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TITLE: STUDY OF THE HOVERING PERIOD AND BUBBLE SIZE IN FULLY DEVELOPED POOL NUCLEATE BOILING OF SATURATED LIQUID WITH A TIME-DEPENDENT HEAT SOURCE

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NOMENCLATURE

A	Heater area contributing to one bubble (m^2)
D	Bubble departure diameter (m)
f	Bubble departure frequency (s^{-1})
g	Gravitational acceleration (m/s^2)
h_{fg}	Latent heat of vaporization (kJ/kg)
q	Surface heat flux (W/m^2)
q_B	Heat flux in the beginning of bubble growth (W/m^2)
q_{CHF}	Critical heat flux (W/m^2)
q_D	Heat flux at bubble departure (W/m^2)
q_{FDB}	Heat flux at the initiation of fully developed nucleate boiling (W/m^2)
z	Instantaneous height of bubble center (m)
t	Time (s)
V	Instantaneous bubble volume (m^3)
V_s	Bubble departure volume in steady-state boiling (m^3)
V_t	Bubble departure volume in transient boiling (m^3)
v_1	Bubble growth rate (m^3/s)
β	Relative rate-of-change in surface heat flux (s^{-1})
γ	Empirical constant (dimensionless)
θ	Contact angle (rad)
λ_T	Taylor instability wavelength (m)
ρ_f	Density of saturated liquid (kg/m^3)
ρ_g	Density of saturated vapor (kg/m^3)
τ	Exponential period (s)
τ_s	Bubble hovering period in steady-state boiling (s)
τ_t	Bubble hovering period in transient boiling (s)

Dimensionless Variables:

a	Transient parameter in linear transients, $a = (dq/dt)\tau_t/q_B$
t^*	Time, $t^* = t/\tau$
V^*	Bubble departure volume, $V^* = V_t/V_s$
α	Transient parameter in exponential transients, $\alpha = \tau_t/\tau$
ξ	Volumetric ratio of the accompanying liquid to the moving bubble
τ_t^*	Bubble hovering period, $\tau_t^* = \tau_t/\tau_s$

STUDY OF THE HOVERING PERIOD AND BUBBLE SIZE IN FULLY DEVELOPED POOL NUCLEATE BOILING OF SATURATED LIQUID WITH A TIME-DEPENDENT HEAT SOURCE *

by

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ABSTRACT

In this paper, the bubble behavior in saturated pool boiling with a time-dependent heat source is analyzed. The study is restricted to the period from fully developed nucleate boiling until critical heat flux occurs. The hovering period and the departure volume of the bubble are selected as the characteristic parameters for bubble behavior. These parameters are quantified by solving the equation of motion for an idealized bubble. This equation is solved for cases in which the surface heat flux changes linearly and exponentially as a function of time. After nondimensionalization, the results are compared directly with the results of the steady-state problem. The comparison shows that the transient heat input has practically no effect on the hovering period. However, the transient heat flux causes a decreased volume at bubble departure. The volume decrease is dependent on the severity of the transient. These results are in qualitative agreement with the experimental observation quoted in the literature.

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I. INTRODUCTION

Boiling heat transfer with a time-dependent heat source is of interest in several nuclear reactor safety applications. One application in light-water nuclear reactor (LWR) technology involves the reactivity-initiated accidents (RIA), where a sudden increase in power generation may occur. Therefore, as part of a reliable safety evaluation of an RIA, an accurate boiling heat transfer modeling with transient heat input is necessary. Consequently, several investigators concerned themselves with related studies [1-13].

