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THE EFFECT OF MOTION ON BUBBLE COLLAPSE

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Abstract—The effects of constant and radius-dependent translational bubble velocity on the collapse rate of a single bubble in a single and two-component system, either pure or containing non-condensables, are analysed and compared. A quasi steady-state in a potential or modified potential flow field is assumed.

An attempt is then made to analyse the combined effects of bubble rise velocity and main stream cross flow in forced convection surface boiling in slightly subcooled water. The results are in excellent agreement with available experimental data for most of the condensation process. Ideas for farther improvements are explored, and a general framework for analyzing bubble collapse in a flow field has been suggested.

NOMENCLATURE

$\tilde{A}$, velocity ratio, equations (6) or (17);
C, constant, equation (9);
C_p, specific heat capacity, continuous phase;
Fo, Fourier number $(\alpha t/R_0^2)$ or $(\alpha t/R_m^2)$;
G, density ratio, dispersed phase, (ρ_L/ρ_v);
h, heat-transfer coefficient;
Ja, Jacob number $[\rho C_p(T^* - T_\infty)/\lambda\rho_v)]$;
k_v, velocity factor;
k, thermal conductivity, continuous phase;
Nu, Nusselt number $[2Rh/k]$;
P^*, system pressure corresponding to T^*;
Pe, Péclét number $(= 2RU/\alpha)$;
Pe_0, Péclét number $(= 2R_0U_0/\alpha)$;
Pe_m, Péclét number $(= 2R_mU_m/\alpha)$;
Pr, Prandtl number, continuous phase;
q, instantaneous heat flux;
R, radius of bubble $(= R(t))$;
R_f, final radius of the bubbles;
R_0, initial radius of bubble;
R_m, maximum bubble radius, after detachment;
$\dot{R}$, radial velocity $(= dR/dt)$;
$\hat{R}$, specific gas constant;
T, temperature;
T^*, saturation temperature corresponding to P^*;
T_w, temperature, wall;
T_∞, approach continuous phase temperature;
t, time;
t_f, time, complete condensation;
U, relative vapor–liquid velocity;
U_b, bubble free rise velocity, radius dependant;
U_0, bubble free rise velocity, constant;
U_l, perpendicular, horizontal bulk velocity;
U_m, rise velocity of bubble of radius R_m;
U_{max}, maximum relative velocity $[=(U_m^2 + U_l^2)^{\frac{1}{2}}]$;
V_R, horizontal to (constant) vertical velocity ratio, (U_l/U_m);
y_0, initial concentration on noncondensables, mole fraction.

Greek letters

α, thermal diffusivity, continuous phase;
β, dimensionless radius (R/R_0);
β_f, final dimensionless radius (R_f/R_0);
λ, latent heat of evaporation, dispersed phase;

θ, dimensionless temperature $(T - T_\infty)/(T^* - T)$;
θ_w, dimensionless wall temperature $(T_w - T_\infty)/(T^* - T)$;
ρ, density, continuous phase;
ρ_L, density, liquid, dispersed phase;
ρ_v, density, vapor, dispersed phase;
τ, dimensionless time, equation (6);
τ_0, running dimensionless time, pure vapor condensation;
τ_1, running dimensionless time, correction due to inerts;
τ_H, dimensionless time, equation (2);
τ_f, final dimensionless condensation time.

INTRODUCTION

BUBBLE dynamics in stagnant, subcooled, liquids were investigated, experimentally [1–4] and analytically [5–8], but mainly, in non-flow systems. An experimental and theoretical study, based on an integral approach to the governing conservation equations, on the condensation of an injected steam bubble attached to the nozzle in subcooled water was reported recently [9].

Comparatively, little has been reported on the effect of the relative motion of the vapor bubbles and the continuous phase on bubble growth and/or collapse rates. Photographic studies of surface boiling in forced convection flow of highly [10] and slightly [11] subcooled water were reported. These, however were usually analysed by the non :flow "assymptotic" solutions for heat-transfer-controlled bubble growth and collapse, represented by [8]:

$$\tau_H = \frac{2}{3}\frac{R_0}{R} + \frac{1}{3}\left[\frac{R}{R_0}\right]^2 - 1 \qquad (1)$$

where R and R_0 are the instantaneous and initial bubble radius, respectively, and

$$\tau_H = \frac{4}{\pi}\left(\frac{\rho C_p(T^* - T_\infty)}{\rho_v \lambda}\right)^2 \cdot \frac{\alpha t}{R_0^2} \equiv \frac{4}{\pi}(Ja)^2\, Fo \qquad (2)$$

where T^* denotes the saturation temperature at the pressure of the system and T_∞ is the bulk or approach temperature.

