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Vaporization of a heated liquid into a saturated stream

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Abstract—Vaporization of a liquid from a heated surface to a saturated nonreactive stream is considered. The surface temperature is sufficiently below the boiling point so that the vaporization rate is controlled by gas-phase transport processes rather than heat transfer. For low free-stream temperature, the vapor diffusing from the surface is found to condense through homogeneous nucleation within the thermal boundary layer. The resultant effects are the thinning of the vapor boundary layer and an enhancement in the vaporization rate. The transport of nucleated particles also contributes to the vaporization process. The important particle transport mechanisms are thermophoresis, Brownian diffusion and eddy diffusion. It is found that these mechanisms act in concert within one portion of the boundary layer and in mutual opposition within another portion. A detailed discussion is provided on the influence of free-stream temperature on the vaporization rate, and boundary-layer profiles of vapor mass fraction, supersaturation ratio, nucleation rate and aerosol density.

1. INTRODUCTION

IN A RECENT paper [1], the problem of mass transfer of a trace species from a superheated stream to a subcooled surface was addressed. Three critical surface temperatures were identified. The first is the saturation temperature (dew point) to which a surface must be cooled before vapor mass transfer can occur. A second temperature, lower than the dew point, is one at which the gas stream becomes supersaturated nowhere except at the surface. There exists a third temperature, lower than the second, corresponding to which a portion of the boundary layer in the vicinity of the surface becomes supersaturated enough to initiate homogeneous nucleation. The ensuing boundary-layer nucleation has a first-order effect on vapor mass transfer. It was found to act as an inhibitor to mass transfer from a turbulent stream but as a promoter if the flow field is laminar. It always decreases the vapor mass fraction and hence the vapor deposition flux. For laminar flow, this is more than compensated by the deposition of nucleated particles with the resultant deposition flux, particle plus vapor, exceeding the value calculated from ignoring boundary-layer nucleation. For turbulent flow, the decrease in vapor deposition flux due to boundary-layer nucleation is not compensated by particle deposition partly because of turbulent diffusion of once-nucleated particles across the particle boundary layer; and because an intermediate temperature range exists in which mass transfer decreases with surface subcooling.

This paper deals with a related problem in which opposite temperature conditions prevail, i.e. the wall is hotter than the gas. Thus, the problem is one of vaporization from a heated surface rather than condensation to a cooled surface as in ref. [1]. The intention of this work is to study the influence of free-stream temperature on the vaporization rate of a liquid held at a constant temperature. Particular interest is in situations in which the vapor diffusing from the surface nucleates within the colder boundary layer. The boundary-layer nucleation causes the vapor mass fraction to decrease locally and the concentration gradient at the surface to increase. It should, therefore, result in enhancement of the vaporization flux. We are interested in determining the magnitude of the enhancement. It is noted that the nucleation tendency increases with lowering of free-stream temperature and leads us to expect that for given T_w, the vaporization rate should increase as T_∞ is lowered. It is mentioned at the outset that the surface temperature is considered to be much below the boiling point so that the heat transfer associated with the vaporization process is small in comparison to that by forced convection. In the situations of interest then the vaporization rate is limited by mass transfer rather than heat transfer.

The problem of vaporization from a heated surface to a cooler gas is encountered in some industrial processes and naturally occurring phenomena. The appearance of fumes over the surface of hot water is perhaps the most common manifestation of boundary-layer nucleation. The fumes are formed when the water vapor leaving the surface condenses (nucleates) in the cooler boundary layer. This situation (hot surface, cold gas) is to be distinguished from fog formation (cold surface, superheated gas) which occurs when a mass of unsaturated air descends upon cold ground, a situation which can be analyzed within the framework of ref. [1]. Another problem of recent interest is in the area of light water reactor safety. It pertains to the potential revaporization of volatile fission products released from breached fuel pins and subsequently deposited on the reactor internal surfaces. The revaporization possibility arises because of the decay heat in fission

NOMENCLATURE

D	diffusivity
J	homogeneous nucleation rate
k	Boltzmann constant
k_g	gas conductivity
MW	molecular weight
n	distribution function
P	pressure
P_v	partial pressure of vapor
P_s	saturation pressure
Pr	Prandtl number
r	particle radius
r^*	critical radius
R	gas constant
S	supersaturation ratio
T	gas temperature
v_{th}	thermophoretic velocity
$\hat{v}$	volume of a condensable molecule
W	flux
y	transverse direction
Y	mass fraction.

Greek symbols

δ	boundary-layer thickness
σ	surface tension
ν	kinematic viscosity
ρ	density
ρ_a	aerosol density
τ	shear stress
δ^*	incompressible displacement thickness.

Subscripts

B	Brownian
l	liquid
p	particle
t	turbulent
v	vapor
w	wall
∞	free stream.

products raising the deposit temperature above that of the gas. It is desired to determine the vaporization rate of the deposited fission products as a function of T_w and T_∞ and how it is influenced by vapor condensation within the boundary layer.

Boundary-layer nucleation inducing enhanced vaporization has been observed experimentally and studied theoretically, see for example refs. [2–4]. The enhancement has been explained mostly on equilibrium arguments or on the basis of specified supersaturation. Only in ref. [4] has attention been paid to the kinetics of the nucleation and particle growth processes. All previous publications have apparently ignored the role of particle diffusion via Brownian motion, thermophoresis or turbulent fluctuations. The objectives of the present work are to clarify the nature of particle diffusion in the vaporization process, and to present a fresh approach to the problem that was used earlier [1] to describe the effect of boundary-layer nucleation on condensation to a subcooled surface.

2. FORMULATION

Consider the convective flow of a nonreactive stream over a heated liquid surface maintained at a constant temperature much below the boiling point at system pressure. The specified surface temperature condition implies that the mass transfer process is one of slow vaporization rather than a rapid boil-off. Furthermore, the effect of mass transfer on fluid mechanics (Stefan flux) and heat transfer is small and may be neglected. It is reasonable then to assume that the unperturbed flow and temperature fields are known *a priori* from classical fluid mechanics. It also follows that under these conditions mass transfer is limited by gas-phase transport processes rather than heat transfer.

