ONSET OF JETTING FOR DISPERSION OF A GAS INTO A LIQUID

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Criteria for determining the conditions for the onset of jetting for a gas dispersing into a liquid are analyzed. The results of an experimental investigation are compared with computed relations.

When gas bubbles are formed from the orifices in a gas-dispersing system several regimes are observed in the liquid layer: static, transient, and dynamic [1]. It is experimentally established [2] that as the flow rate of the gas increases there arises a dispersing regime in which bubbles penetrate into one another, coalesce, and create a complicated pulsating gas–liquid structure at the orifice. Under these conditions, it is quite difficult to distinguish and determine the sizes of separate bubbles. Such a regime is usually called the jetting regime of a gas dispersing into a liquid.

In [3, 4] it was assumed that the condition for the onset of jetting is a continuous rising of gas bubbles in the liquid layer above the orifice. The following expression was obtained for this model:

$$v_{cr} = \frac{2}{3} u_b \left(\frac{d_b}{d_0}\right)^2. \tag{1}$$

The lift velocity of gas bubbles was usually taken as equal to u_b = 0.25 m/sec, while the contact breaking sizes of bubbles were estimated by the relation

$$\frac{d_b}{d_0} = (6\mathrm{We})^{\frac{1}{3}}. \tag{2}$$

It is shown in [5-7] that for deformed bubbles in a low viscosity liquid

$$u_b = \left[\frac{2\sigma}{d_b(\rho' - \rho'')} + \frac{d_b(\rho' - \rho'')g}{2\rho'}\right]^{\frac{1}{2}}. \tag{3}$$

Taking into account Eqs. (2) and (3), expression (1) can be written in the following dimensionless form:

$$\mathrm{Fr}_{cr} = 4.40 \frac{\rho' - \rho''}{\rho'} \mathrm{We}^{\frac{5}{3}} + 5.33\mathrm{We}^2. \tag{4}$$

The analysis of the conditions for the onset of jetting in [8, 9] is based on a computational model in which it was assumed that when a gas bubble breaks away there exists a liquid film, which is subjected to the action of a system of forces, between the orifice and the neck of the bubble. The condition for the onset of jetting is considered to be the instant when the liquid film loses stability and gas from the orifice coalesces with the gas bubble above it. The result of this analysis was a relation which can be represented in the form

$$\frac{1}{2}\left(\frac{\rho''}{\rho' - \rho''}\right)\mathrm{Fr}_{cr} - \frac{1}{4}\left(\frac{\pi}{4}\right)^{\frac{2}{5}}\mathrm{Fr}_{cr}^{\frac{1}{5}} = \mathrm{We}. \tag{5}$$

Kutateladze suggested [6] the following relation for a quantitative characterization of the conditions for the onset of the hydrodynamic regime for the dispersion of gas into the liquid in which the liquid is forced away from the permeable solid wall:

$$k = \frac{v_{cr}\sqrt{\rho''}}{[(\rho' - \rho'')g\sigma]^{\frac{1}{4}}}. \tag{6}$$

From (6) we obtain

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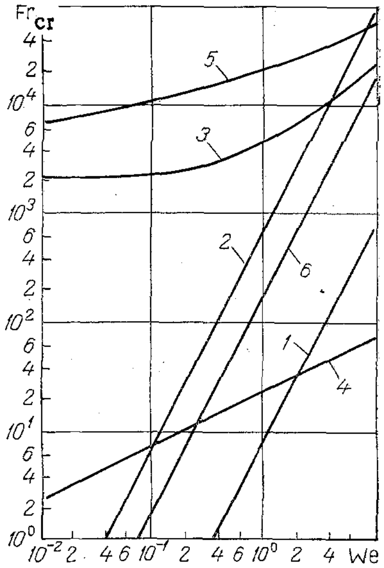

Fig. 1. Critical Froude number as a function of the Weber number: 1) from Eq. (4); 2) from (8); 3) from (5); 4) from (7); 5) from (9); 6) from (10).

