STRUCTURE OF TWO-PHASE PISTON FLOW IN VERTICAL DUCTS

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A simplified model of the piston flow of a two-phase mixture is analyzed. A comparison of the results of the analysis with experimental data exhibits good agreement between them.

One of the main regimes of two-phase flow in ducts is the piston-flow regime [1-3]. It is characterized by the successive passage of large gas voids (pistons, or "slugs") and liquid plugs, which occupy almost the entire cross section of the duct. Heat-exchanger components present in the flow are subjected to powerful transient forces exerted by the flow, which in a number of cases produce vibrations and other unwanted effects. For the engineering analysis of the intensity of the vibrations, which strongly affect the operational reliability of present-day power-generating equipment [4], it is necessary to know the characteristic frequency of the pulsation processes involved in two-phase flow [5]. This can only be accomplished on the basis of a consideration of its internal structure. However, the available information on the internal structure of piston flows has been limited and sporadic to date [6-9].

The objective of the present study is to generalize the authors' own and other published experimental data on the structure of piston flow in vertical ducts of constant cross section on the basis of a simple physical model.

Piston flow is depicted as a periodic sequence of alternating bubble-flow and annular-flow structures (Figs. 1a and 1b). Assuming that the velocity profile conforms to the graph in Fig. 1c, gas bubbles are absent in the liquid wall film, and no-slip conditions exist between the gas bubbles and the liquid in the liquid plug, we obtain relations (1)-(4) below between the fundamental parameters of the model.

The time-average value of the true volume gas content $\bar{\varphi}$ is

$$\bar{\varphi} = (\varphi_{gs}\tau_{gs} + \varphi_{Lp}\tau_{Lp})/T = \varphi_{gs}\psi + \varphi_{Lp}(1-\psi). \qquad (1)$$

Here ψ is the fraction of the time interval between gas slugs relative to the total period:

$$\psi = \tau_{gs}/T = l_{gs}/L. \qquad (2)$$

The mean-square intensity σ_φ of the pulsations of the true volume gas content is

$$\sigma_\varphi^2 = \overline{(\varphi - \bar{\varphi})^2} = (\bar{\varphi} - \varphi_{Lp})(\varphi_{gs} - \bar{\varphi}). \qquad (3)$$

The true velocity of the gas slug is related to the quantities $\bar{\varphi}$, $w''_0 = Q''/A$, $w_{mx} = (Q'' + Q')/A$, $\beta = w''_0/w_{mx}$ by the equation

$$v_{gs} = \frac{w''_0}{\bar{\varphi}} = \frac{\beta w_{mx}}{\bar{\varphi}}. \qquad (4)$$

The velocity of motion of the phase interface in the given model is equal to the velocity of the slugs. In this case the frequency f_0 of the pulsations of the flow parameters is

$$f_0 = \frac{1}{T} = \frac{v_{gs}}{L} = \frac{v_{gs}}{l_{gs} + l_{Lp}}.$$

A number of relations have been published to date [1-3, 10, 11] between the values of the true volume gas content $\bar{\varphi}$ and the volume-flow gas content β. They can be used to determine the velocity v_{gs} of the gas slug according to Eq. (4). Thus, in order to determine the

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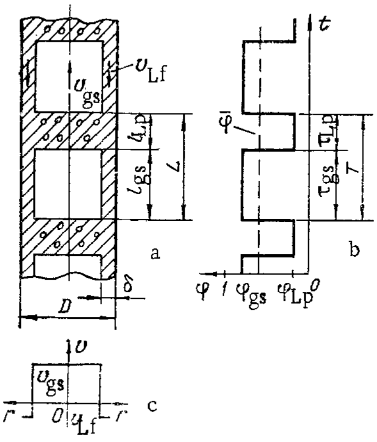

Fig. 1

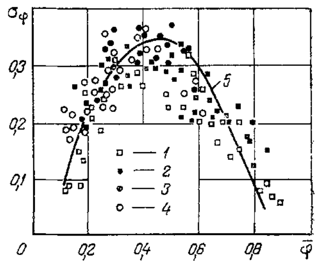

Fig. 2

Fig. 1. Model of piston flow. a) Geometrical structure of the flow; b) time variation of the gas content; c) velocity profile.

Fig. 2. Rms intensity of the pulsations of the true volume gas content vs its average value. 1) Present authors' data for air–water, duct diameter 40 mm, p = 0.1 - 0.2 MPa, w_{mx} = 0.4 - 8 m/sec; 2) present authors' data for air–water, duct diameter 20 mm, p = 0.1 - 0.2 MPa, w_{mx} = 0.3 - 4.8 m/sec; 3) data of [8] for air–water, duct diameter 21 mm, p = 0.1 MPa, w_{mx} = 0.25 = 2 m/sec; 4) data of [9] for steam–water, duct diameter 18 mm, p = 0.1 - 7.0 MPa, w_{mx} = 0.3 - 2.7 m/sec; 5) calculated according to (3).

pulsation frequency it is required to have access to data on the lengths of the gas slug and the liquid plug.

Expressions (1) and (2) imply the relation

$$l_{gs} = l_{Lp}(\bar{\varphi} - \varphi_{Lp})/(\varphi_{gs} - \bar{\varphi}). \tag{6}$$

Substituting Eqs. (4) and (6) into (5), we obtain

$$f_0 = \frac{\beta w_{mx}(\varphi_{gs} - \bar{\varphi})}{\bar{\varphi} l_{Lp}(\varphi_{gs} - \varphi_{Lp})}. \tag{7}$$

To test the fundamental postulates of the model and to determine the unknown values of the parameters entering into it we have carried out an experimental study of the pulsations of the true volume gas content of an adiabatic air–water flow stabilized against the external environment during ascending motion in tubes. The experimental arrangement and the procedure for measuring the instantaneous values of φ are described in [6]. On the basis of simultaneous plots of $\varphi(t)$ in different cross sections of the duct we determined the rms pulsation intensity σ_φ, the velocity v_{gs} of the slugs, and the lengths l_{Lp} of the liquid plugs and l_{gs} of the gas slugs.