Consistent with the heated surface condition, the free-stream temperature is considered to be below T_w. Without loss of generality, the free stream is assumed to be saturated with respect to the vapor of the liquid material. It is easily argued then that since the free stream and surface represent saturation conditions at respective temperatures, in the absence of any heat generation therein, the boundary layer must at least be saturated everywhere. Therefore, should any vapor nucleation occur within the boundary layer, the nuclei formed will be stable. Conditions are favorable for nucleation when $T_\infty \ll T_w$. As T_∞ is decreased, the vapor pressure approaches zero and the vapor diffusing from the wall is likely to attain a high level of supersaturation and undergo homogeneous nucleation.

Two additional assumptions have been invoked during the course of the analysis.

1. Explicit convection terms have been dropped from the conservation equations. The convection effects do enter the problem implicitly through the BL parameters such as δ and temperature profile.
2. The growth of the nucleated particles due to direct vapor condensation has been neglected. This is appropriate because under the specified conditions, $T_w \ll$ boiling point and $T_\infty < T_w$, the vapor should constitute a trace species (i.e. low partial pressure) and the particle growth rate is directly proportional to the partial pressure of the vapor [5].

2.1. *Particle field*

The particles are nucleated from the impurity vapor in the boundary layer. Neglecting convection (assumption 1), the particles are transported because of diffusion and thermophoresis. The resulting particle size distribution function is governed by the following conservation equation [1, 5–8].

$$\frac{\partial}{\partial y}(v_{\mathrm{th}} n) = \frac{\partial}{\partial y}\left(D_{\mathrm{p}}\frac{\partial n}{\partial y}\right) + J\delta(r - r^*). \tag{1}$$

The distribution function $n(r, y)\,\mathrm{d}r$ is defined as the number of particles per unit volume in the size range r and $r + \mathrm{d}r$. The wall boundary condition for n is obtained by requiring that it vanish at the surface because of strong Van der Waal's forces. The free-stream boundary condition for n is arbitrary and for simplicity it is assigned a zero value.

$$n(r, 0) = 0 \tag{2}$$

$$n(r, \delta) = 0. \tag{3}$$

Homogeneous nucleation. According to the classical nucleation theory, the homogeneous nucleation rate is given by the following equation [9].

$$J = \beta(4\pi r^{*2})ZN \exp(-\Delta G/kT) \tag{4}$$

where β, r^*, Z, N and ΔG are, respectively, the collision rate of monomers of the impurity vapor with a flat surface, critical size of the embryo, Zeldovich factor, concentration of the monomers and change in Gibbs free energy due to the formation of the embryos. The critical size is given as a function of the supersaturation ratio ($S = P_{\mathrm{v}}/P_{\mathrm{s}}$) by the Gibbs–Thomson relationship:

$$r^* = \frac{2\sigma\hat{v}}{kT \ln S}. \tag{5}$$

Particle diffusion. In a laminar stream, the particle diffusivity is identical to the Brownian diffusivity (D_{B}) given by the Stokes–Einstein equation [9] after correcting for the slip between the particles and gas molecules when the particle size is of the same order as the mean free path.

$$D_{\mathrm{B}} = \frac{kTCn}{6\pi r\mu}. \tag{6}$$

In a turbulent stream, the effective diffusivity of the particles equals the sum of the Brownian and turbulent diffusivities. For the particle size of interest (less than 10 Å radius), the response frequency of the particles is higher than the frequency of the energy-containing eddies. Thus, the particles can exactly follow the turbulent fluctuations, implying that the turbulent diffusivity of particles should equal the eddy diffusivity. Therefore,

$$D_{\mathrm{p}}(r, y) = D_{\mathrm{B}}(r, y) + v_{\mathrm{t}}(y). \tag{7}$$

Thermophoresis. A particle suspended in a gas with an imposed temperature gradient experiences a thermal force producing motion directed toward lower temperatures. In the free molecular regime the thermophoretic velocity may be expressed as [9]

$$v_{\mathrm{th}} = -0.1436\left(\frac{k_{\mathrm{g}}}{p}\right)\frac{\partial T}{\partial y}. \tag{8}$$

2.2. *Vapor field*

Neglecting the convection terms, the vapor mass fraction is given by the following conservation equation.

$$\frac{\partial}{\partial y}\left(\rho D_{\mathrm{v}}\frac{\partial Y}{\partial y}\right) = \frac{4}{3}\pi\rho_{\mathrm{l}} r^{*3} J. \tag{9}$$

The boundary conditions for Y are:

$$Y(0) = Y_{\mathrm{w}} \tag{10}$$

$$Y(\delta) = Y_{\infty}. \tag{11}$$

To a first approximation, the mass fraction Y_{w} may be simply related to the saturation pressure at the wall temperature

$$Y_{\mathrm{w}} = \frac{P_{\mathrm{s}}(T_{\mathrm{w}})}{P}\left(\frac{MW_{\mathrm{v}}}{MW}\right). \tag{12}$$

For a saturated stream Y_{∞} is similarly related to $P_{\mathrm{s}}(T_{\infty})$.

2.3. *Temperature field*

For the laminar boundary layer, given T_{w}, T_{∞} and δ, the temperature profile is assumed to be cubic.

$$\frac{T - T_{\mathrm{w}}}{T_{\infty} - T_{\mathrm{w}}} = \frac{3}{2}\left(\frac{y}{\delta}\right) - \frac{1}{2}\left(\frac{y}{\delta}\right)^3. \tag{13}$$

For turbulent flow, the temperature and velocity profiles are derived by assuming that the shear stress and heat flux are constant within the boundary-layer. The temperature profile is then given by the following equation [1].

$$\frac{T - T_{\mathrm{w}}}{T_{\infty} - T_{\mathrm{w}}} = \frac{\int_0^y \mathrm{d}y/(v/Pr + v_{\mathrm{t}}/Pr_{\mathrm{t}})}{\int_0^\delta \mathrm{d}y/(v/Pr + v_{\mathrm{t}}/Pr_{\mathrm{t}})}. \tag{14}$$

The turbulent eddy viscosity is evaluated from the Van Driest model [10]. Reference [1] should be consulted for more details concerning v_{t}, Pr_{t}, and turbulent boundary-layer thickness.

