4. B. N. Zaslavskii and I. M. Sotnikov, Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 20-26 (1983).
5. H. Lamb, Hydrodynamics [Russian translation], Moscow–Leningrad (1947).
6. H. Yamada and T. Matsui, Phys. Fluids, 21, No. 2, 292-294 (1978).
7. P. G. Saffman, Stud. Appl. Math., 49, No. 4, 371-380 (1970).
8. V. I. Boyarintsev, A. S. Savin, and E. S. Levchenko, Abstracts of Reports. All-Union Congress on Theor. and Appl. Questions of Turbulent Flows [in Russian], Tallin (1985).
9. K. V. Migalin, V. K. Lyakhov, and S. Ya. Grabarnik, Izv. Vyssh. Uchebn. Zaved., Aviats. Tekh., No. 1, 108-111 (1987).

INVESTIGATION OF PRESSURE FLUCTUATIONS IN A HORIZONTAL GAS–FLUID FLOW

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A method is proposed to compute the amplitude of pressure fluctuations in a horizontal gas–liquid flow.

The fluid in a gas–liquid plug flow is distributed between the seals (plugs) and the liquid film (Fig. 1) in a gas–fluid plug flow. The rapidly moving seal captures the liquid from the film and accelerates it to the velocity of the plug. The same quantity of liquid is lost here from the rear part of the plug by forming a film with the free surface which is retarded because of the braking action of the tube walls and then is captured by the next plug.

The pressure profile along the length of the flow at a fixed time is shown in Fig. 1. The abrupt growth of the pressure in the forward part of the plug Δp_a is due to forces needed to accelerate the liquid from the film to the velocity of the plug. In the next zone the linear diminution of the pressure occurs because of friction. The pressure in the film zone is almost constant since the flow velocity is much less than in the plug.

We find the amplitude of the pressure fluctuations in the stream, equal to Δp_a, from the impulse equation

$$\Delta p_a = \frac{G_c}{F}(u_1 - u_2). \tag{1}$$

The mass flow rate of the liquid captured from the film G_c is found from the mass conservation equation

$$G_c = \rho_\ell F \varphi_{\ell 2}(c - u_2). \tag{2}$$

Analysis of the material balance equation of the liquid and gas phases showed [1] that the velocity of the liquid in the plug is quite close to the average velocity of the mixture over the tube section

$$u_1 = u_m = \frac{1}{F}\left(\frac{G_\ell}{\rho_\ell} + \frac{G_g}{\rho_g}\right). \tag{3}$$

Experimental confirmation of this situation is disclosed by the discrepancy of less than 5% between u_1 and u_c [1].

The phase velocity that equals the mean true gas velocity over the section u_g according to experimental data [1, 2] exceeds the fluid velocity in the plug by a quantity due to the influx of liquid from the film

$$c = u_g = \frac{\beta_g}{\varphi_g} u_m = u_1 + \frac{G_c}{\rho_\ell F \varphi_{\ell 1}} = u_1 + \frac{\varphi_{\ell 2}}{\varphi_{\ell 1}}(c - u_2). \tag{4}$$

The joint solution of (1)-(4) yields

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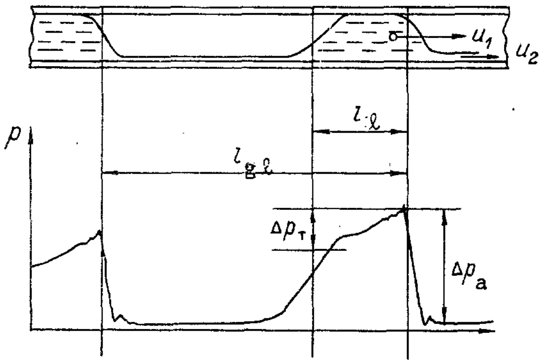

Fig. 1. Pressure profile along the length of a gas–liquid plug flow.