The effect of the translational velocity of a bubble on the collapse rate was studied theoretically by Clark *et al.* [12], experimentally and theoretically by Wittke and Chao [13] for a single component (steam–water) system and by Sideman *et al.* [14, 15] for the more general case of two-component (say, pentane in water) system. These works deal with relatively large ($R_0 > 1{\cdot}0$ mm) bubbles and, assuming a constant rise velocity in a potential or modified-potential [14] flow fields, present a numerical solution for the unsteady-state energy equation. These solutions, though exact, are relatively complicated and an approximate but general analytical solution, encompassing single and two component systems, including the effect of non-condensables, was recently reported [16]. This general solution, more recently extended to single [17, 18] and multi-train bubble systems [19], was obtained, similar to Ruckenstein's [20, 21] analysis of the effect of translational bubble motion on bubble growth, by assuming quasi-steady state and a potential—or modified potential—flow field. The general expression is given by

$$Nu = \frac{2}{\sqrt{\pi}}(k_v\, Pe)^{\frac{1}{2}} \qquad (3)$$

where $Nu \equiv 2R\,h/k$, $Pe \equiv 2RU/\alpha$ and k_v, the velocity factor by which the potential flow solution for flow around a sphere is 'transformed' to yield the average heat flux that would be obtained in a viscous flow field, is given by [15].

$$k_v = 0{\cdot}25\, Pr^{-\frac{1}{3}} \qquad (4)$$

for a two component system and $k_v = 1$ for a single component system.

It is important to emphasize at this point that equation (3) was derived under quasi-steady state conditions ($Pe \gg 1$ and $\dot{R} \ll U$) and is limited to $Pe \gg Ja$ [21]. Here R, the radius, U, the relative (vapor–liquid) velocity and h, the heat-transfer coefficient, denote instantaneous values prevailing in a given system at a given instant.

Whereas large ($0.4 > R_0 > 0.2$ cm), bubbles exhibit constant rise-velocity [22], this work is an attempt to analyse the effect of the radius-dependent rise velocity associated with relatively small bubbles. Also, with reference to the experimental data of Abdelmessih [11], an attempt is made to analyse the effect of fluid velocity on bubble collapse in slightly subcooled water.

It is perhaps relevant to note in this connection that the numerous studies associated with forced-convection-boiling incorporate the overall effects of boiling and forced convection and are therefore outside the scope of this paper.

THE COLLAPSE HISTORY

Rewriting equation (3) in terms of the instantaneous heat flux, q, and the local temperature driving force $\Delta T = (T_w - T_\infty)$, where T_w is the wall temperature of the bubble, and equating with the flux obtained by a simple energy balance at the wall of the collapsing bubble, i.e. $q = \lambda \dot{R} \rho_v$, yields

$$\dot{R} = -\frac{k\Delta T}{\rho_v \lambda}\left[\frac{2Uk_v}{\pi \alpha R}\right]^{\frac{1}{2}} \qquad (5)$$

where U is the instantaneous relative vapor–liquid velocity.

We now define dimensionless parameters with reference to a single bubble of radius R_0 rising freely in an infinite expanse of the continuous phase at a constant velocity U_0:

$$\theta_w = \frac{T_w - T_\infty}{T^* - T_\infty}; \qquad Pe_0 = \frac{2R_0 U_0}{\alpha};$$

$$\beta = R/R_0 \qquad (6)$$

and

$$\tau \equiv Ja\, Pe_0^{\frac{1}{2}}\, Fo; \qquad \tilde{A} = \left(\frac{U}{U_0}\right)^{\frac{1}{2}}.$$

Equation (5) reduces to

$$\dot{\beta} = \frac{\mathrm{d}\beta}{\mathrm{d}\tau} = -\left(\frac{k_v}{\pi}\right)^{\frac{1}{2}} \frac{1}{\beta^{\frac{1}{2}}} \tilde{A}\theta_w;$$

$$\beta = 1 \text{ at } \tau = 0. \qquad (7)$$

Note that for a constant rise-velocity $\tilde{A} = 1$; for a pure system not containing non-condensables $T^* = T_w$ and $\theta_w = 1$; for a single component system, and if the potential flow field assumption holds, $k_v = 1$.

Integration of equation (7) requires explicit expressions relating the instantaneous radius to θ_w which depends on the inerts concentration in the vapor and to $\tilde{A}$, the relative rise velocity.