The studies of Oker and Merte [1], Sakurai and Shiotsu [2], and Faw *et al.* [3] are mainly concerned with the inception of nucleate boiling and the incipient boiling superheats during power transients. Tachibana *et al.* [4], Sakurai *et al.* [5], Kawamura *et al.* [6], and Sakurai and Shiotsu [7] studied experimentally the pool boiling with time-dependent heat input. Although, these studies cover the entire nucleate boiling curve up to the time of critical heat flux (CHF), emphasis is mostly placed upon the inception of CHF during power transients. The studies of Tachibana *et al.* [4] and Kawamura *et al.* [6] also include photographic investigation of the bubbles in nucleate boiling up to CHF. These studies are very useful for qualitative observations; however, they provide very little quantitative information about the bubble behavior. The transient boiling with forced convective conditions has likewise been the subject of experimental studies [8,9]. Similar to pool boiling studies, these studies emphasize the transient CHF phenomenon and do not quantify the bubble behavior. Transient boiling literature also includes theoretical CHF studies [10,11]. In his theoretical CHF model, Pasamehmetoglu [11] assumes that the hovering period at the CHF level during power transients is not much smaller than the hovering period in steady boiling. Using this assumption, he successfully compares the model with the experimental CHF data. The present study provides a theoretical justification for this assumption. The effect of a power surge on the bubble growth rates and the bubble shapes has been studied experimentally by Shultz and Cole [12,13]. In these studies, the power surge is activated in a nonboiling state; thus, the investigations are mostly concerned with the behavior of the first few bubbles following the inception of nucleate boiling.

In the present paper, the effect of transient surface heat flux on the bubble behavior in a saturated liquid is analyzed. The study is restricted to the period between fully developed nucleate boiling and CHF. The hovering period and the departure volume of the bubble are chosen as the characteristic parameters for the bubble behavior for the following reasons:

1. As cited by Ivey [14], almost all the steady-state nucleate boiling studies involve the product fD^{γ}, where f is the bubble departure frequency, D is the bubble departure diameter and γ is an empirical constant. In fully developed nucleate boiling, the relationship between the hovering period and the frequency becomes trivial because the bubble initiation is almost instantaneous. A new bubble starts growing at the nucleation site as soon as the previous bubble departs from the surface. For this reason, in this boiling regime, the vapor slugs departing from the surface are often referred to as vapor columns [14,15,16]. Such columnar vapor escape paths are observed because, some distance away from the heating surface, the trailing bubble may accelerate as a result of the wake of the leading bubble, and this results in bubble coalescence.

2. The bubble hovering period becomes an important parameter when transient boiling is modeled through a quasi-steady approach. As mentioned by Nelson [17], such an approach is valid only when the time constant of the phenomenon is much smaller than the time constant of the transient. Pasamehmetoglu [11] shows that the time constant of the boiling phenomenon at high heat fluxes is related directly to the bubble hovering period.

The current analysis is based on the equation-of-motion solution for an idealized bubble, as given by Katto and Yokoya [18]. This equation is solved with exponentially and linearly increasing surface heat-flux conditions. The impedus for the exponential transient stems from the fact that LWR power transients in an RIA are characterized by an almost exponential increase in the power-generation rate. It can be shown [11] that the surface heat flux can be related to the power-generation rate through a simple volume-to-surface area ratio if the following conditions are satisfied:

i. The convective heat-transfer coefficient is high (elevated pressures).
ii. The heater's thermal resistance is small.
iii. Exponential period is not too small.

The experimental study of Sakurai and Shiotsu [7] shows that the above simple relation yields an accurate result with a small-diameter (d = 1.2 mm) electrical heater at high heat fluxes (fully developed nucleate boiling) for pressures above 0.2 MPa and for exponential periods above 5 ms. Thus, an exponential transient is chosen in the present study because it is more likely to model an actual RIA. The results of a linear power transient are also included to illustrate the history effects on the bubble behavior through a comparison with the results of the exponential transient. The solutions for both transients are nondimensionalized with respect to the solution of the equivalent steady-state problem. Such solutions reveal directly the effect of the transient heat flux on the bubble behavior. The results are graphically illustrated, and comments on their qualitative comparison with the existing literature are included within the paper.