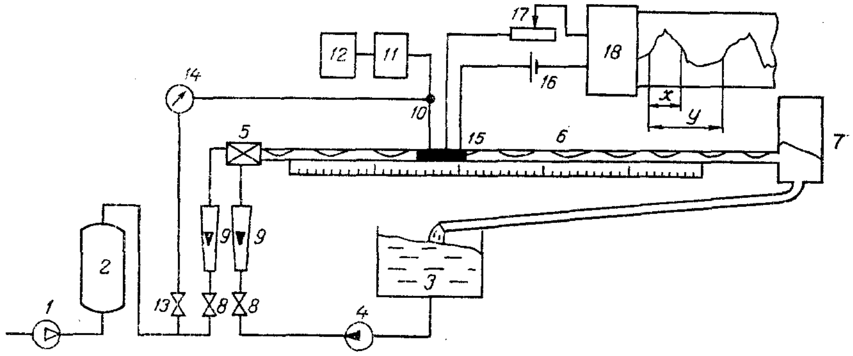

Fig. 2. Diagram of the experimental installation.

$$\Delta p_y = \rho_\ell \varphi_{\ell 1} \left(\frac{1-k}{k}\right)^2 \left(\frac{\varphi_{\ell 1}}{\varphi_{\ell 2}} - 1\right) u_m^2 . \tag{5}$$

The ratio between the true and the discharge gas content $k = \phi_g/\beta_g$ for the plug gas–liquid flow is computed from the formula [3]

$$k = k_v[1 - \exp(-4{,}4\sqrt{\mathrm{Fr}/\mathrm{Fr}_s})]. \tag{6}$$

The magnitudes of the true volume liquid concentrations in this expression in the plug zone $\phi_{\ell 1}$ and the film $\phi_{\ell 2}$ can be expressed in terms of the length of the gas–liquid plug $\ell_{g\ell}$ and the liquid seal ℓ_ℓ. By definition of the true volume flow concentration $\phi_\ell = 1 - k\beta_g = [\phi_{\ell 1}\ell_\ell + \phi_{\ell 2}(\ell_{g\ell} - \ell_\ell)]/\ell_{g\ell}$, from which

$$\varphi_{\ell 2} = \frac{1 - \varphi_{\ell 1}\bar{l}_\ell}{1 - \bar{l}_\ell} = \frac{k\beta_g}{1 - \bar{l}_\ell}, \tag{7}$$

where $\bar{\ell}_\ell = \ell_\ell/\ell_{g\ell}$. Substituting this expression into (5) we obtain

$$\Delta p_a = \rho_\ell \varphi_{\ell 1} \left(\frac{1-k}{k}\right)^2 \left[\frac{\varphi_{\ell 1}(1 - \bar{l}_\ell)}{(1 - \varphi_{\ell 1}\bar{l}_\ell) - k\beta_g} - 1\right] u_m^2 . \tag{8}$$

The true volume liquid content in the plug is usually close to one. However, some authors [4, 5] noted the appearance of a noticeable quantity of gas in the liquid seals as the mixture velocity increased, which is associated with vortex formation in the forward part of the plug during capture of the liquid from the film. Evidently, the maximal amplitude of the fluctuations is achieved for $\phi_{\ell 1} = 1$, i.e., when there is no gas in the seals. Consequently, we obtain the following expression to estimate the greatest possible amplitude

$$\Delta p_a = \rho_\ell \left(\frac{1-k}{k}\right)^2 \left(\frac{1}{1 - \frac{k}{1 - l_\ell}\beta_g} - 1\right) u_m^2 . \tag{9}$$

The ratio of the length of the liquid seal to the length of the gas-liquid plug $\bar{\ell}_\ell$ must be known for computations using this equation.