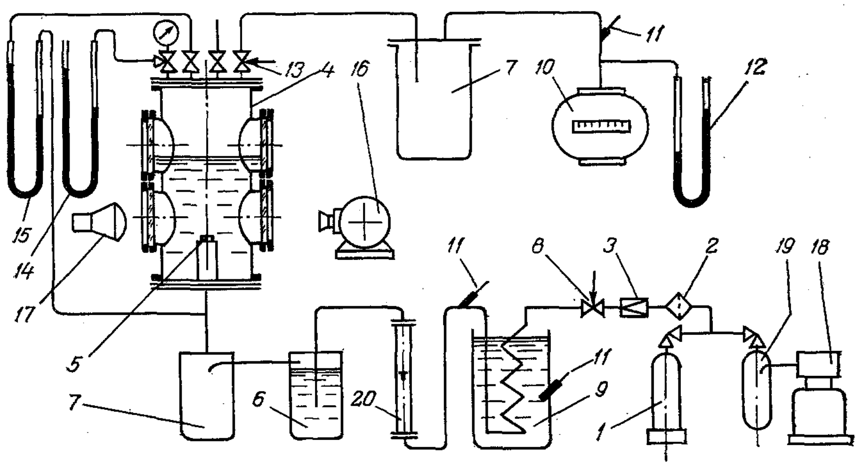

Fig. 2. Diagram of the experimental setup: 1) flask; 2) filter; 3) reducer; 4) steel vessel; 5) nozzle; 6) humidifier; 7) steam trap; 8) regulating valve; 9) thermostat; 10) gas meter; 11) thermometer; 12) manometer; 13) regulating valve; 14) manometer; 15) differential manometer; 16) high-speed camera; 17) flash lamp; 18) compressor; 19) receiver; 20) rotameter.

$$\mathrm{Fr_{cr}} = k^2 \left(\frac{\rho' - \rho''}{\rho''}\right) \mathrm{We}^{\frac{1}{2}}. \tag{7}$$

In order to determine the gas flow rate corresponding to the onset of jetting, Brauer [10] obtained an empirical equation, which has the following dimensionless form:

$$\mathrm{Fr_{cr}} = 675 \left(\frac{\rho' - \rho''}{\rho'}\right)^2 \mathrm{We}^2. \tag{8}$$

The results of an experimental investigation of the transition from jetting to bubbling is represented in [11] by the relation

$$\mathrm{Fr_{cr}} = \frac{h}{d_0}\left(\frac{\rho' - \rho''}{\rho''}\right) + 14.6 \left(\frac{\rho' - \rho''}{\rho''}\right) \mathrm{We}^{\frac{1}{2}}. \tag{9}$$

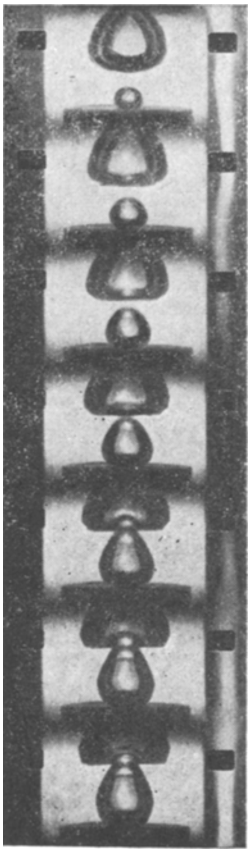

Fig. 3. Motion picture frames showing the onset of jetting. The system is nitrogen–water; d_0 = 2.15 mm; v_0 = 2.86 m/sec; We = 1.6; Fr = 387.

We calculated (Fig. 1) the critical Froude number as a function of the Weber number from Eqs. (4), (5), (7), (8), and (9) for system pressures close to atmospheric ($\rho''/\rho' = 10^{-3}$). In (7), the parameter k was set as equal to 0.15 and in (9), h/d_0 = 6. It is evident from the figure that the computed relations presented for determining the conditions for the

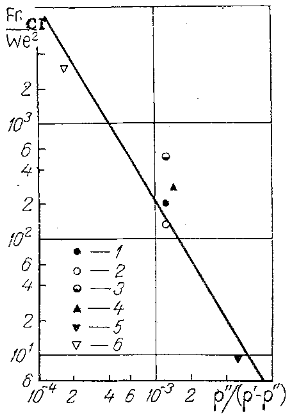

Fig. 4. Graph of the results of the investigation of the conditions for the onset of jetting: 1) nitrogen–water, nozzle; 2) nitrogen–water, nozzle with a capillary pipe; 3) nitrogen–water, opening in an element Ø 89·4.5 mm; 4) nitrogen–isopropyl alcohol, nozzle; 5) freon-12–water, nozzle; 6) helium–water, nozzle.

onset of jetting differ significantly. At the present time, there is no unified generally accepted and physically sound model for the transition from bubbling to jetting. The available experimental data are very limited, often contradictory, and are distinguished by a certain uncertainty.

The experimental investigation of the conditions for the onset of jetting for a gas dispersing into a liquid was carried out on an experimental setup, the line diagram for which is shown in Fig. 2. Gas from the high pressure flask entered through the filter and the reducer into a steel vessel with viewing windows for visual observation and photographing. The gas was input into the liquid layer through replaceable cylindrical nozzles with an orifice diameter of 1-6 mm, as well as through an orifice in the wall of the cylindrical element with diameter 89 mm, length 100 mm, and wall thickness 4.5 mm.

The gas was first humidified and then passed through a steam trap. The flow rate of the gas was varied by a fine regulating valve. The experiments were carried out under isothermic conditions ($t \sim 20°C$) on the following systems: water—nitrogen; isopropyl alcohol—nitrogen; water—freon-12; water—helium at pressures of 10^5-$2 \cdot 10^6$ Pa. The gas temperature was maintained equal to the temperature of the liquid with the help of a thermostat and was controlled by a copper—constantan thermocouple, placed at the inlet to the nozzle. The volume flow rate of gas was measured with the help of a GSB-400 gas meter and a timer.