A. PURE VAPORS

We begin with the simple case of pure vapors, where $T_w = T^*$, i.e. the wall temperature is identical with the saturation temperature, and $\theta_w = 1$.

1. *Constant bubble velocity*

For large bubbles ($0.2 < R_0 < 0.4$ cm) the rise velocity is practically independent of the radius [22, 23] and $\tilde{A} = 1$. Integration of equation (7) yields:

$$\beta = \left[1 - \frac{3}{2}\left(\frac{k_v}{\pi}\right)^{\frac{1}{2}} \tau\right]^{\frac{2}{3}} \qquad (8)$$

or

$$\tau_0 = \tfrac{2}{3}(\pi/k_v)^{\frac{1}{2}}(1 - \beta^{\frac{3}{2}}). \qquad (8a)$$

The final dimensionless bubble diameter $\beta_f = 0$ for a single component system and the dimensionless time for complete condensation $\tau_f = 1.182$. For a two component system, where the condensate accumulates within the confines of the two-phase bubble, $\beta_f = (R_f/R_0) = (\rho_v/\rho_L)^{\frac{1}{3}} \equiv G^{-\frac{1}{3}}$ and τ_f depends upon the vapor and liquid densities of the volatile dispersed phase. For the pentane–water system, for instance, $G^{-\frac{1}{3}} = 0.1684$ and $\tau_f = 2.912$.

2. *Radius-dependent rise velocity*

For small bubbles, $R_0 < 0.1$ cm,

$$U_b = C\sqrt{R} \text{ cm/s}; \qquad R_0 \geq R \qquad (9)$$

where U_b denotes the radius-dependent free rise velocity of the bubble and $C = 1{\cdot}74\,[2g(\rho_c - \rho_v)/\rho_c]^{\frac{1}{2}}$ [23]. (Based on solid spheres, Ruckenstein [20] suggested $C = 6{\cdot}6\,[\mathrm{m}^{\frac{1}{2}}/\mathrm{s}]$ for steam bubbles of all sizes in pure water.) Substituting U_b for U in equations (5) and (6) in the range $R_0 \geqslant R$, where at the limit ($R = R_0$) $U_0 = C\sqrt{R_0} = \text{const.}$ yields $\tilde{A} = (R/R_0)^{\frac{1}{4}} = \beta^{\frac{1}{4}}$, independent of the value of the constant C in equation (9).

Equation (7) now becomes

$$\dot{\beta} = -\left(\frac{k_v}{\pi}\right)^{\frac{1}{2}} \frac{1}{\beta^{\frac{1}{4}}} \theta_w \tag{10}$$

and integration with $\theta_w = 1$, yields

$$\beta = \left[1 - \frac{5}{4}\left(\frac{k_v}{\pi}\right)^{\frac{1}{2}} \tau\right]^{\frac{4}{5}} \tag{11}$$

or

$$\tau_0 = \tfrac{4}{5}(\pi/k_v)^{\frac{1}{2}}(1 - \beta^{\frac{5}{4}}). \tag{11a}$$

Again, $\beta_f = 0$ for a single component system and $\tau_f = 1{\cdot}418$. For a two-component system, $\beta_f = 1/G^{\frac{1}{3}}$ and, for pentane–water system, $\tau_f = 3{\cdot}357$. A comparison of equations (8) and (11) for $\beta_f = 0$ is presented in Fig. 1(a).

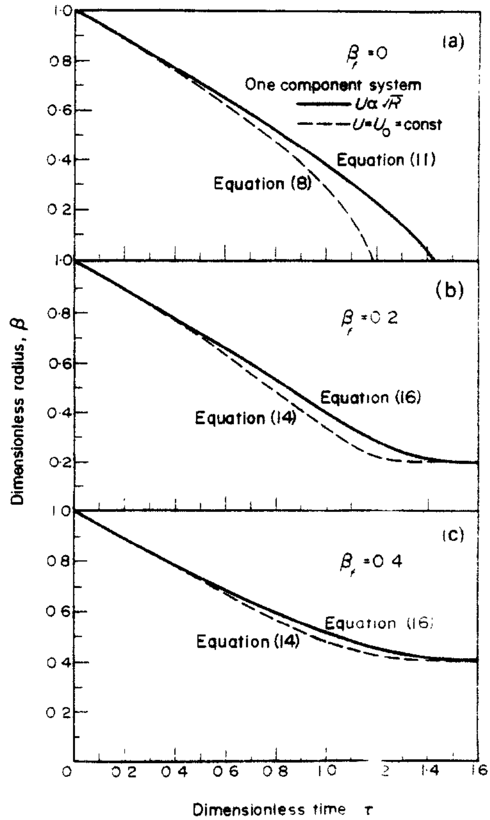

FIG. 1. Comparison of constant and radius dependent rise velocity.