II. EQUATION OF MOTION FOR AN IDEALIZED BUBBLE

In saturated pool boiling over a horizontal surface, an ideal bubble growing from a nucleation site P is shown in Fig. 1 This bubble's upward motion is caused by buoyancy and the equation describing this motion [18] is given by

$$\frac{d}{dt}\left[(\xi\rho_f + \rho_g)V\frac{ds}{dt}\right] = (\rho_f - \rho_g)gV \quad , \tag{1}$$

where ξ is the volumetric ratio of the accompanying liquid to the moving bubble, V is the instantaneous bubble volume and ds/dt is the rise velocity of the bubble center. The time t is measured from the beginning of the bubble growth. Thus, the instantaneous bubble volume may be written as

$$V = \int_0^t v_1 dt \quad , \tag{2}$$

where v_1 is the volumetric growth rate of the bubble. In saturated nucleate boiling, v_1 may be written in terms of the surface heat flux as follows:

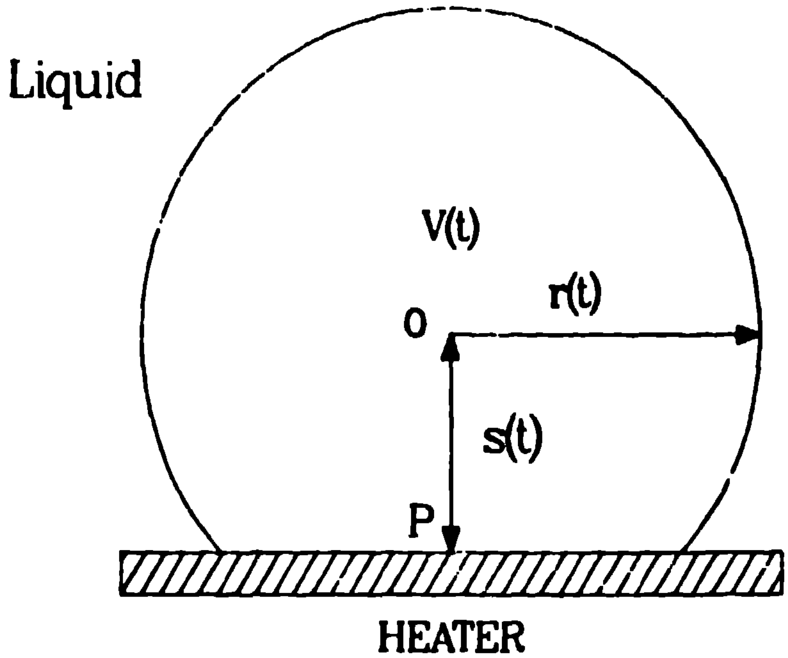

Fig. 1.
Idealized vapor bubble model of Katto and Yokoya [18].

$$v_1 = \frac{A}{\rho_g\, h_{fg}} q \quad . \tag{3}$$

In this equation, A represents the heater area contributing to one bubble. In fully developed conditions, A is controlled by Taylor instability. For a flat plate, for instance, it is equal to λ_T^2, where λ_T is the Taylor instability wavelength. As part of the idealized bubble assumption, the bubble is assumed [18] to depart from the surface when the elevation of the bubble center, s, becomes equal to the bubble radius .

With these assumptions, an initial condition given by

$$s(0) = 0 \quad , \tag{4}$$

and the functional form of the surface heat flux, Eq. (1) may be integrated to yield the hovering period and the bubble volume at the departure. When the surface heat flux is steady, v_1 becomes constant and the integration process yields the following results as reported by Katto and Haramura [19]:

$$t_e = \left(\frac{3}{4\pi}\right)^{1/5} \left[\frac{4(\xi\rho_f + \rho_g)}{g(\rho_f - \rho_g)}\right]^{3/5} \left(\frac{A}{\rho_g\, h_{fg}} q\right)^{1/5} \tag{5}$$

and

$$V_s = \frac{A}{\rho_g h_{fg}} q \tau_s \tag{6}$$

where τ_s is the hovering period of the bubble and V_s is the bubble volume at the departure. Equations (5) and (6) may be combined into a product, $fD^{1/2}$. As reported by Katto and Yokoya [18], when this product is compared to the empirical correlation of Ivey [14], the result is quite favorable in the fully developed nucleate boiling regime. This result lends confidence to the use of the simple equation of motion given by Eq. (1). In the next section, Eq. (1) is integrated with transient surface heat fluxes.

