GAS—BUBBLE FORMATION IN LIQUID LAYER

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The dynamics of bubble formation and breakaway when a gas issues into a liquid is considered. The different modes of gas-bubble formation in a liquid layer are indicated. The results of analytic investigation are compared with experimental data.

The main characteristics of a gas—liquid layer are the volumetric gas content and phase-contact surface. When the liquid layer is relatively small, these characteristics depend on the rate of gas-bubble formation at the inlet, the breakaway size, and the frequency of breakaway from the gas-distributor equipment.

Analysis of the available work on the determination of gas-bubble breakaway size [1-18] shows that, by making a number of physical assumptions, it has been possible to derive various relations which describe the experimental data in known ranges of the parameters determining the process. However, these relations [2, 4, 10-12, 14] do not have sufficiently clear and physically well-founded limits of application, which complicates the method of calculation of the gas-bubble breakaway size. The available empirical recommendations [4, 5, 13, 17] are restricted by the experimental conditions and cannot claim to be of wide use in computational practice.

The present work considers the equilibrium equation for a gas bubble at the moment of breakaway from the inlet under the action of four forces: the uplift force $F_g = \pi d_b^3(\rho' - \rho'')g/6$, the surface tension $F_\sigma = \pi d_0 \sigma$, the hydrodynamic pressure of the gas $F_p = \rho'' v_0^2 \pi d_0^2/4$, and the inertial force of the liquid $F_i = d(mu)/d\tau$, which determines the change in growth rate of the bubble surface with time.

In solving this problem in [2, 9, 10, 17], the system of forces that are acting was taken to include not only the inertial force of the liquid but also the hydrodynamic drag or viscous force. It is by no means certain that the use of this force in the conditions of gas-bubble formation in the liquid layer has an adequate physical basis. In the given conditions, the gas bubbles do not have the flow regions characteristic of a bubble ascending in the volume of a liquid, and therefore they should not experience a hydrodynamic-drag of the usual form. Experimental results [19] show that change in liquid viscosity by two orders of magnitude has practically no effect on the breakaway size of the gas bubble. Therefore, the viscous force will not be considered in the present work.

The radial growth rate of the bubble surface at constant gas flow rate through an inlet is given by the expression

$$u \equiv \frac{dR}{d\tau} = \frac{Q_0}{4\pi R^2}\,. \tag{1}$$

The liquid mass whose motion is due to the radial growth rate of the bubble as it forms is taken to be proportional to the bubble volume

$$m = \varepsilon_m \frac{4\pi}{3} R^3 \rho'. \tag{2}$$

Taking account of Eqs. (1) and (2), the expression for the inertial force of the liquid takes the form

$$F_i = \varepsilon_m \frac{\pi d_0^4 \rho' v_0^2}{48 d_b^2}\,. \tag{3}$$

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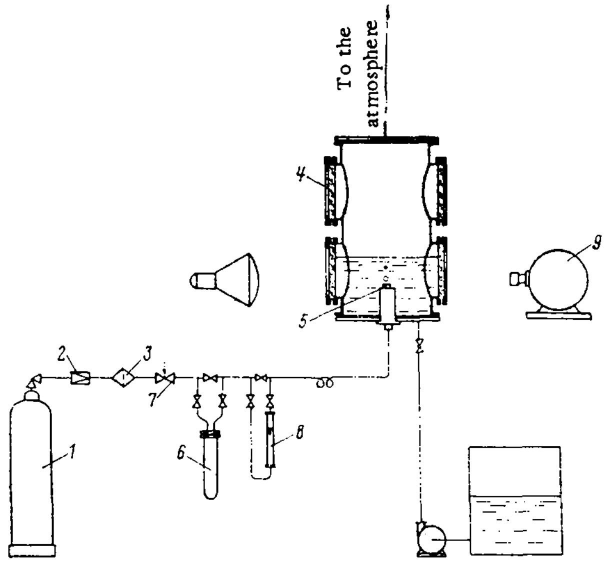

Fig. 1. Experimental apparatus.