A picture of the gas dispersing into the liquid was taken with high-speed SKS-1M camera with a Gelios-40 objective. The exposure rate was varied in the range 1500-2500 frames/sec. The film was processed with an EDI-52 type film reader with magnification of 10-20.

Figure 3 shows a typical sequence of motion pictures of the dispersion of a gas into a liquid layer, when bubbles at the orifices begin to penetrate into one another and coalesce. This picture corresponds to the transition from a dynamic bubbling regime into a jetting regime.

Figure 4 shows a graph of the experimental data corresponding to the conditions indicated. The experimental data are described by the relation

$$Fr_{cr} = 2.4 \cdot 10^{-3} \left(\frac{\rho' - \rho''}{\rho''} \right)^{1.65} We^2. \qquad (10)$$

NOTATION

$We \equiv \sigma/(\rho' - \rho'')gd_0^2$, Weber's number; $Fr_{cr} \equiv v_{cr}^2/gd_0$, Froude's number; σ, coefficient of surface tension; ρ' and ρ'', liquid and gas densities, respectively; $g = 9.8$ m/sec^2, acceleration of gravity; d_0, orifice diameter; v_{cr}, velocity of the gas in the orifice with the onset of jetting; d_b, separation diameter of a bubble; h, height of the level of clear liquid; u_b, lift velocity of a bubble.

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DETERMINATION OF PARTICLE DENSITY IN TWO-PHASE FLOW

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A method is proposed for determining the mass concentration of the dispersed phase in gas flows from the displacement of the Mach disk during discharge of an underexpanded stream into a vacuum.

The development of a number of fields of engineering and technology, in particular plasma metallurgy and chemistry, requires devising new methods for monitoring the mass fraction of the dispersed phase. Many methods are known for determining the content of the dispersed phase, based on the sampling of particles, the interaction of the medium with corpuscular and electromagnetic probing radiation, and the variation of the electrokinetic and aerodynamic properties of the medium [1-4]. However, the upper limit of the values of the mass fraction of the dispersed phase φ which can be measured by any of these methods is severely restricted. When aspiration methods are used in high-speed high-temperature flows with a large particle content, particles are deposited in the samplers and clog them. The radiation scattering and absorption coefficients of the medium and the variation of its electrical and aerodynamic parameters at high particle densities become nonlinear functions whose form we cannot predict theoretically. Thus, the measurement of values of the mass fraction of the dispersed phase which are near unity is a complex problem.

A method proposed in [5] is based on the determination of the effect of the dispersed phase on the position of the normal shock in an underexpanded jet. It was found experimentally [6] that the introduction of solid particles into a supersonic underexpanded gas jet emerging from a nozzle has an appreciable effect on the shape and position of shock waves. As φ is increased, the jet spreads out, and the normal shock approaches the nozzle exit.

The position of the normal shock on the jet axis can be very accurately determined with a total pressure transducer using a standard technique, or by any noncontact method. Thus, e.g., in dense streams shadow devices [7] can be used, and in diffuse gases glow discharge [8] or an electron beam [9].

The effect of the solid phase on the position of the normal shock in a supersonic underexpanded jet of a mixture can be calculated by using a flow model [10] describing the properties of the jet under the assumption that it is equivalent to two-phase flow of a gas with an effective value of the isentropic exponent given by

$$\lambda = \gamma \frac{1+\varphi(\bar{c}_p/c_p)}{1+\varphi\gamma(\bar{c}_p/c_p)}, \tag{1}$$

where γ is the isentropic exponent, and $\bar{c}_p/c_p$ is the ratio of the specific heats of the particles and of the gas at constant pressure. For one-dimensional two-phase flow [11] with equal velocities and temperatures of particles and gas, the relative change of the distance from the nozzle exit to the normal shock as a function of φ and the Mach number Ma at the nozzle exit is given by

$$\frac{\overline{X}}{X_0} = \left\{\frac{\lambda^2(\lambda-1)(\gamma+1)(2\gamma-1)[1+2/(\lambda-1)\,\overline{\mathrm{Ma}}^2]}{(\lambda+1)(2\lambda-1)\gamma^2(\gamma-1)[1+2/(\gamma-1)\,\mathrm{Ma}^2]}\right\}^{1/2}\left(\frac{\overline{\mathrm{Ma}}}{\mathrm{Ma}}\right)^2, \tag{2}$$

where $\overline{X}_0$ and X_0 are, respectively, the positions of the normal shock in pure gas and in the presence of the dispersed phase; $\overline{\mathrm{Ma}}$ and Ma are the Mach numbers at the nozzle exit under those same conditions. When the velocity of the particles in the stream is less than the velocity of the gas, i.e., for large enough particles, the position of the normal shock is given by

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