The recommendations known at this time for determination of the plug length are quite contradictory. It is impossible to use some [1] for specific computations because they require knowledge of quantities not ordinarily known in practice. Others [4], developed on

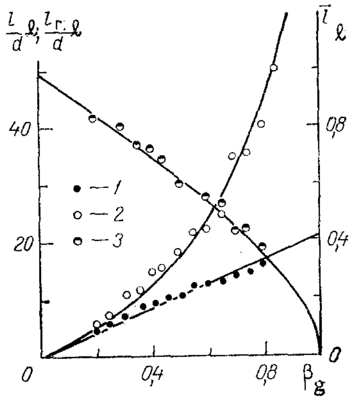

Fig. 3

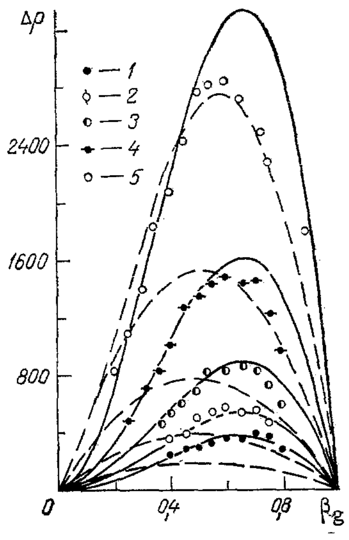

Fig. 4

Fig. 3. Plug lengths in a horizontal gas–liquid flow: 1) length of the liquid part of the plug ℓ_ℓ; 2) length of the gas–liquid plug $\ell_{g\ell}$; 3) relative length of the liquid part of the plug $\bar{\ell}_\ell$.

Fig. 4. Amplitude of the pressure fluctuations in a horizontal gas–liquid flow in a tube d = 56 mm: 1) Fr = 1; 2) 2; 3) 4; 4) 8; 5) 16. Solid lines are a computation using the method proposed and the dashes are a computation according to [5]. Δp, mm water column.

the basis of experimental material obtained in a broad range of tube diameters, physical properties of the liquid and the gas, yield physically impossible results in the limit cases of a single-phase flow. Consequently, the purpose of our paper is the experimental invesgigation of the influence of different two-phase flow parameters on the plug length and the generalization of known results of other researchers, as well as comparison of computations of the pressure fluctuation amplitudes by means of (9) with values obtained for $\bar{\ell}_\ell$ taken into account and those measured in tests.

The measurements were performed on the experimental installation whose block diagrams represented in Fig. 2. air from the compressor 1 is delivered through the plenum 2 and water from the tank 3 is pumped by 4 into the mixer 5 in the form of a T-joint. The motion of the gas–liquid mixture occurred in horizontal glass tubes of length 4.2 m and inner diameter of 13, 20, and 56 mm, after the experimental section 6 the mixture went to the separator 7 from which the air was ejected into the atmosphere while the water was returned to the tank 3. The liquid and gas mass flow rates were regulated by valves 8 and measured by rotameters of the RS-3, RS-5, and RS-7 type [9].

A membrane strain gauge sensor of sensitivity 2 mm of a water column per 1 mm of the recorder scale 12 mounted at a distance of 2.7 m from the mixer was the pressure sensor 10. A counterpressure whose magnitude was regulated by the valve 13 and selected by using the manometer 14 so that the sensor would operate on the linear section of the characteristic was delivered to the membrane sensor. The signal from the sensor was magnified by a TA-9 type strain station 11.

The plug lengths were measured by using the electrical dip stick 15 made from copper electrically insulated wire of 0.5 mm diameter and placed in the stream by an uninsulated endface at a distance of 1-1.5 mm from the upper generator of the tube, while the working fluid was the comparison electrode. A constant voltage was delivered to the electrodes from a galvanic cell 16 of 165 U type, which was regulated by the potentiometer 17. The current in the electrical dip stick loop was recorded on 18. The passage of the liquid plug whose length was determined from the formula ℓ_ℓ = cx/W was determined by an abrupt rise in the current. The length of the gas–liquid plug was computed from the formula $\ell_{g\ell}$ = cy/W.