For the moment of bubble breakaway from the inlet, the following relation is obtained

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

Certain transformations bring Eq. (4) to the form

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

For near-atmospheric pressures, when $\rho' \gg \rho''$, this relation is simplified

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

Two conclusions follow from Eq. (6).

1) At $\mathrm{Fr} \ll 4(\rho'/\rho'')\mathrm{We}$,

$$L^5-6\mathrm{We}L^2=\frac{\varepsilon_m}{8}\mathrm{Fr}. \tag{7}$$

The solution of Eq. (7) for $\mathrm{Fr} \ll (48/\varepsilon_m)\mathrm{We}L^2$ takes the form

$$L=(6\mathrm{We})^{\frac{1}{3}}. \tag{8}$$

In the given case, Eq. (6) reduces to the well-known particular solution when the gas-bubble breakaway size is determined solely by the value of We.

2) At $\mathrm{Fr} \gg 4(\rho'/\rho'')\mathrm{We}$, Eq. (6) takes the form

$$L^5+\frac{3}{2}\frac{\rho''}{\rho'}\mathrm{Fr}\,L^2=\frac{\varepsilon_m}{8}\mathrm{Fr}. \tag{9}$$

It is evident from Eq. (9) that the gas-bubble breakaway size depends only on Fr.

Thus, there are evidently different modes of gas-bubble formation in the liquid layer. At relatively small Fr, the gas-bubble breakaway size is determined solely by We (static mode). In the other limiting case, when Fr is sufficiently large, there appears a dynamic mode, in which the gas-bubble breakaway size depends solely on Fr. Between these limiting modes, there is a transitional mode, where bubble breakaway

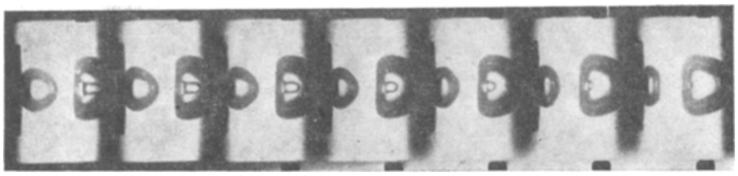

Fig. 2. Cinerecordings of gas-bubble breakaway: water—nitrogen system; $d_0 = 4$ mm; $f = 27.8$ sec^{-1}; Fr = 32.4; We = 0.46.

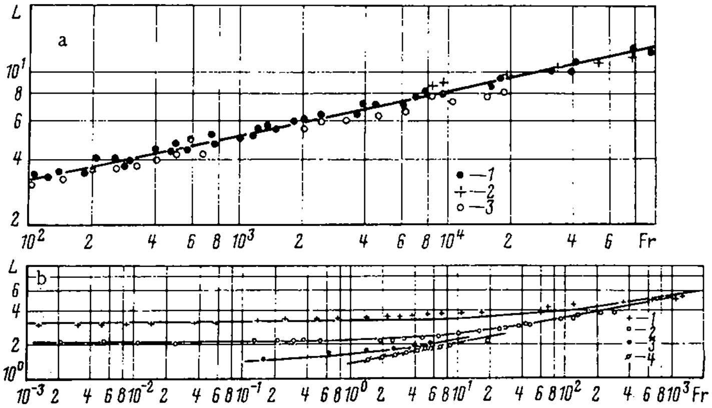

Fig. 3. Comparison of Eq. (6) with experimental results: a) water—air, We = 1.41-5.17 [2] (1); methanol—air, We = 2.0-5.17 [20] (2); water—nitrogen, We = 0.47-1.86 [15] (3); b) water—nitrogen, We = 5.7 (present work) (1); water—nitrogen, We = 1.6 (present work) (2); water—air, We = 0.46 [13] (3); water—nitrogen, We = $7.8 \cdot 10^{-2}$ [15] (4).

from the inlet is controlled by the whole system of forces acting on it and the gas-bubble breakaway size is determined by both We and Fr.