3. SOLUTION

The neglect of particle growth rate simplifies the solution by decoupling the vapor field from the particle field. It permits one to solve for the vapor field first and use that information to determine the particle field.

3.1. *Vapor field*

A closed-form solution for the vapor mass fraction can be derived by twice integrating equation (9)

$$Y = Y_{\mathrm{w}} + W_{\mathrm{v}}(0)\int_0^y \frac{\mathrm{d}\xi}{\rho D_{\mathrm{v}}} + \int_0^y \frac{\mathrm{d}\xi}{\rho D_{\mathrm{v}}}\int_0^\xi \frac{4}{3}\pi r^{*3}\rho_{\mathrm{l}} J\,\mathrm{d}\eta. \tag{15}$$

Equation (15) requires an iterative solution because $W_v(0)$, the vapor flux at the wall, is not known *a priori*. A simple iteration scheme based on binary search has been found to be convenient and convergent. It consists of obtaining an initial estimate for $W_v(0)$ from equation (15) by neglecting the nucleation term. This always represents an underestimate since the effect of boundary-layer nucleation is to enhance the vaporization flux. In order to bracket the solution, the second guess for $W_v(0)$ should be on the high side (overestimate) and is obtained by multiplying the first estimate by a factor, say 10. Once the solution is bracketed, the interval between the two estimates is successively halved while keeping the solution bracketed. The solution converges within 30 iterations and to any level of desired accuracy. A converged solution is obtained when the difference between $Y(\delta)$ calculated from equation (15) and given Y_∞ becomes less than the specified tolerance.

3.2. *Particle field*

Equation (1) may be integrated twice to obtain the distribution function.

$$n(r, y) = \frac{N_p(0)\displaystyle\int_0^y \frac{I(\xi)}{D_p}\,\mathrm{d}\xi - \int_0^y \frac{I(\xi)}{D_p}\left[\int_0^\xi J\delta(r-r^*)\,\mathrm{d}\eta\right]\mathrm{d}\xi}{I(y)} \tag{16}$$

where

$$N_p(0) = \left(D_p \frac{\partial n}{\partial y}\right)_w \tag{17}$$

and

$$I(y) = \exp\left[-\int_0^y \frac{v_{th}}{D_p}\,\mathrm{d}\eta\right]. \tag{18}$$

The wall flux $N_p(0)$ may be calculated by applying the boundary condition of equation (2) to equation (16)

$$N_p(0) = \frac{\displaystyle\int_0^\delta \frac{I(\xi)}{D_p}\left[\int_0^\xi J\delta(r-r^*)\,\mathrm{d}\eta\right]\mathrm{d}\xi}{\displaystyle\int_0^\delta \frac{I(\xi)}{D_p}\,\mathrm{d}\xi}. \tag{19}$$

In order to calculate the total particulate flux at the wall, one has to integrate the product of N_p and particle mass over the particle size spectrum

$$W_p(0) = \int_0^\infty \frac{4}{3}\pi r^3 \rho_l N_p(0)\,\mathrm{d}r. \tag{20}$$

A concise expression for $W_p(0)$ can be constructed by defining an average diffusivity $(\bar{D}_p)$.

$$W_p(0) = \frac{\displaystyle\int_0^\delta \frac{\bar{I}(\xi)}{\bar{D}_p}\left[\int_0^\xi \frac{4}{3}\pi r^{*3}\rho_l J\,\mathrm{d}\eta\right]\mathrm{d}\xi}{\displaystyle\int_0^\delta \frac{\bar{I}(\xi)}{\bar{D}_p}\,\mathrm{d}\xi} \tag{21}$$

where $\bar{I}(y)$ is given by equation (18) with D_p replaced by $\bar{D}_p$.

One can define an aerosol density ρ_a as

$$\rho_a(y) = \int_0^\infty \frac{4}{3}\pi r^3 \rho_l n(r, y)\,\mathrm{d}r. \tag{22}$$

Again, a concise expression for the aerosol density can be obtained by substituting equation (16) into equation (22) and using $\bar{D}_p$

$$\rho_a(y) = \frac{W_p(0)\displaystyle\int_0^y \frac{\bar{I}(\xi)}{\bar{D}_p}\,\mathrm{d}\xi - \int_0^y \frac{\bar{I}(\xi)}{\bar{D}_p}\left[\int_0^\xi \frac{4}{3}\pi r^{*3}\rho_l J\,\mathrm{d}\eta\right]\mathrm{d}\xi}{\bar{I}(y)}. \tag{23}$$

As noted earlier, one first determines the vapor field and hence the variation of the nucleation rate, J, and the critical size, r^*, in the boundary layer. Then, by a simple integration the aerosol density can be computed from equation (23) and the particulate flux at wall from equation (20). Finally, the total vaporization flux is obtained as sum of $W_v(0)$ and $W_p(0)$.

4. RESULTS AND DISCUSSION

Illustrative calculations have been performed for vaporization of CsI into a saturated stream. Steam is assumed to be the gaseous medium whose density is approximated by equation of state for ideal gases, viscosity by Sutherland's equation, and thermal conductivity as directly proportional to the gas temperature. The product of gas density and molecular diffusivity is taken as constant (4.17×10^{-5} kg m^{-1} s^{-1}), and the liquid density as 4150 kg m^{-3}. The free-stream velocity and temperature are 5 m s^{-1} and 1000 K, respectively, and the pressure is atmospheric. The nominal boundary-layer thickness is 1 cm for laminar flow calculations and 5 cm for the turbulent flow. The corresponding Reynolds numbers based on boundary-layer thickness and free-stream conditions are 332 and 1660, respectively.