B. UNPURE VAPORS

In the presence of non-condensables $T_w \neq T^*$. The partial pressure of the inert gas increases as the bubble contracts, simultaneously reducing the partial pressure of the vapors, until, as $T_w \to T_\infty$, condensation stops and $\beta = \beta_f$.

Integration of equation (7), accounting for the inerts contents, requires explicit expressions relating θ_w to the inerts concentration and the instantaneous radius of the bubble. Assuming an homogeneous distribution within the bubble, the initial inert concentration, y_0 (mole fraction), is related to the final bubble radius, β_f by [15]:

$$\beta_f = \left[\frac{\hat{R}T^{*2}y_0}{\lambda(T^* - T_\infty)} + \frac{1}{G}\right]^{\frac{1}{3}}; \qquad G \equiv \rho_L/\rho_v \tag{12}$$

where $\hat{R}$ is the gas constant. The term $1/G$, due to the accumulation of condensate within the confines of the 'two-phase' bubble, vanishes for a single component system.

In terms of β_f and β, the dimensionless bubble-wall temperature is given by [15]:

$$\theta_w = \frac{\beta^3 - \beta_f^3}{\beta^3 - 1/G}. \tag{13}$$

1. *Constant rise velocity*

Introducing (13) into (7) and integrating yields a closed-form solution

$$\tau = \tau_0(\beta) + \tau_1(\beta, \beta_f) \tag{14}$$

where $\tau_0(\beta) = \tau_0$ is given by equation (8a) and $\tau_1(\beta, \beta_f)$, the correction term for the effect of non-condensables, is given by

$$\tau_1 = \left(\frac{\pi}{k_v}\right)^{\frac{1}{2}} \frac{\beta_f^3 - (1/G)}{3\beta_f^{\frac{3}{2}}} \times \ln \frac{(1 - \beta_f^{\frac{1}{2}})(\beta^{\frac{1}{2}} + \beta_f^{\frac{1}{2}})}{(1 + \beta_f^{\frac{1}{2}})(\beta^{\frac{1}{2}} - \beta_f^{\frac{1}{2}})}. \quad (15)$$

For a single phase bubble $k_v = 1$ and $1/G = 0$.

2. *Radius-dependent rise-velocity*

Introducing (13) into (10) yields

$$d\tau = \left(\frac{\pi}{k_v}\right)^{\frac{1}{2}} \frac{\beta^{\frac{1}{2}}(\beta^3 - 1/G)}{(\beta^3 - \beta_f^3)} d\beta \quad (16)$$

which can be integrated numerically. Figures 1(b) and 1(c) represent equation (14) and the integrated equation (16) for $\beta_f = 0{\cdot}2$ and $\beta_f = 0{\cdot}4$, respectively, for a single component system where $1/G = 0$ and $k_v = 1$. As seen from the figures, the effect of the variable velocity is less pronounced as the inerts content increases. This is to be expected since in this case the radius, hence the velocity, changes relatively slower due to the lower condensation rate.

EXTENSION TO SUBCOOLED FORCED-FLOW BOILING

Abdelmessih *et al.* [11] have recently reported data on the effect of fluid velocity on the growth and collapse of steam bubbles in slightly subcooled distilled water, and attempted to correlate some of the data, Fig. 2. with equation (1). derived [8] for a stagnant bubble in a non-flow system. Obviously, the effect of the relative motion between the bubbles and the liquid must be incorporated in order to obtain a better agreement between experiment and theory.

We concern ourselves only with the collapse period of his data (Fig. 2), and denote the maximum radii of the detached bubbles as R_m.

The effect of motion on the collapse rate is now given by equation (5) or (7), where U is taken to represent the relative velocity resulting from the free-rise velocity and the normal fluid velocity.

