) \tag{26}$$

$$S^* = 3/2\sin(x^*) \qquad S^{*\prime} = 3/2\cos(x^*) \tag{27}$$

$$D^* = 9/4\sin(x^*)\cos(x^*) \quad D^{*\prime} = 9/4\,[\cos^2(x^*) - \sin^2(x^*)] \tag{28}$$

The integration is undertaken as before, but in this case the symmetry initial condition is applied in a straightforward fash-

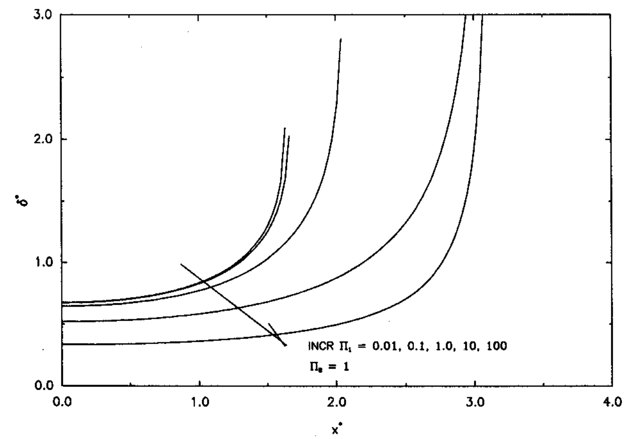

Fig. 5 Predicted condensate-layer behavior on a sphere in a uniform flow.

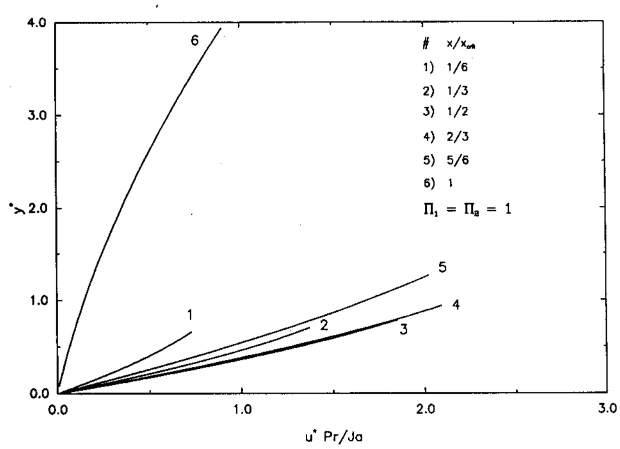

Fig. 6 Condensate-layer velocities on a sphere in a uniform flow.

ion. The heat transfer results are summarized and presented in Fig. 4. The average Nusselt numbers presented in Fig. 4 are based on x^*_{crit}, as the trends are easier to interpret in this fashion.

In this case Eq. (14) takes the form

$$3/4\sin(x^*) + \Pi_1\sin(x^*)\delta^{*2} + 9/4\,\Pi_2\sin(x^*)\cos(x^*) = 0 \tag{29}$$

This may be satisfied in $0 \le x^* \le \pi$, due to the adverse pressure gradient effect, and thus one may expect to encounter a critical position when this occurs. Indeed, such behavior is observed in the typical condensate-layer profiles shown in Fig. 5, and the velocity profiles shown in Fig. 6.

Summary

The model given by Eq. (9) is the result of extending and merging several extant techniques. It offers advantages over previous generalizations through its inclusion of vapor shear and pressure gradient effects, and through its flexibility in applying boundary conditions. Furthermore, as an engineering tool, the model is much easier to apply than numerical solution of the full coupled two-phase conservation equations. However, even with the usual restrictions (outlined previously), this model evidently fails under very high vapor velocity conditions through a premature singularity. Because of this, and due to neglected waviness in the condensate layer, the model should be cautiously applied when $\tilde{Re} > 3\ 10^5$.

Applied to a conical geometry, the analysis revealed a limited range where pressure gradient effects appear to be important. At Π_1 greater than about 1000 pressure gradient effects are unimportant, as one would expect for a low-velocity flow. As the vapor velocity past the cone increases (i.e., decreasing Π_1), there is an increasing sensitivity to pressure gradient, but the trend reverses, and for Π_1 below about 0.01 the heat transfer is again insensitive to the pressure gradient. This behavior is in marked contrast to that observed for the sphere, where the reversals do not occur.

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