4.1. *Laminar flow*

Figure 1 illustrates the influence of free-stream temperature on the vaporization flux. As plotted, a

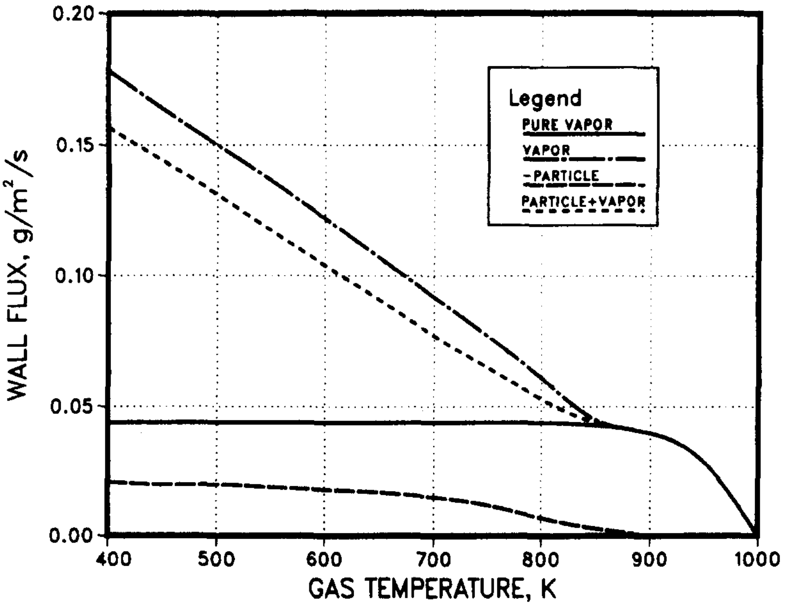

FIG. 1. Variation of vaporization flux with gas temperature in laminar flow.

positive value of wall flux refers to the vaporization process. The pure vaporization flux (W_{vp}), obtained from neglecting the boundary-layer nucleation, is also shown for reference, and is given by the following equation

$$W_{vp} = (Y_\infty - Y_w) \Big/ \int_0^\delta d\xi/\rho D_v. \qquad (24)$$

As the free-stream temperature is decreased, Y_∞ becomes vanishingly small and, since the product ρD_v is a constant, W_{vp} asymptotically approaches the limit $-\rho D_v Y_w/\delta$. The limiting value is attained in Fig. 1 for $T_\infty < 800$ K.

Inclusion of boundary-layer nucleation changes the vaporization behavior markedly. The vaporization flux, $W_v(0)$, is not observed to approach any asymptotic value; instead, it increases monotonically as T_∞ is lowered. At $T_\infty = 400$ K, $W_v(0)$ is more than four times larger than W_{vp}. The point at which W_v and W_{vp} first deviate, 850 K in Fig. 1, represents the critical gas temperature for onset of boundary-layer nucleation.

The contribution of particle diffusion to the vaporization process can also be ascertained from Fig. 1. Note the negative sign in front of the 'particle' label in the legend implies that the nucleated particles are diffusing towards rather than away from the wall. Since the gas is colder than the wall, the thermophoretic velocity is positive (directed away from the wall) and has a blowing effect. On the other hand, since the wall was treated as perfectly absorbing, $n(r, 0) = 0$, the Brownian diffusion has a suction effect, i.e. draws the particles to the wall. Thus, thermophoresis opposes Brownian diffusion. The net particle flux at the wall, $W_p(0)$, has to be suction-like because the particle source (the nucleation process) is not at the wall but in the boundary layer. As T_∞ is reduced, thermophoretic velocity increases but so does the particle production rate (J). The result is that $W_p(0)$ initially increases in magnitude as T_∞ is reduced from 900 to 500 K and then becomes independent of T_∞.

The opposite signs of $W_p(0)$ and $W_v(0)$ imply that particle diffusion diminishes the net vaporization rate, $W_p(0)+W_v(0)$. The overall effect of boundary-layer nucleation, however, is to enhance the vaporization process, as is clearly evident in Fig. 1.

Figure 2 exhibits the influence of gas temperature on the boundary-layer variation of vapor mass fraction. As T_∞ is reduced, the nucleation rate increases causing local depression in vapor mass fraction. For fixed Y_w then, the gradient of Y in the near-wall region increases resulting in the observed enhancement of the vaporization rate. It may also be noted that the gradient at the edge of the boundary layer decreases with reduction in T_∞. Since the flux is proportional to the gradient of Y, the vapor flux out of the boundary layer must also decrease with reduction in T_∞. Now, with convection neglected, the sum of W_v and W_p is constant everywhere. Therefore, the reduction in vapor flux at $y = \delta$ must be accompanied with concomitant increase in particle flux. Thus, as T_∞ is reduced, boundary-layer nucleation enhances the vaporization flux above the asymptotic limit of equation (32), and the mode of transport at $y = \delta$ changes from one of vapor diffusion to particle diffusion.

In formulating the model, it was assumed that the mass, momentum and diffusion boundary-layer thicknesses are equal and given. This assumption may have to be scrutinized in view of the source (nucleation) term present in the vapor conservation equation. The indication from Fig. 2 is that nucleation causes thinning of the vapor boundary layer.