III. SOLUTION OF THE BUBBLE EQUATION OF MOTION WITH TRANSIENT SURFACE HEAT FLUX

For an exponential transient, the surface heat flux is given by

$$q(t) = q_B \exp(t/\tau) \tag{7}$$

Substituting Eq. (7) into Eq. (3) and subsequently integrating Eq. (2), the instantaneous bubble volume may be obtained as follows:

$$V = \frac{A}{\rho_g h_{fg}} q_B \tau[\exp(t/\tau) - 1] \quad . \tag{8}$$

Once the bubble volume is known as a function of time, as given by Eq. (8), Eq. (1) may be integrated twice, using the initial condition from Eq. (4), to yield

$$s = \left(\frac{\rho_f - \rho_g}{\xi\rho_f + \rho_g}\right) g \left[\tau t - \int_0^t \frac{t'}{\exp(t'/\tau) - 1} dt'\right] \quad . \tag{9}$$

Using the departure criterion for the idealized bubble, which can mathematically be expressed as

$$s(\tau_t) = r(\tau_t) = \left[\frac{3\,V(\tau_t)}{4\pi}\right]^{1/3} \quad , \tag{10}$$

the transient hovering period may be obtained from the following equation:

$$\left[\frac{\rho_f - \rho_g}{\xi\rho_f + \rho_g}\right] g^3 \left[\tau\tau_t - \int_0^{\tau_t} \frac{t}{\exp(t/\tau) - 1} dt\right]^3 = \left(\frac{3}{4\pi}\right) \frac{A}{\rho_g h_{fg}} q_B \tau[\exp(t/\tau) - 1] \quad . \tag{11}$$

Equation (11) does not have a closed form solution. Nevertheless, for a given set of system variables, it can be solved numerically to yield the bubble-hovering period τ_t. Then, the solution of Eq. (11) may be replaced into Eq. (8) to obtain the bubble volume at departure as follows:

$$V_t = \frac{A}{\rho_g h_{fg}} q_B \tau[\exp(\tau_t/\tau) - 1] \quad . \tag{12}$$

The system contains the following independent variables: (1) system pressure, (2) heater geometry, (3) initial heat flux, q_B, and (4) exponential period τ of the transient. The number of independent variables may be reduced to one by nondimensionalizing Eq. (11). Since the principle interest of the present study is to investigate the effect of the transient heat flux on bubble behavior, the nondimensionalization is done with respect to the steady-state parameters resulting from the solution of the equivalent steady-state problem. The equivalent steady-state problem is defined as follows:

i. The boiling occurs at the same pressure as the transient problem.
ii. The heater geometry is the same as in the transient problem.
iii. The surface heat flux is constant and equal to the surface heat flux corresponding to the heat flux at the bubble departure in the transient problem.

The relation between the initial heat flux, q_B, and the departure heat flux, q_D, may be obtained from Eq. (7), as

$$q_B = q_D \, exp\,(-t/\tau) \tag{13}$$

Substituting Eq. (13) into Eqs. (11) and (12), using Eqs. (5) and (6), in which q is replaced by q_D, and the dimensionless variables defined in the nomenclature, the following expressions may be obtained for the dimensionless hovering period and the departure volume of the bubble:

$$\tau_t^* = \frac{\{\alpha[1 - exp\,(-\alpha)]\}^{1/5}}{\left\{4\left[\alpha - \int_0^{\alpha} \frac{t^*}{exp(t^*)-1} dt^*\right]\right\}^{3/5}} , \tag{14}$$

and

$$V_t^* = \tau_t^* [1 - exp\,(-\alpha)]/\alpha \quad . \tag{15}$$

Equation (14) still requires a numerical integration. However, the only independent variable in Eqs. (14) and (15) is the exponential transient parameter, α. Another advantage of this nondimensionalization scheme is that the solutions of Eqs. (14) and (15) give a direct comparison between the bubble behaviors in transient and steady-state boiling. The results of Eqs. (14) and (15) are illustrated graphically in Sec. IV.

The bubble behavior with a linear increase in the surface heat flux may be analyzed through a similar procedure. Such a surface heat flux is given by

$$q(t) = q_B + (dq/dt)t \quad . \tag{16}$$

The results for a linear transient may be obtained through a integration procedure similar to that for an exponential transient. The hovering period, τ_t, is given by the numerical solution of the following equation:

$$\left(\frac{3}{4\pi}\right) \frac{A}{\rho_g h_{fg}} q_B\left(\tau_t + \frac{\beta}{2}\tau_t^2\right) = \left(\frac{\rho_f - \rho_g}{\xi\rho_f + \rho_g}\right)^3 g^3 \left\{\frac{\tau_t^2}{6} - \frac{\tau_t}{3\beta} + \frac{2}{3\beta^2} ln\left(\frac{\beta}{2}\tau_t + 1\right)\right\} \quad . \tag{17}$$

where β is the relative rate of change of the surface heat flux and is equal to $(dq/dt)/q_B$.

Then the bubble volume at departure becomes

$$V_t = \frac{A}{\rho_g\, h_{fg}} q_B \left(\tau_t + \frac{\beta}{2}\tau_t^2\right) \quad . \tag{18}$$

The intermediate details are very similar to the solution of the exponential transients and are not repeated here. Equations (17) and (18) may be nondimensionalized with respect to the solution of the equivalent steady-state problem. which is defined as before. The definitions of the dimensionless variables in linear transients are given in the nomenclature list. The following results are obtained for the dimensionless hovering period and the bubble volume:

$$\tau_t^* = \left(\frac{1}{4}\right)^{3/5} \left(\frac{1+a/2}{1-a}\right)^{1/5} \left[\frac{6a^2}{a^2+2a-4ln(a/2+1)}\right]^{3/5} \quad , \tag{19}$$

and

$$V_t^* = \left(\frac{1+a/2}{1+a}\right)\tau_t^* \quad . \tag{20}$$

The plots of these equations are also included in Sec. IV.

The predictive equations for the bubble-hovering period and departure volume obtained in this section are not valid for the entire boiling curve. They are bounded by the onset of the fully developed nucleate boiling at the lower end and by the onset of the CHF at the upper end. The lower bound is imposed by the use of the heater area contributing to one bubble. A, as being independent of the surface heat flux. Such an assumption may be justified if the transient starts in a fully developed nucleate boiling regime in which the Taylor wave pattern is already established. On the other hand. if the transient starts in the isolated nucleate boiling regime or in the nonboiling regime. the bubble nucleation density is a function of the wall superheat. which. in turn. is strongly influenced by the nature of the transients. At the upper end. beyond the CHF point. a stable liquid film on the heater surface cannot be sustained. Since such a stable liquid film is essential for bubble growth model used in the analysis. Eqs. (2) and (3) cannot be used beyond this limit. These upper and lower limits bring a restriction on the values of the transient parameters. α and a, in Eqs. (14). (15). (19). and (20). Since q_B and q_D must both remain in the fully developed nucleate boiling regime. the ratio q_D/q_B must be smaller than the ratio q_{CHF}/q_{FDB}. where q_{CHF} denotes the critical heat flux and q_{FDB} denotes the heat flux for the onset of the fully developed boiling. Using the Zuber [15] correlation for the former and the correlation of Moissis and Berenson [16] for the latter. it can be shown that this ratio may be approximated by