Since small bubbles are considered, equation (9) is assumed to apply to the rise velocity. The horizontal component of the bubble velocity is assumed to be identical with U_b, the normal bulk fluid velocity. This is consistent with a rough estimation of the horizontal velocity of the bubbles shown in Fig. 3 of [11]. Thus, with $U_b \sim \sqrt{R}$ and U_m which corresponds to R_m, now replacing U_0 in equation (6), the relative velocity term, $\tilde{A}$, takes the form:

$$\tilde{A} = \left[\frac{\sqrt{(U_b^2 + U_l^2)}}{U_m}\right]^{\frac{1}{2}} = (V_R^2 + \beta)^{\frac{1}{2}} \quad (17)$$

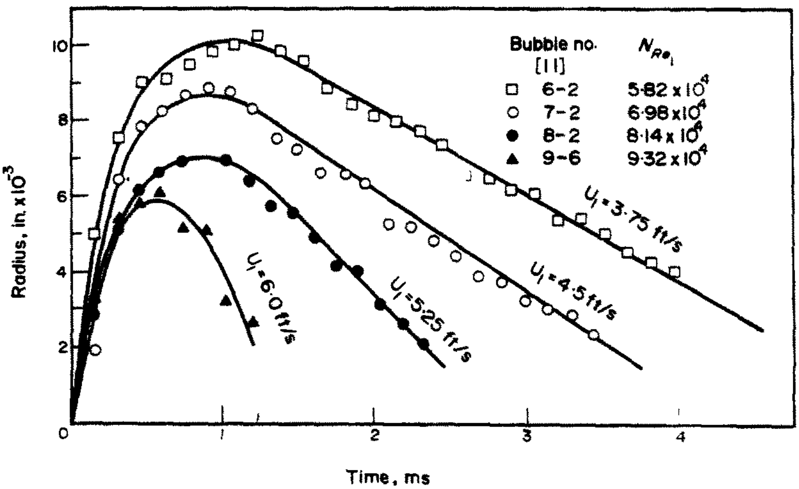

FIG. 2. Effect of liquid velocity on bubble growth and collapse at a heat flux of $q/A = 1{\cdot}3 \times 10^5$ Btu/hft^2 [11].

where

$$V_R = U_l/U_m.$$

For the single component, steam–water, system $k_v = 1$ and equation (7), or (10), becomes

$$\dot{\beta} = -\left(\frac{1}{\pi}\right)^{\frac{1}{2}}(V_R^2+\beta)^{\frac{1}{4}}\frac{1}{\beta^{\frac{1}{2}}}\theta_w. \quad (18)$$

Or, introducing (13) with $1/G = 0$:

$$d\tau = -\sqrt{\pi}\frac{\beta^{\frac{1}{2}}}{(\beta+V_R^2)^{\frac{1}{4}}}\frac{\beta^3-\beta_f^3}{\beta^3}d\beta. \quad (19)$$

The integrated values of equation (19) are presented in Fig. 3 for a pure system ($\beta_f = 0$) and various values of V_R. Although Fig. 3 is quite general, the values of V_R were chosen to correspond to the specific experimental values of U_b, R_m (and U_m) presented in Fig. 2.

In order to compare equations (1) and (19) with the experimental data, we utilize in Fig. 4 Abdelmessih *et al.*'s plot (Fig. 8, Ref. [11]) with τ_H rather than τ as the abcissa. Note that the four curves for $V_R \neq 0$ in Fig. 3 (β vs τ) are approximately represented in Fig. 4 (β vs τ_H) by a single curve. This is due to the fact that (for the same time!) $\tau/Pe_m^{\frac{1}{2}} \approx$ const. for the system studied, and the four curves *practically* converge into a single one.

It is interesting to note that the data presented in Fig. 2 shows that

$$R_m\sqrt{(U_l^2+U_m^2)} = R_m U_{max} \simeq \text{const.}:$$
$$U_l \gg U_m \geqslant U_b. \quad (20)$$

This is generally consistent with the observations that the radius of the bubbles at detachment is inversely proportional to the normal, main stream, velocity to some power [23, 24]. However, the effect of the main stream velocity may have affected the relationship between the detachment radius and its maximum growth value, R_m, resulting with the relationship presented in by equation (20).

As already seen from Fig. 1, the effect of variable velocity as compared to constant velocity motion is relatively small. This is demonstrated again in Fig. 4, where the dotted line represents τ_H vs β calculated by equation (8) with $U = U_{max}$ for each run. In this case we define the Péclét number in equation (6) with U_{max} rather than with U_m (or U_0) and therefore $\mathring{A} = 1$. Since $(U_{max} R_m) =$ const., the Péclét