Figure 3 depicts the variation of aerosol density in the

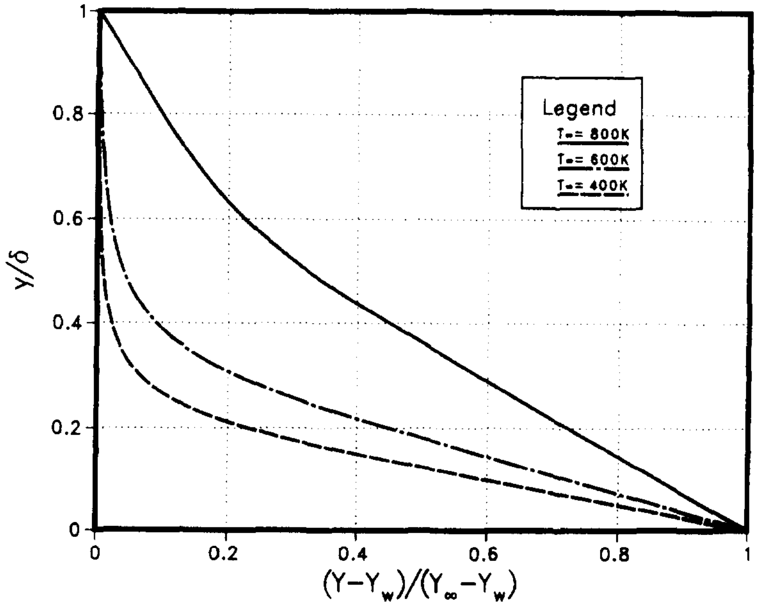

FIG. 2. Effect of boundary-layer nucleation on the mass fraction profile of condensible vapor in laminar flow.

boundary layer. Because of the boundary conditions imposed on n, zero at the two ends of the boundary layer, aerosol density displays a maxima whose magnitude increases with reduction in T_∞ and the location (y_{max}) shifts upwards. For $y > y_{max}$, thermophoresis and Brownian diffusion act in concert. For $y < y_{max}$, the two mechanisms oppose each other. For very small $y < y_c$, Brownian diffusion dominates over thermophoresis and the net particle flux is towards the wall. In the rest of the boundary layer, the net particle flux is directed away from the wall. Finally, in the region $y_c < y < y_{max}$, thermophoresis dominates over Brownian diffusion.

Figure 4 shows the variation in the supersaturation ratio of CsI vapor. In general, the lower the T_∞, the higher the supersaturation level. The extremely high level of S attained near $y = \delta$ for $T_\infty = 400$ K is inconsequential because of the associated small partial pressure. Note that at trace concentrations, very high levels of supersaturation can be maintained without spontaneous nucleation.

Figure 5 depicts the boundary-layer variation in the

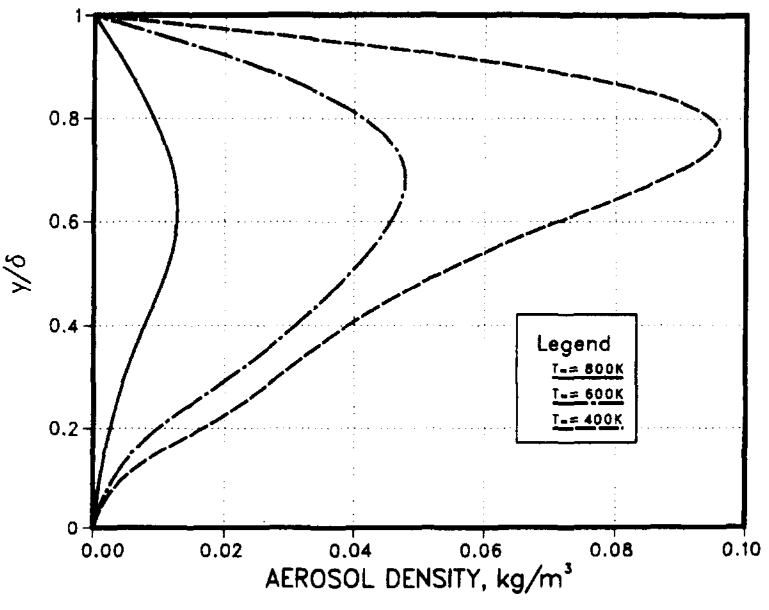

FIG. 3. Aerosol density profile across the laminar boundary layer.

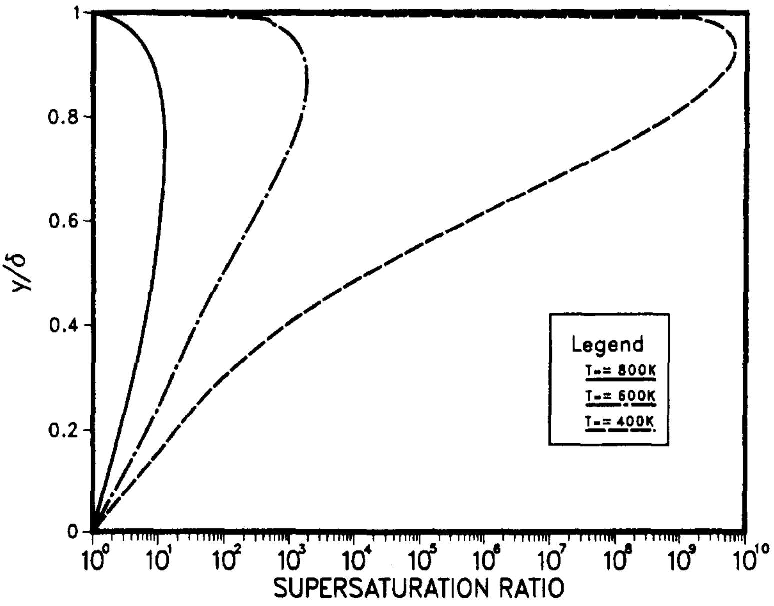

FIG. 4. Variation of supersaturation ratio across the laminar boundary layer.

mass nucleation rate defined as $4/3\pi r^{*3}\rho_l J$. As expected, it bears an inverse relationship with T_∞. It also exhibits a peak in the boundary layer whose magnitude increases with reduction in T_∞ and the location shifts closer to the wall. The area under the curve and the y axis represents the total condensation rate in the boundary layer. For $T_\infty = 800$ K, this area represents a fraction of the total amount vaporized from the surface. On the other hand, for $T_\infty = 400$ K the area nearly corresponds to the total vaporization rate. Note that the nucleation rate in the vicinity of $y = \delta$ is vanishingly small in spite of the extremely large value of S in that region, Fig. 4. It is interesting to observe the existence of a negative correlation between the locations of peaks in nucleation rate and the aerosol density. As T_∞ is lowered, the former shifts towards the wall whereas the latter displays the opposite trend, even though the nucleation term constitutes the only source for the population equation. This behavior is ascribed in part to the thermophoretic velocity, which is directly proportional to $T_w - T_\infty$, driving the particles out of the boundary layer. It may also be an artifact of the arbitrarily prescribed edge boundary condition for n. The implicit assumption concerning the equality of