$$\frac{q_{CHF}}{q_{FDB}} = \frac{1.19}{\theta^{1/2}} \left[\frac{\rho_f - \rho_g}{\rho_g}\right]^{1/2} \quad , \tag{21}$$

where θ is the contact angle. Therefore. the ratio may assume very large values for surfaces with good wetting characteristics. On other surfaces and on a nonwetted surface with large contact angle. the initiation of the fully developed nucleate boiling may be considerably delayed. In the present study. it will be assumed that this ratio remains on the order of unity.

IV. RESULTS

Figures 2 and 3 show the plot of the dimensionless hovering period and the departure volume of a bubble, respectively, as functions of the dimensionless transient parameters. Notice that the bubble behavior in both the exponential and linear transients is shown on the same figure for comparison purposes. The transient parameters α and a may be related to each other because the following conditions are satisfied: (1) the departure heat fluxes in both transients are equal, because they are both equal to the same heat flux in the equivalent steady-state problem, and (2) because a and α are the independent variables, they can be selected such that the ratio q_D/q_B becomes equal in both transients. Actually, instead of a or α, q_D/q_B may be used as a common independent variable in linear and exponential transients. This common transient parameter is shown as the top abcissa of Figs. 2 and 3.

In these figures, the following trends are observed :

1. As long as the transient is confined within the region between the onset of fully developed boiling and the CHF, the bubble-hovering period is unaffected by the transient. As shown in Fig. 2, in exponential transients the hovering period is practically independent of the transient parameter α and is equal to the hovering period in steady boiling. In linear transients, the hovering period slightly increases with increasing a; however, the maximum deviation from the steady-state hovering period remains less than 10%. Therefore, it can be concluded that the hovering period is simply a function of the departure heat flux and is relatively independent of the surface heat flux history.
2. As a direct consequence of the above observation, the bubble departure volume depends strongly on the transient heating. Figure 3 shows that the bubble volume decreases to about 50% of the steady-state volume for values of α as small as 1.5 in exponential transients. Similarly, the bubble volume becomes almost 60% of the steady-state value for values of a as small as 4 in linear transients.

Finally, the plot of the product fD is shown in Fig. 4. This product is chosen as representative of the bubble behavior because the bubble rise velocity is shown [14] to be proportional to this product. The dimensionless form of fD is given by the following equation:

$$(fD)^* = (V_t^*)^{1/3}/\tau_t^* \quad . \tag{22}$$

Equation (22) represents the ratio of the bubble rise velocity in transient boiling to the bubble rise velocity in steady-state boiling. Figure 4 shows that the bubble rise velocity in transient boiling is slightly lower than the rise velocity in steady-state boiling.

These results are qualitatively supported by several experiments. The photographic studies of Tachibana *et al.* [4], and Kawamura *et al.* [6], show that the departure volume of the bubble in transient boiling is smaller than the volume in steady-state boiling. It is very hard to quantify these pictures and to compare the results with the present study, because all of these transients are initiated from either a nonboiling or an isolated boiling region. Therefore, for very fast transients, the delay in the formation of Taylor wave pattern may be quite important. Nevertheless, the pictures reveal that, even for milder transients, the size of the departing bubble decreases at high heat fluxes, with increasing rate of change of the surface heat flux.