Figure 2 shows our results obtained for σ_φ as a function of $\bar{\varphi}$. Also plotted on the same graph are the data of Subbotin and others [8, 9]. The quantity σ_φ was determined from the quantities ψ, $\bar{\varphi}$, φ_{Lp}, φ_{gs} measured experimentally by the cited authors, according to the relation

$$\sigma_\varphi^2 = (\varphi_{gs} - \bar{\varphi})^2\psi + (\varphi_{Lp} - \bar{\varphi})^2(1 - \psi).$$

It is seen that despite the very broad range of variation of the regime parameters, the experimental data are tightly clustered around the curve calculated according to Eq. (3) for φ_{gs} = 0.79 and φ_{Lp} = 0.11.

The results of generalizing the experimental data on the lengths l_{Lp} and l_{gs} are shown in Fig. 3. Particularly noteworthy is the fact that the lengths of the liquid plugs for both air–water and steam–water flows are independent of the flow regime parameters and are

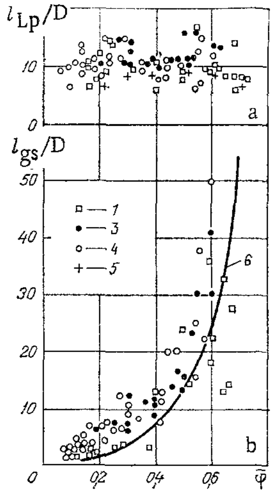

Fig. 3

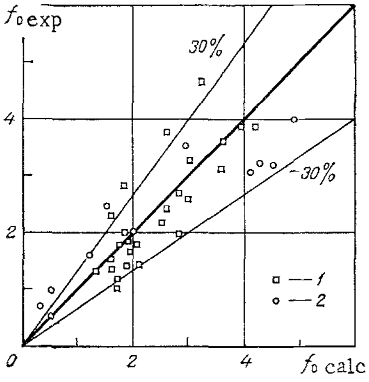

Fig. 4

Fig. 3. Dimensionless lengths of the liquid plugs (a) and gas slugs (b) vs true volume gas content. 1-4) See Fig. 2; 5) data of [7] for air-water, duct diameter 27.6 mm, p = 0.1 - 0.2 MPa, w_{mx} = 0.3 - 2.3 m/sec; 6) calculated according to (6).

Fig. 4. Comparison of the calculated and experimental values of the frequency (Hz) of pulsations of the two-phase flow. 1) Cylindrical duct, diameter 40 mm, p = 0.1 - 0.2 MPa, w_{mx} = 0.4 - 8 m/sec; 2) annular duct, diameter 30/16 mm, p = 0.14 - 0.26 MPa, w_{mx} = 0.8 - 2.4 m/sec.

determined entirely by the diameter of the duct (see Fig. 3a). The following relation can be used to determine l_{Lp}, correct to within the statistical scatter limits:

$$l_{Lp}/D = 10. \tag{8}$$

The indicated effect is evidently attributable to the stability of the vortex generated in the liquid plug as a result of the velocity difference between the central region of the duct and the wall zone. Of course, the size of the vortex is determined primarily by the duct diameter D.

Relations (6) and (8) can be used to determine the lengths of the gas slugs analytically. It is evident from Fig. 3b that the resulting analytical curve corresponds qualitatively to the experimental data obtained over a wide range of pressures and flow velocities of air-water and steam-water mixtures.

It is important to stress the fact that the experimental data are well described by single curves only as a function of the true volume gas content. Attempts to generalize the data in other coordinates cause them to be segregated. This fact evinces the decisive role of the true volume gas content in the evolution of the flow structure.

It follows from expressions (6) and (8) that the length of the gas slug varies from zero to infinity as $\bar{\varphi}$ varies from $\varphi_{Lp} \simeq 0.11$ to $\varphi_{gs} \simeq 0.79$. It appears that the case $l_{gs} = 0$ can be identified with the transition from bubble to piston flow, and the case $l_{gs} = \infty$ with the transition from piston to annular flow. Accordingly, the values of $\bar{\varphi}$ = 0.11 and 0.79 can be used as the limiting values for the existence of the piston-flow regime. The results are in satisfactory agreement with the data of [1-3, 10].

With regard for the characteristics obtained for the gas slugs and liquid plugs, the equation (7) for the frequency f_0 acquires the form

$$f_0 = \frac{\beta w_{mx}(0.79 - \bar{\varphi})}{6.8\bar{\varphi}D}. \tag{9}$$

Figure 4 shows the experimental data for a vertical tube and an annular duct in comparison with calculations according to Eq. (9). The characteristic diameter of the annular duct was determined from the channel cross section: $D = \sqrt{4A/\pi}$. The experimental and calculated values of f_0 agree within ±30% limits.

NOTATION

φ, true volume gas content; t, time; τ, time interval; T, period; l, length; L, total length; D, duct diameter; A, channel cross section; v, true velocity; w_0, reduced velocity of medium; Q, volume flow; f_0, frequency of pulsations of two-phase flow parameters; β, volume flow gas content; p, pressure. Indices: $^-$(overbar), time average; ", gaseous phase; ', liquid phase; gs, gas slug; Lp, liquid plug; Lf, liquid film; mx, two-phase mixture; exp, experimental; calc, calculated.

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