DYNAMICS OF VAPOR-BUBBLE SEPARATION FROM A NOZZLE WITHIN THE VOLUME OF AN UNDERHEATED FLUID

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We examine the dynamics of the formation and separation of vapor bubbles on the discharge of a vapor into an underheated fluid. The results of this analytical study are compared against experimental data.

The direct contact between the vapor phase and a fluid underheated to saturation temperature occurs in a variety of engineering processes. It assumes particular attention in contemporary thermal power engineering. Under conditions of surface boiling of liquids, the intensity with which the vapor phase is removed from the heating surface and the value of the critical heat-flux density are determined by the dynamics of the formation of vapor bubbles and the rate at which they condense in the region of the underheated core of the liquid below. Vapor-phase condensation in the underheated liquid determines the operational efficiency of systems designed to localize emergency situations at an atomic power plant.

Let us examine the equation for the equilibrium of a vapor bubble, subjected at the instant of separation from the nozzle orifice to the action of the following forces: the buoyancy force $F_g = \pi d_b^3(\rho' - \rho'')g/6$, hydrodynamic vapor pressure $F_p = \pi\rho'' v_0^2 d_0^2/4$, surface tension $F_\sigma = \pi d_0 \sigma$, and the force of liquid inertia $F_b = d(mu)/d\tau$, the latter ascribed to the change in the rate of bubble surface growth over time.

A significantly unique feature of the mechanism involved in the formation of the vapor bubbles under the conditions being examined here is the simultaneous presence of two oppositely-directed radial velocities of bubble-surface displacement within the volume of the liquid; the growth of the bubbles is due to the influx of vapor through the nozzle orifice and its simultaneous condensation. The velocity of bubble-boundary displacement in the positive direction (growth) is determined by the expression

$$\left(\frac{dR}{d\tau}\right)_1 = \frac{V_0}{4\pi R^2}. \tag{1}$$

Analysis of the solutions for the rate of bubble growth [1-4] within the volume of a super-heated liquid and the rate of condensation within the volume of an underheated liquid [5-9] demonstrates that these processes are described in analogous fashion and are distinguished only by direction [10]. Under the conditions of the present problem, the vapor bubble condenses during the period of its formation at the nozzle surface. In this connection, it is assumed that the rate of bubble condensation is determined by the expression

$$\left(\frac{dR}{d\tau}\right)_2 = -\beta \frac{a'}{R} \mathrm{Ja}^2. \tag{2}$$

Here $2/\pi \le \beta \le 8/\pi$ [6, 8, 9].

The resulting velocity of bubble-surface boundary displacement is equal to

$$u \equiv \frac{dR}{d\tau} = \left(\frac{dR}{d\tau}\right)_1 + \left(\frac{dR}{d\tau}\right)_2 = \frac{V_0}{4\pi R^2} - \beta \frac{a'}{R} \mathrm{Ja}^2. \tag{3}$$

When the resulting velocity of bubble-surface displacement is equal to 0, a detachment-free regime of vapor injection into the liquid layer sets in. The existence of such a regime has been established experimentally [11, 12] in the boiling of various liquids under conditions of underheating. We assume the following liquid mass (proportional to bubble volume [13]),

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whose motion is governed by the radial velocity of bubble-surface displacement during the bubble formation stage:

$$m = \varepsilon_m 4\pi\rho' R^3/3. \tag{4}$$

With consideration of (3) and (4), the expression for the inertial force of the liquid has the form

$$F_i = \frac{4\pi}{3}\varepsilon_m \rho' R^2 \left(\frac{V_0}{4\pi R^2} - \frac{\beta a' \mathrm{Ja}^2}{R}\right)\left(\frac{V_0}{4\pi R^2} - \frac{2\beta a' \mathrm{Ja}^2}{R}\right) \tag{5}$$

or, after a number of transformations

$$F_i = \frac{\pi\varepsilon_m}{48}\frac{\rho' v_0^2 d_0^4}{d_i^2} - \frac{\pi\beta\varepsilon_m}{2}\frac{\rho' a' v_0 d_0^2 \mathrm{Ja}^2}{d_i} - \frac{8\pi\beta^2\varepsilon_m}{3}\rho' a'^2 \mathrm{Ja}^4. \tag{6}$$

For the instant of vapor-bubble separation from the orifice we have

$$\frac{\pi d_i^3}{6}(\rho' - \rho'')g + \frac{\pi}{4}\rho'' v_0^2 d_0^2 = \pi d_0 \sigma + \frac{\pi\varepsilon_m}{48}\frac{\rho' v_0^2 d_0^4}{d_i^2} - \tag{7}$$

$$- \frac{\pi\beta\varepsilon_m}{2}\frac{\rho' v_0 a' d_0^2 \mathrm{Ja}^2}{d_i} + \frac{8\pi}{3}\beta^2\varepsilon_m \rho' a'^2 \mathrm{Ja}^4.$$

Equation (7) can be reduced to dimensionless form:

$$L^5 + \left(\frac{3}{2}\mathrm{Fr}_* - 6\,\mathrm{We} - 16\beta^2\varepsilon_m k_1 \mathrm{Ja}^4\right)L^2 + 3\beta\varepsilon_m k_2 \mathrm{Ja}^2 L - \frac{\varepsilon_m \rho'}{8\rho''}\mathrm{Fr}_* = 0. \tag{8}$$

For the conditions of vapor injection into the saturated-liquid layer (Ja = 0) Eq. (8) assumes the form

$$L^5 + \left(\frac{3}{2}\mathrm{Fr}_* - 6\,\mathrm{We}\right)L^2 - \frac{\varepsilon_m \rho'}{8\rho''}\mathrm{Fr}_* = 0. \tag{9}$$

Equation (9) was initially derived in an examination of the regimes encountered in the formation of gas bubbles within a liquid layer, and this equation was confirmed through the results of direct measurements [13, 14].