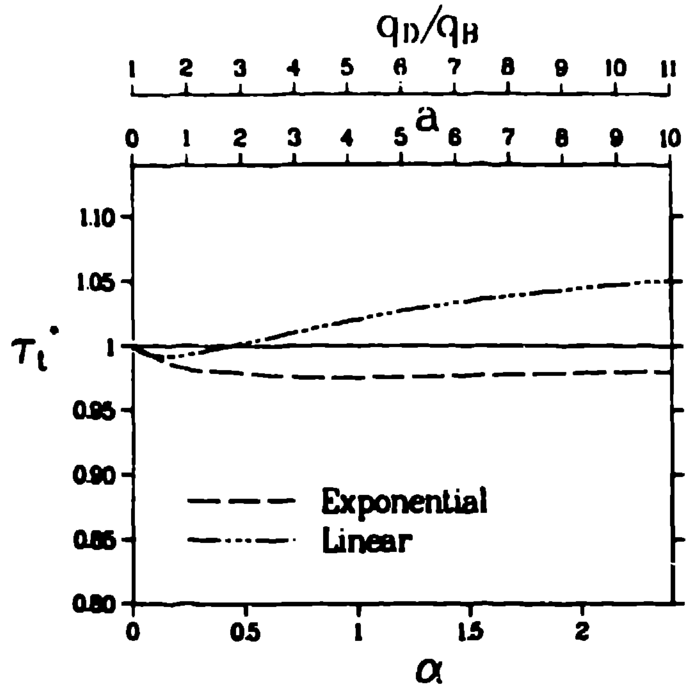

Fig. 2.
Dimensionless hovering period of a bubble in transient boiling as a function of the dimensionless transient parameters.

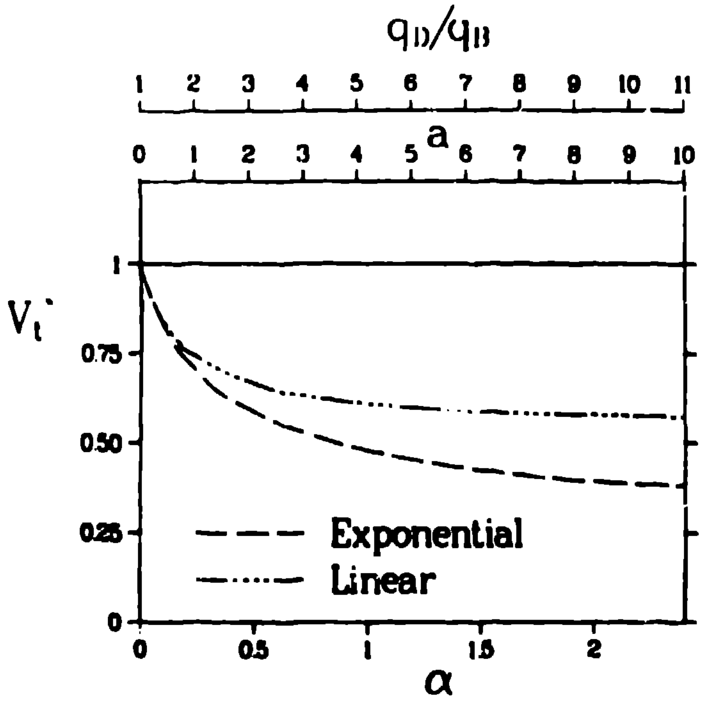

Fig. 3.
Dimensionless departure volume of a bubble in transient boiling as a function of dimensionless transient parameters.