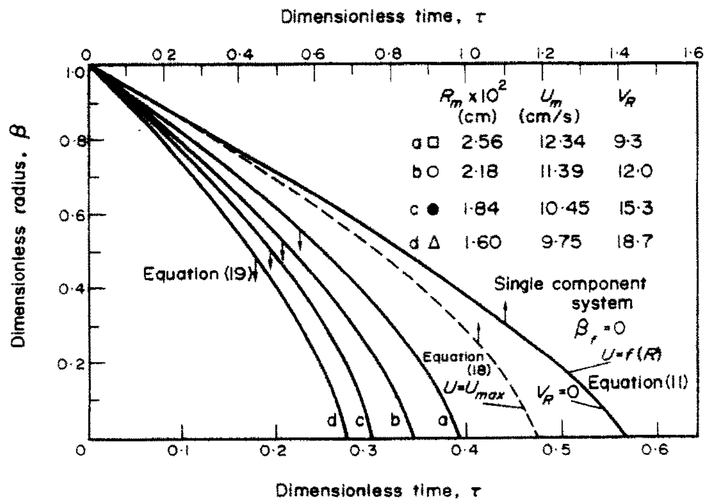

FIG. 3. Effect of main stream cross flow velocity on bubble collapse.

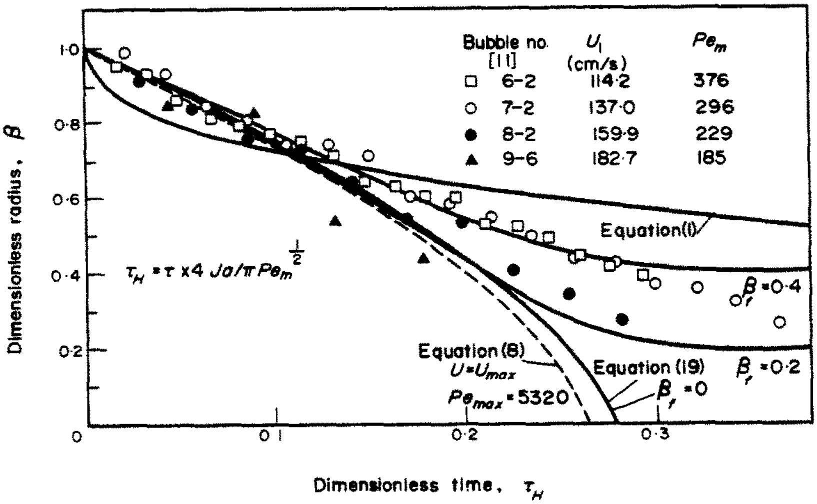

FIG. 4. Comparison of experimental data with theory.

number is now constant i.e. $Pe_{max} = (2R_m U_{max}/\alpha) = 5320$ for all runs. Note that by defining the Péclét number in this manner, and assuming equation (20) to be universally true, we obtain that the 'universal' single curve for β vs τ derived for the constant velocity (equation 8), (presented as $V_R = 0$ in Fig. 3) may be used to account for the effect of the main bulk velocity too. If non-condensables are present, one may use equation (14) in a similar fashion.

Returning to Fig. 4, one can see that the theoretical approach used here fits the data much better than the stagnant bubble solution represented by equation (1). In the range of $1 > \beta > 0{\cdot}6$, corresponding to some 80 per cent of the possible (volumetric) condensation, we note agreement with the pure vapor solution ($\beta_f = 0$). However, the agreement is better with the solution of equation (19) with $\beta_f = 0{\cdot}4$, which accounts for the presence of noncondensables in the vapor. Although no information is available as to the exact amount of air in this system [11], small amounts of air (0·001–0·004 molar fraction) may have been present. This is consistent with our experience [16] with de-aerated pentane.

In spite of the good agreement between the theory presented here and the experimental data, some assumptions remain in doubt and require further illumination. While the potential flow-field assumption is well founded for relatively large ($R_0 > 0{\cdot}1$ mm) bubbles, it is commonly assumed that smaller bubbles behave as solid spheres. The latter is, in a sense, the justification for assuming the relationship given in equation (17) for the resultant bubble velocity. The apparent conceptual conflict may nevertheless be resolved by reference to equation (3), where k_v, the velocity factor, is introduced to "modify" the potential flow field. This correction, incidentally, would raise the theoretical curves for $\beta_f = 0$ in Fig. 4, particularly in the region of low β and thus improve the correlation.

However, one must note that equation (4) was essentially applied for relatively large bubbles, and a different expression for k_v, somewhat along the conceptual lines of the velocity factor suggested by Conkie and Savic [25], Griffith [26], Chao [27] or Lochiel and Calderbank [28] may be more applicable. These require the knowledge of the true bubble velocity hence none were used here. It is also possible that at this small size range $U_b \sim R^n$ where $2 \geqslant n \geqslant 1$ rather than $n = \frac{1}{2}$ used here. However, since $U_b \ll U_l$ the change will be relatively small. Neither of these ideas were tested, particularly since we only attempted to convey a general frame-work for the effect of motion on bubble collapse.