The equations obtained above for the gas-bubble breakaway size in the transient and dynamic modes of formation include the proportionality coefficient ε_m, which is also required for the determination of the region of existence of each mode. Both the value of ε_m and the method for its direct determination are unknown. In the present work, it was estimated using new experimental data and those from the literature on the gas-bubble breakaway size for different geometric, physical, and mode parameters of the gas—liquid system.

The apparatus used in the experiments is shown in Fig. 1. Gas from cylinder 1 was fed through reducer 2 and filter 3 to a vertical vessel of diameter 200 mm and height 500 mm. For visual observation and motion-picture recording of the processes occurring, the vessel was fitted with viewing windows 4. The gas was fed into the liquid through interchangeable cylindrical nozzles 5 with calibrated apertures of diameter 1-6 mm. As a preliminary, the gas was passed through wetting vessel 6. The gas flow rate was varied by a fine-control valve 7. The operating conditions of the apparatus were monitored by means of a rotameter 8 and a strobescopic tachometer. Bubble formation and breakaway was recorded by a SKS-1M high-speed motion-picture camera 9 with a Helios-40 objective. The motion-picture recordings were analyzed using an ÉDI-452 motion-picture decoder at a magnification of the recorded object with respect to the standard by a factor of 10-30. The motion-picture recordings of gas-bubble breakaway shown in Fig. 2 clearly reveal an inertial effect in the region at the back of the bubble due to closure of the bubble surface after breakaway from the nozzle [18].

On the basis of the experimental data corresponding to relatively high Froude number (Fr > 10^2), the coefficient of proportionality ε_m may be determined from Eq. (6). In Fig. 3a, experimental material is compared with Eq. (6) for $\varepsilon_m = 32$. As is evident from Fig. 3a, Eq. (6) provides a good description of the results of direct measurement. For the range of Fr shown in Fig. 3a, Eq. (6) may be approximated by the relation

$$L = 1.3\,\mathrm{Fr}^{0.2}. \qquad (10)$$

In Fig. 3b, Eq. (6) with $\varepsilon_m = 32$ is compared with experimental data corresponding to wide ranges of the Froude ($10^{-3} < \mathrm{Fr} \leq 10^3$) and Weber numbers ($7.3 \cdot 10^{-2} < \mathrm{We} \leq 6.3$). As is evident from Fig. 3b, the experimental data agree with Eq. (6).

On the basis of the foregoing, it may be concluded that Eq. (5) accurately reflects the corresponding dependence over the whole of the practically useful range of the parameters governing the process.

The frequency of gas-bubble formation is also used to analyze the structure of the gas–liquid layer. The volumetric flow rate of gas through the aperture of the gas-distributor apparatus, the gas-bubble breakaway size, and the frequency of bubble formation are related by the expression

$$Q_0 = f\pi d_b^3/6. \tag{11}$$

Considering the equation for the gas-bubble breakaway diameter in conjuction with Eq. (11) allows the frequency of gas-bubble formation in the liquid layer to be calculated.

Equation (11) may be written in the form

$$f = \frac{3}{2}\frac{v_0 d_0^2}{d_b^3} \tag{12}$$

or the dimensionless form

$$K_f = \frac{3}{2}\mathrm{Fr}^{\frac{1}{2}} L^{-3}. \tag{13}$$

NOTATION

$\mathrm{We} = \sigma/(\rho' - \rho'')gd_0^2$, Weber number; $\mathrm{Fr} = v_0^2/gd_0$, Froude number; $K_f = f\sqrt{d_0/g}$; $L = d_b/d_0$; V_b, bubble breakaway volume; $d_b = (6V_b/\pi)^{1/3}$, bubble breakaway diameter; R, current radius of bubble; d_0, inlet diameter; f, bubble breakaway frequency; ρ', ρ'', liquid and gas densities; $g = 9.8\ \mathrm{m/sec^2}$, acceleration due to gravity; σ, surface tension; Q_0, volumetric flow rate of gas through inlet; v_0, gas velocity at inlet; τ, time.

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