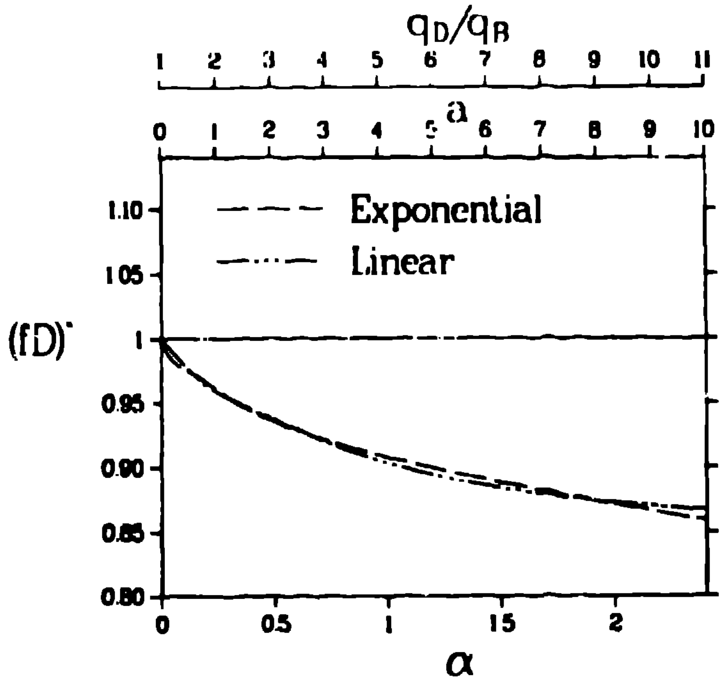

Fig. 4.
Dimensionless bubble rise velocity in transient boiling as a function of dimensionless transient parameters.

The present study is also in qualitative agreement with the experimental observations of Schultz and Cole [12] concerning the effect of the growth rate on the bubble shape. Schultz and Cole [12] summarize their observations, stating, "Large growth rates are characterized by significant liquid inertia, which tends to flatten the bubble. Slower growing bubbles are more influenced by surface tension stresses and tend toward a spherical shape."

Although the surface tension forces are not modeled, the present study yields similar results in terms of the growth-rate effects on the bubble shape due to the the counteracting effects of liquid inertia and buoyancy. As present analysis is formulated, the transient surface heat flux is always lower than the equivalent steady-state heat flux. Thus, the bubble growth rate is smaller in transient boiling. As a result, the buoyancy dominates and the bubble becomes a perfect sphere with a smaller vapor content, and departs. On the other hand, in steady boiling in which the growth rate is greater, the liquid inertia becomes significant. Consequently, a larger buoyancy force, thus a larger volume, is needed before the bubble can become a perfect sphere and depart. Within the context of an idealized bubble, which is illustrated in Fig. 1, a flattened bubble means that the the height of the bubble center, s, is smaller than the bubble radius. Therefore, the present results may be summarized in a conclusion similar to that of Schultz and Cole [12]: "Large growth rates are characterized by significant liquid inertia, which tends to suppress the bubble on the heating surface until it reaches a large volume. Slower growing bubbles are more influenced by the buoyancy force and tend toward a spherical shape, and thus depart with smaller volume."

V. SUMMARY AND CONCLUSIONS

In the present paper, the effect of time-dependent heat flux on bubble behavior is studied theoretically. The study is restricted to fully developed and saturated nucleate pool boiling. The hovering period and the departure volume of the bubble are obtained through the solution of an idealized bubble equation of motion. The surface heat flux is assumed to vary exponentially and linearly. The resulting expressions are nondimensionalized such that they yield a direct comparison with the steady-state parameters. The results for exponential transients are given by Eqs. (18) and (19) for the hovering period and the departure volume, respectively. Similarly, Eqs. (23) and (24) are the results for linear transients. These results are graphically illustrated in Figs. 2 and 3. The bubble rise velocity in transient boiling is also compared to the bubble rise velocity in steady-state boiling using these results. This comparison is shown in Fig. 4.

In conclusion, the effects of the transient boiling on the bubble behavior may be summarized as follows:

1. The bubble-hovering period is not significantly affected by the transient.
2. As a result of item 1, the departure volume of the bubble is smaller in transient boiling than in steady boiling.
3. The bubble rise velocity in transient boiling is slightly smaller than the bubble rise velocity in steady boiling.

These results are valid as long as the transient boiling is confined to the period between the onset of fully developed boiling and the onset of CHF. The photographic studies of Tachibana *et al.* [4] and Kawamura *et al.* [6] are in qualitative agreement with the present results. The present solution also agrees with the experimental observations of Schultz and Cole [12] concerning the effect of variable bubble-growth rates on the bubble shapes.

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