CONCLUSION

A general framework for the effect of bubble motion on the collapse rate has been suggested for a single bubble of constant and variable rise velocity, including the effect of cross flow. This analysis can easily be extended to include the effect of non-homogeneous distribution of non-condensables within the bubble [29], and following the outlines suggested elsewhere [17, 19] could most probably be applied to multi-bubble systems.

REFERENCES

1. F. C. GUNTHER and F. KREITH, Photographic study of bubble formation in heat transfer to subcooled water, Prog. Rept. No. 4-120. Jet Prop. Lab. Calif. Inst. Tech. (1950).
2. M. E. ELLION, A study of the mechanism of boiling heat transfer, Memo. No. 20-88, Jet Prop. Lab. Calif. Inst. Tech. (1954).
3. K. NISHIKAWA, H. KUSADA and K. YAMASAKI, Growth and collapse of bubbles in nucleate boiling, *Bull. Japan Soc. Mech. Engrs* **8** (30), 205 (1965).
4. V. E. SCHROCK and J. P. PERRAIS, Dynamics of bubbles in a known temperature distribution, *Proceedings 1966 Heat Transfer and Fluid Mechanics Institute*, edited by M. A. SAAD and J. A. MILLER, p. 122. Stanford Univ. Press, (1966).
5. N. ZUBER, Hydrodynamic aspects of boiling heat transfer, USAEC Rept. AECU-4439; Ph.D. Thesis, Univ. of Calif. Los Angeles (1959).
6. S. G. BANKOFF and R. D. MIKESELL, Bubble growth rates in highly subcooled nucleate boiling, *Chem. Engng Prog. Symp. Ser.* No. 29 (1959).
7. L. A. SKINNER and G. S. BANKOFF, Dynamics of vapor bubbles in general temperature fields, *Physics Fluids* **8**, 1417 (1965).
8. L. W. FLORSCHUETZ and B. T. CHAO, On the mechanisms of vapor bubbles collapse, *J. Heat Transfer* **87**, 209 (1965).
9. J. DENEKAMP, A. KOGAN and A. SOLAN, On the condensation of an injected vapor bubble in a sub cooled liquid stream, Proc. Int. Symp. on Two-Phase Systems, *Progress in Heat and Mass Transfer*, Vol. 6, edited by HETSRONI, SIDEMAN and HARTNETT, Pergamon Press, Oxford (1972).
10. F. C. GUNTHER, Photographic study of surface boiling heat transfer to water with forced convection, *Trans. ASME* **73**, 115 (1951).
11. A. H. ABDELMESSIH, F. C. HOOPER and S. NANNGIA, Flow effects on bubble growth and collapse in surface boiling, *Int. J. Heat Mass Transfer* **15**, 115 (1972).
12. N. TOKADA, W. J. YANG and J. A. CLARK, Dynamics of moving gas bubbles in injection cooling, *J. Heat Transfer* 371 (1966).
13. D. D. WITTKE and B. T. CHAO, Collapse of vapor bubbles with translatory motion, *J. Heat Transfer* **89**, 17 (1967).
14. S. SIDEMAN and G. HIRSCH, Direct contact heat transfer with change of phase: condensation of single bubbles in immiscible liquid media-preliminary studies, *A.I.Ch.E. Jl* **11**, 1019 (1965).
15. J. ISENBERG and S. SIDEMAN, Direct contact heat transfer with change of phase: bubble condensation in immiscible liquids, *Int. J. Heat Mass Transfer* **13**, 945 (1970).
16. J. ISENBERG, S. SIDEMAN and D. MOALEM, Direct contact heat transfer with change of phase: bubble collapse with translatory motion in single and two component systems, Proc. 4th Int. Heat Trans. Conf. Paris, Vol. V. pp. 25–28 (1970).
17. D. MOALEM, S. SIDEMAN, G. HETSRONI and A. ORELL, Condensation of a bubble train. An approximate solution, Proc. Int. Symp. on Two-Phase Systems, Haifa, (1971). *Progress in Heat and Mass Transfer*. Vol. 6, edited by HETSRONI, SIDEMAN and HARTNETT, Pergamon Press, Oxford, (1972).
18. D. MOALEM, S. SIDEMAN, G. HETSRONI and A. ORELL, Direct contact heat transfer with change of phase; Condensation of a bubble train. Submitted to *Int. J. Mass Transfer* (June 1972).
19. D. MOALEM and S. SIDEMAN, Analysis of direct contact condensers. Single and two component systems, Int. Centre for Heat Mass Trans., 5th Int. Seminar, Recent Devlp. in Heat Exchangers, Trogir, Yugoslavia (1972).
20. E. RUCKENSTEIN, On heat transfer between vapor bubbles in motion and the liquid from which they are generated, *Chem. Engng Sci.* **10**, 22 (1959).
21. E. RUCKENSTEIN and E. DAVIS, The effects of bubble translation on vapor bubble growth in a superheated liquid, *Int. J. Heat Mass Transfer* **14**, 939 (1971).
22. D. HAMMERTON and F. H. GARNER, Gas absorption from single bubbles, *Trans. Inst. Chem. Engrs* **32**, S18 (1954).
23. L. M. JIJI and J. A. CLARK, Incipient boiling in forced convection channel flow, ASME Paper No. 62-W-202 (1962).
24. L. S. TONG, L. E. EFFERDING and A. A. BISHOP, A photographic study of subcooled boiling flow and DNB of Freon-113 in a vertical channel, Winter Annual Meeting, ASME paper 66-WA/HT-39, N.Y. (1966).
25. W. R. CONKIE and P. SAVIC, Calculation of the influence of internal circulation in a liquid drop on heat transfer and drag, Nat. Res. Council Can. Rept. M.T.-23 (1953).
26. R. M. GRIFFITH, Mass transfer from drops and bubbles, *Chem. Engng Sci.* **12**, 198 (1960).
27. B. T. CHAO, Motion of spherical gas bubbles in a viscous liquid at large Reynolds numbers, *Physics Fluids* **3**, 69 (1962).
28. A. C. LOCHIEL and P. H. CALDERBANK, Mass transfer in the continuous phase around axisymmetric bodies of revolution, *Chem. Engng Sci.* **19**, 471 (1964).
29. D. MOALEM and S. SIDEMAN, Bubble condensation with non-homogeneous distribution of non-condensables, *Int. J. Heat Mass Transfer* **14**, 2151 (1971).