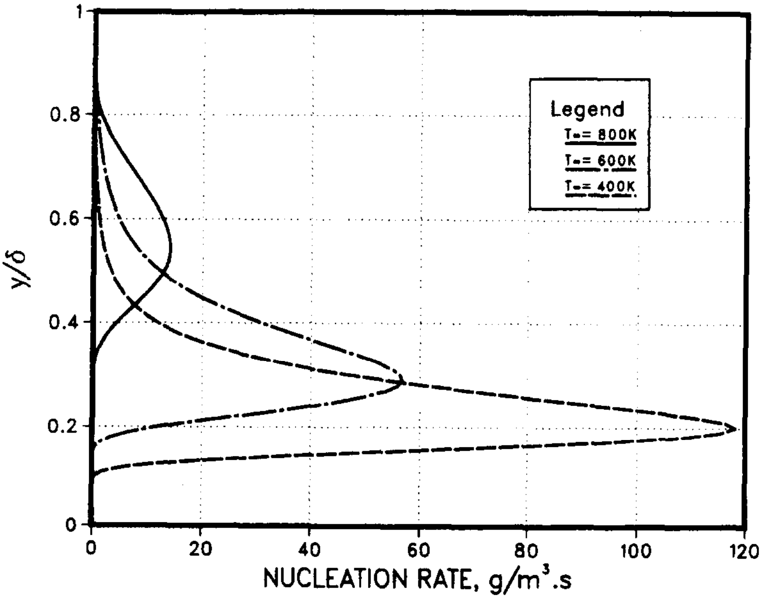

FIG. 5. Effect of gas temperature on the nucleation rate within the laminar boundary layer.

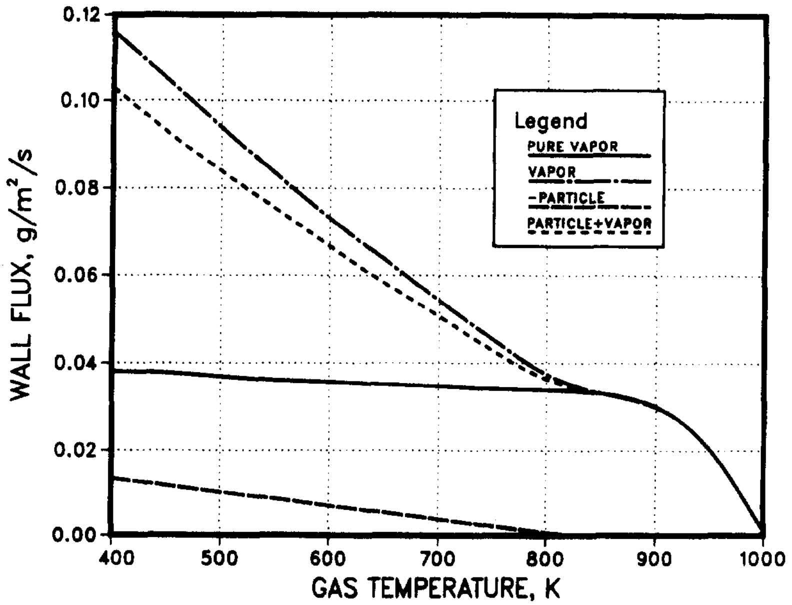

FIG. 6. Variation of vaporization flux with gas temperature in turbulent flow.

particle and vapor boundary layers must also be questioned. The issue can only be resolved with a proper inclusion of the convection terms. But, we stress that so long as particle growth is neglected, the vaporization rate is independent of the particle behavior.

4.2. *Turbulent flow*

For turbulent flow, all properties (ρ, D_v, D_B, k_g, μ) have been calculated at a reference temperature defined as [11]

$$T_{ref} = 0.28T_\infty + 0.72T_w.$$

Figure 6 shows the influence of gas temperature on the vaporization flux. The results resemble their laminar counterparts but for two reservations. First, the pure vaporization flux is not a true constant at low gas temperature. This is because of the temperature dependence of the physical properties. Second, the particle arrival rate, $W_p(0)$, at the wall varies almost linearly with T_∞ without approaching any asymptotic limit. As in laminar case, boundary-layer nucleation bears a profound influence on the vaporization rate enhancing it by more than 100% at $T_\infty = 400$ K. Also, the effect of particle diffusion to the wall is to mitigate the vaporization flux.

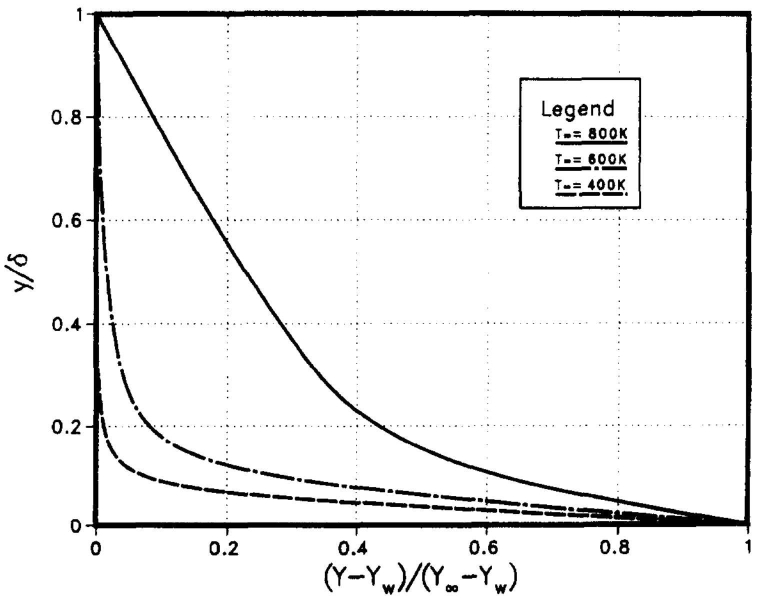

FIG. 7. Effect of boundary-layer nucleation on the mass fraction profile of condensible vapor in turbulent flow.