Under the conditions of the present problem, the values for the proportionality factor ε_m, as well as the methods for its direct determination, are unknown. In order to determine this coefficient on the basis of Eq. (8), we made use of experimental data on the detachment dimensions of the vapor bubbles within the volume of an underheated liquid for a variety of geometric, physical and regime parameters in a "vapor-liquid" system [15].

The coefficient β in Eq. (8) was assumed to be equal to 1.592. The experimental material [15] corresponded to the following range of changes in the generalized variables: $\mathrm{Ja} = 1.5$–150; $\mathrm{Fr}_* = 4.7$-12.8; $\mathrm{We} = 0.06$-0.44; $k_1 = (0.3\text{-}5.5)\cdot 10^{-8}$; $k_2 = (0.3\text{-}7.2)\cdot 10^{-3}$.

The found values for the coefficient ε_m were represented as functions of the above-cited generalized variables. Processing of the experimental data enabled us to obtain a theoretical equation in the form

$$\varepsilon_m = 54.6\left(\frac{\mathrm{We}}{\mathrm{Ja}}\right)^{1.15}. \tag{10}$$

The regression equation was presented in logarithmic form. The coefficients in Eq. (10) were determined from a system of normal equations by the method of least squares, with a regression-equation correlation ratio of 0.83. The calculations were performed by Engineer U. M. Brumshtein on an ES-1035 computer with a specially compiled program.

NOTATION

$\mathrm{Fr}_* \equiv \dfrac{\rho'' v_0^2}{(\rho' - \rho'')g d_0}$, modified Froude number; $\mathrm{We} \equiv \dfrac{\sigma}{(\rho' - \rho'')g d_0^2}$, Weber number;

$\mathrm{Ja} \equiv \dfrac{\rho' c_p' \Delta T}{\rho'' r}$, Jacobi number; $k_1 \equiv \dfrac{\rho'(a')^2}{(\rho' - \rho'')g d_0^3}$; $k_2 \equiv \dfrac{\rho' a' v_0}{(\rho' - \rho'')g d_0^2}$, dimensionless parameters; $L \equiv d_b/d_0$ and d_b, detachment dimensions of the bubble; d_0, diameter of nozzle orifice; ρ' and ρ'', densities of liquid and vapor; v_0, vapor velocity in nozzle orifice; σ, coefficient of liquid surface tension; a', coefficient of thermal diffusivity for the liquid; c_p', liquid heat capacity; r, heat of vapor formation; $\Delta T = T_s - T_\ell$, temperature head; T_s, saturation temperature; T_ℓ, liquid temperature; R, instantaneous bubble radius; V_0, volumetric vapor blow rate; τ, time; g, gravitational acceleration.

LITERATURE CITED

1. V. Fritz and V. Ende, Problems in the Physics of Boiling [Russian translation], Moscow, (1964), pp. 162-188.
2. M. Plesset and S. Zwick, Problems in the Physics of Boiling [Russian translation], Moscow (1964), pp. 189-211.
3. H. Forster and N. Zuber, Problems in the Physics of Boiling [Russian translation], Moscow (1964), pp. 212-250.
4. V. F. Prisnyakov, Inzh.-Fiz. Zh., 18, No. 5, 912-915 (1970).
5. S. G. Bankoff and R. D. Mikesell, Chem. Eng. Progr. Sympos., 95, 29-55 (1959).
6. N. Zuber, Int. J. Heat Mass Transf., 2, No. 1, 83-102 (1961).
7. Florshchyuts and Chao, "Heat Transfer," Trans. Am. Soc. Engs., No. 2, 58-72 (1965).
8. A. A. Voloshko and A. V. Vurgaft, Inzh.-Fiz. Zh., 19, No. 2, 206-210 (1970).
9. V. F. Prisnjakov, Int. J. Heat Mass Transf., 14, No. 3, 353-356 (1971).
10. V. F. Prisnyakov, The Physical Theory of Liquid Boiling [in Russian], Dnepropetrovsk, (1977).
11. Yu. A. Kirichenko and N. M. Levchenko, "Investigating the internal characteristics of boiling in underheated cryogenic fluids," Preprint, FTINT Akad. Nauk Ukr. SSR, Khar'kov, (1977).
12. D. M. Kostanchuk, "Investigating the internal characteristics and intensity of heat exchange in the boiling of water with underheating," Author's Abstract of Candidate's Dissertation, Kiev, (1971).
13. A. A. Voloshko, A. V. Vurgaft, and V. N. Frolov, Inzh.-Fiz. Zh., 35, No. 6, 1066-1071 (1978).
14. A. A. Voloshko and V. N. Frolov, Heat and Mass Exchange in Chemical Technology [in Russian], No. 7 (1979).
15. A. D. Kondrat'ev, Inzh.-Fiz. Zh., 50, No. 6, 963-969 (1986).

LAMINAR FLOW REGIME OF A CONDENSATE IN A HORIZONTAL ANNULAR CHANNEL

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We present a method for calculating the angle of the rivulet level in the laminar regime encountered in condensation in an annular channel. The theoretical results are compared to the experimental data derived in studying the hydrodynamic and heat exchange in heat-exchange installations of a new type, namely, vapor-dynamic thermosiphons.

Heating tubes and thermosiphons are finding ever-increasing application in the development of contemporary technological processes involving the exploitation of heat from low-potential sources, in the development of cooling systems for equipment subjected to thermal stresses, for radioelectronic installations, and in the exploitation of secondary and alternative energy sources.

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