EFFET DU MOUVEMENT SUR LA DEGENERESCENCE D'UNE BULLE

Résumé—On analyse et compare les effets des vitesses de translation de la bulle, constantes ou dépendantes du rayon, sur la vitesse de dégénérescence d'une bulle unique dans un système à un ou deux composants, soit pur soit contenant des incondensables.

On analyse les effets combines de l'accroissement de vitesse de la bulle et de l'écoulement forcé principal près de la surface de l'eau légèrement sous-refroidie. Les résultats sont en excellent accord avec les données expérimentales connues pour la plupart des processus de condensation.

On explore quelques idées sur des améliorations ultérieures et on suggère un cadre général pour analyser la dégénérescence de la bulle dans un champ d'écoulement.

DER EINFLUSS DER BEWEGUNG AUF DEN BLASENKOLLAPS

Zusammenfassung—Die Einflüsse einer konstanten und radiusabhängigen translativen Blasengeschwindigkeit auf die Blasenkondensationsgeschwindigkeit werden untersucht und verglichen, für Ein-und Zweistoffsysteme, mit und ohne Anteil an nichtkondensierenden Bestandteilen. Vorausgesetzt wird ein quasi-stationäres Potential- oder modifiziertes Potential-Strömungsfeld.

Es schliesst sich auch eine versuchsweise Analyse der kombinierten Effekte von Blasenaufstiegsgeschwindigkeit und Haupt-Querströmung bei Zwangskonvektion an für Sieden in leicht unterkühltem Wasser. Die Ergebnisse stimmen sehr gut mit verfügbaren experimentellen Werten für den grössten Teil des Kondensationsprozesses überein. Ideen für weitere Verbesserungen werden untersucht und ein allgemeines Gerüst zur theoretischen Untersuchung des Blasenkollapses in einem Strömungsfeld wird vorgeschlagen.

ВЛИЯНИЕ ДВИЖЕНИЯ НА «СХЛОПЫВАНИЕ» ПУЗЫРЕЙ

Аннотация—Приводится анализ и сравнение влияния постоянной и зависимой от радиуса поступательной скорости пузырей на скорость «схлопывания» единичного пузыря в одно- или двухкомпонентных системах, чистых или содержащих неконденсирующиеся элементы. Состояние потенциального или модифицированного потенциального поля течения предполагается квазистационарным. Сделана попытка проанализировать совместное влияние скорости подъема пузыря и основного потока на процесс кипения слегка недогретой воды при вынужденной конвекции. Полученные результаты отлично согласуются с имеющимися экспериментальными данными для большинства процессов конденсации. Разработана методика дальнейшего усовершенствования, и предложена общая схема анализа схлопывания пузырей в поле течения.