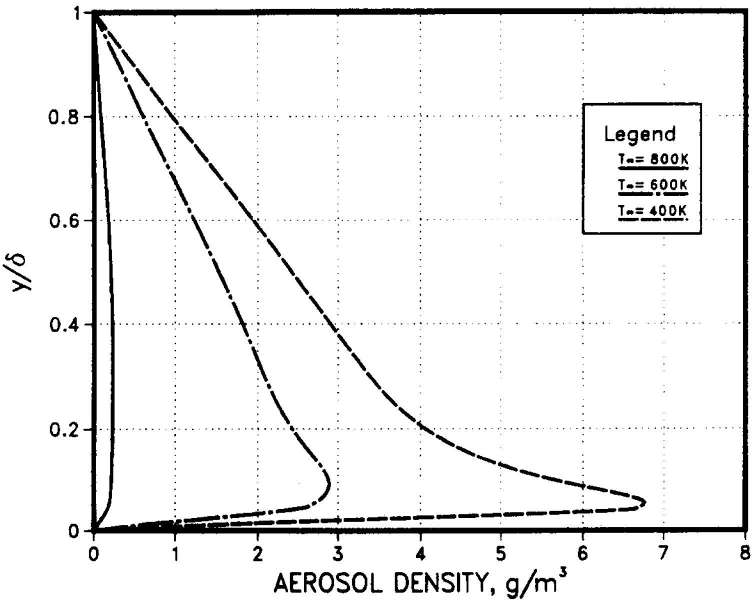

FIG. 8. Aerosol density profile across the turbulent boundary layer.

Figure 7 portrays the influence of gas temperature on the boundary-layer variation of nondimensional vapor mass fraction. As in the laminar case, the ensuing boundary-layer nucleation at low T_∞ steepens the gradient at the wall and reduces it at the edge. The result is an enhanced vaporization flux and thinning of the vapor boundary layer. The latter effect is not explicitly included in the formulation.

Figure 8 exhibits the variation of aerosol density in the boundary layer. On comparing with Fig. 3 for laminar case, the peak in ρ_a is smaller in magnitude and located close to the wall rather than at the edge of the boundary layer. The lower magnitude results from the greater diffusivity of particles in a turbulent stream. For the same reason, thermophoresis plays a less dominant role and one which is confined to the wall region.

Finally, Figs. 9 and 10 show the variations of the supersaturation ratio and nucleation rate $(4/3\pi r^{*3}\rho_l J)$ in the boundary layer. The trends are similar to those noted earlier in Figs. 4 and 5 for laminar flow. The

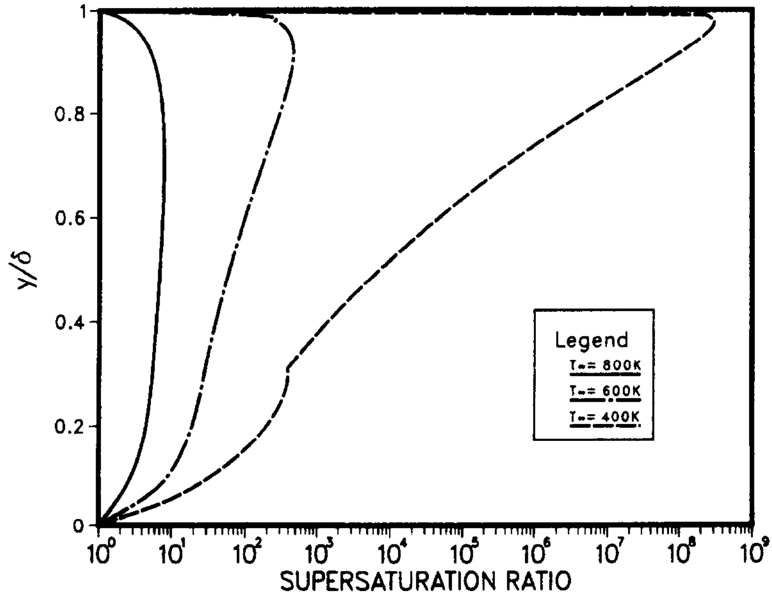

FIG. 9. Variation of supersaturation ratio across the turbulent boundary layer.

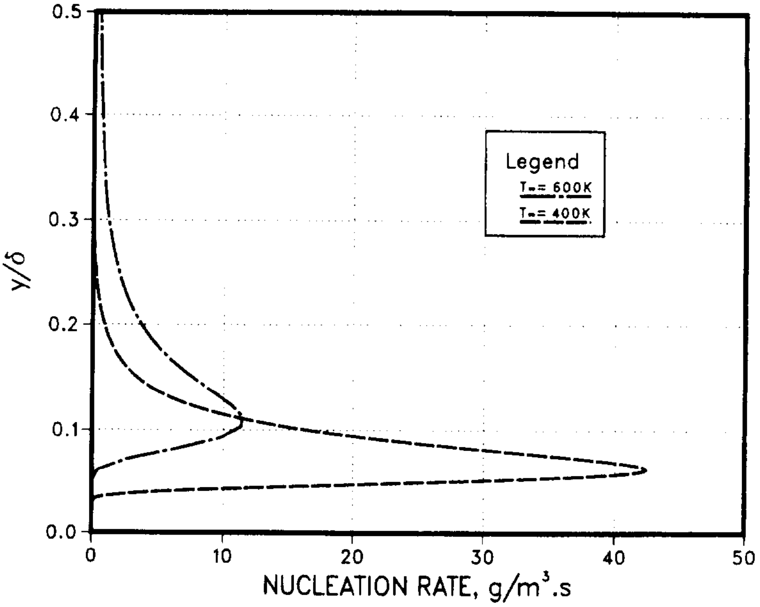

Fig. 10. Effect of gas temperature on the nucleation rate within the turbulent boundary layer.

difference worth mentioning is that for turbulent flow, the peaks in nucleation rate and aerosol density are both present in the vicinity of the wall.