The plug flow of a gas–liquid mixture is probabilistic in nature since the plug lengths fluctuate in a certain range. For instance, according to the data of [1] the deviation of the length of a liquid plug from the mean value reaches 35% and the pressure drop on the plug (the sum of Δp_a and Δp_f) is 20%. In practice it is important to know not only the mean values of the plug lengths and the pressure fluctuation amplitudes but also the maximally possible magnitudes.

Tests were performed for fixed values of the mixture Froude number equal to 1, 2, 4, 8, 16 and a varying bulk mass flow rate gas content from 0.2 to 0.8 with a spacing of 0.05. Twenty measurements were made in each mode.

The results of measuring the average values of the liquid and gas–liquid plug lengths as well as the quantities $\tilde{\ell}_\ell$ are represented in Fig. 3. The solid lines correspond to empirical formulas obtained by processing experimental data:

$$l_\ell = 21d\beta_g, \tag{10}$$

$$l_{g\ell} = \frac{85\beta_\ell^{1,25}d}{1+2\beta_\ell}, \tag{11}$$

$$\bar{l}_\ell = 1 - k\left(1 + \frac{0,0026}{\beta_\ell\beta_g^2}\right)\beta_g. \tag{12}$$

Results of measuring averaged values of the pressure fluctuation amplitude in a 56-mm-diameter tube are represented in Fig. 4. Results of computations using (9) in which the magnitude of $\bar{\ell}_\ell$ was computed by using (12) are shown by solid lines and computations using the method in [5] by dashes. Comparison of the experimental and computed values shows that for moderate gas-contents our method yields better agreement. As the gas content increases the liquid seals become aerated resulting in a diminution in the fluctuation amplitude as compared with that computed by means of (9). In this case better agreement is disclosed by the method in [5].

In the interests of the best agreement with experiment, a correction factor

$$\Delta p_a = \rho_\ell\left(\frac{1-k}{k}\right)^2\left(1,1 - \frac{\mathrm{Fr}}{16}\beta_g^4\right)\left(\frac{1}{1-\dfrac{k}{1-\bar{l}_\ell}\beta_g} - 1\right)u_m^2 \tag{13}$$

is introduced into (9).

The magnitudes of the root-mean-square deviations from the mean values of ℓ_ℓ, $\ell_{g\ell}$, Δp_a increase noticeably as the mass flow rate gas content rises to 30% for ℓ_ℓ, 37% for $\ell_{g\ell}$, and 22% for Δp_a. Consequently, the magnitude of the fluctuation amplitude with this deviation taken into account should be taken into account in the computations.

NOTATION

G, mass flow rate, kg/sec; u, velocity, m/sec; c, phase velocity, m/sec; W, rate of tape advancement, m/sec; d, tube diameter, m; F, area of a tube section, m^2; ℓ, plug length, m; x, distance on the tape where current growth is observed, m; y, distance on the tape between two successive current rises, m; p, pressure, Pa; ρ, density, kg/m^3; β, mass flow rate gas content, dimensionless; ϕ, true gas content, dimensionless; k, a parameter, dimensionless; $Fr = u^2/gd$, Froude criterion. Subscripts: ℓ, liquid; g, gas; gℓ, gas–liquid; m, mixture; c, capture; a, acceleration; f, friction; s, self-similar; v, viscosity; 1, plug; 2, film.

LITERATURE CITED

1. A. E. Duckler and M. G. Hubbard, Ind. Eng. Chem. Fund., 14, 337-347 (1975).
2. N. N. Alin and O. V. Klapchuk, Zh. Prikl. Mekh. Tekh. Fiz., No. 2, 92-99 (1980).
3. V. A. Mamaev, G. É. Odishariya, O. V. Klapchuk, et al., Motion of Gas–Liquid Mixtures in Tubes [in Russian], Moscow (1978).
4. V. G. Pikin, "Investigation of plug gas–liquid flows in industrial oil and gas collection systems," Author's Abstract of Candidate's Dissertation, Groznyi (1978).
5. A. I. Guzhov, Combined Collection and Transport of Oil and Gas [in Russian], Moscow (1973).