5. CONCLUSIONS

Vaporization of a liquid from a heated surface to a saturated stream has been analyzed. For a low enough free-stream temperature, the vapor diffusing from the surface condenses (nucleates) to form fumes within the boundary layer. The obvious effect of condensation is to diminish the local concentration of the vapor. For a given wall temperature or equivalently Y_w, this results in steepening of the concentration gradient at the wall. Since the vaporization flux is proportional to the gradient, the vaporization process is stimulated. Another effect of boundary-layer nucleation is the thinning of the vapor boundary layer. The resulting reduction in mass transfer resistance also contributes to the enhancement in the vaporization rate.

The transport of nucleated particles plays an interesting though secondary role in the vaporization process. The transport occurs by Brownian diffusion, thermophoresis and eddies in case of turbulent flow. For a heated, perfectly absorbing wall, thermophoresis and diffusion act in opposition in the vicinity of the surface but in concert near the edge of the boundary layer. For a heated surface, thermophoresis always drives the particles to the core. One effect of particle transport is that it redeposits to the wall some of the particles formed from homogeneous nucleation of the vapor. In this manner, it acts to mitigate the net vaporization rate from the surface.

The primary difference between the laminar and turbulent flows arises from the nature of thermophoretic convection. In laminar flow, thermophoresis acts everywhere. In turbulent flow, its role is confined to the wall region because of the steep temperature gradient there and because of eddy diffusion dominating the particle transport away from the surface. The result is that the aerosol density peaks near the boundary-layer edge in laminar flow and in the vicinity of the wall in turbulent flow.

Further work is required to refine the vaporization model. Two of the many assumptions that must be relaxed are the neglect of the convection terms in the governing equations and the growth of the nucleated particles. Inclusion of the convection terms will obviate the necessity of assuming equal boundary-layer thicknesses for particle and vapor transport. The particle growth term is important at high particle loading and its inclusion will lead to an even higher vaporization rate estimate.

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VAPORISATION D'UN LIQUIDE CHAUD DANS UN ECOULEMENT SATURE

Résumé—On considère la vaporisation d'un liquide à partir d'une surface chaude dans un écoulement saturé inerte. La température de surface est suffisamment au dessous du point d'ébullition de telle sorte que la vaporisation est contrôlée par le transport en phase gazeuse plutôt que par le transfert de chaleur. Pour les températures basses de l'écoulement, la vapeur qui diffuse à partir de la surface se condense par nucléation homogène dans la couche limite thermique. Les effets résultants sont l'amincissement de la couche limite de vapeur et l'accroissement du flux de vaporisation. Le transport des particules nucléées contribue aussi au mécanisme de vaporisation. Les mécanismes de transport de particules sont la thermophorèse, la diffusion brownienne et la diffusion turbulente. On trouve que ces mécanismes agissent ensemble dans la majeure partie de la couche limite et en opposition mutuelle dans l'autre partie. Une discussion détaillée est conduite sur l'influence de la température de l'écoulement libre sur le flux vaporisé, des profils de couche limite sur la fraction massique de vapeur, du rapport de sursaturation, de la vitesse de nucléation et de la densité d'aérosol.

VERDAMPFEN EINER BEHEIZTEN FLÜSSIGKEIT IN EINE GESÄTTIGTE STRÖMUNG

Zusammenfassung—Es wird das Verdampfen einer Flüssigkeit von einer beheizten Oberfläche in eine gesättigte, nicht reagierende Strömung betrachtet. Die Oberflächentemperatur liegt ausreichend weit unterhalb des Siedepunktes, so daß die erzeugte Dampfmenge eher durch die Gasphasentransportvorgänge als durch Wärmeübertragung gesteuert wird. Bei niederer Temperatur der ungestörten Strömung kondensiert der von der Oberfläche wegdiffundierende Dampf bei homogener Keimbildung innerhalb der thermischen Grenzschicht. Als Folge ergibt sich eine Ausdünnung der Dampfgrenzschicht und eine Erhöhung der erzeugten Dampfmenge. Der Transport der keimbildenden Teilchen trägt auch zum Verdampfungsvorgang bei. Die wichtigsten Teilchentransport-Mechanismen sind die Thermophorese, die Brown'sche Molekularbewegung und die Wirbelausbreitung. Diese Mechanismen wirken innerhalb eines bestimmten Teils der Grenzschicht zusammen und innerhalb des übrigen Teils einander entgegen. Es folgt eine ausführliche Erörterung des Einflusses der Temperatur der ungestörten Strömung auf die erzeugte Dampfmenge, die Verteilung des Massendampfgehalts in der Grenzschicht, das Übersättigungsverhältnis, die Keimbildungsrate und die Aerosoldichte.

ИСПАРЕНИЕ НАГРЕТОЙ ЖИДКОСТИ В НАСЫЩЕННЫЙ ПОТОК

Аннотация—Рассматривается испарение жидкости с нагретой поверхности в насыщенный нереагирующий поток. Температура поверхности значительно меньше точки кипения, таким образом скорость испарения контролируется процессами переноса в газовой фазе. Найдено, что при низкой температуре свободного потока пар, диффундирующий с поверхности, однородно конденсируется внутри теплового пограничного слоя. Результирующие эффекты—утончение пограничного слоя пара и увеличение скорости испарения. Перенос зародившихся частиц также вносит вклад в процесс испарения. Важными механизмами переноса частиц являются термофорез, броуновская диффузия и вихревая диффузия. Найдено, что в пределах какой-то части пограничного слоя эти механизмы действуют совместно, а в другой они взаимно противопоставлены. Детально обсуждается влияние температуры свободного потока на скорость испарения, а также определяются профили конденсации пара в пограничном слое, степень пересыщения, скорость зародышеобразования и плотность аэрозоля.