CALCULATION OF PRESSURE PULSATION INTENSITY AND GAS CONTENT IN AN ADIABATIC TWO-PHASE FLOW

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A calculation technique is developed for evaluating the intensity of pressure pulsations, longitudinal pressure drop, and gas content in a two-phase adiabatic flow. Calculations are compared to experimental data.

The motion of two-phase mixtures is accompanied by stable and very significant pulsations in pressure, friction on the channel walls, gas content, and other flow parameters [1-9]. They develop because of a characteristic feature of two-phase flows — the nonstationariness of the motion of the individual gases [4, 9-11].

The study of nonstationary processes in a two-phase flow stabilized by external conditions is important both for clarification of features of flow hydrodynamics, and for evaluation of the dynamic effect of the flow upon components of heat exchange equipment employing two-phase heat exchange fluids.

In the present study we will employ a nonstationary homogeneous flow model [10-12]. A one-dimensional adiabatic stabilized two-phase flow in a channel of constant section will be considered in the absence of volume gravitational forces. In accordance with these assumptions, the equations of motion and flow continuity have the form

$$\rho_{mix}\frac{\partial w_{mix}}{\partial t}+\rho_{mix}w_{mix}\frac{\partial w_{mix}}{\partial z}=-\frac{\partial P}{\partial z}-\xi\,\frac{\rho_{mix}w_{mix}^2}{2d}, \tag{1}$$

$$\frac{\partial\rho_{mix}}{\partial t}+\frac{\partial\rho_{mix}w_{mix}}{\partial z}=0. \tag{2}$$

Adding Eq. (2), multiplied by $w_{mix}$, to Eq. (1), and considering the well-known relationships of the homogeneous flow model:

$$w_{mix}=\frac{G_{mix}}{F\rho_{mix}},\ G_{mix}=G_1+G_2,\ \rho_{mix}=\rho_1(1-\beta)+\rho_2\beta, \tag{3}$$

we obtain

$$-\frac{\partial P}{\partial z}=\frac{1}{F}\left(\frac{\partial G_{mix}}{\partial t}+\frac{\partial G_{mix}w_{mix}}{\partial z}+\xi\,\frac{G_{mix}w_{mix}}{2d}\right). \tag{4}$$

The flow parameters are considered to be random functions of ergodic random processes. In this case the statistical average of the parameters over the set of random functions

$$\tilde{\chi}=\int_{-\infty}^{\infty}\chi\tilde{p}(\chi)\,d\chi, \tag{5}$$

where $\tilde{p}(\chi)$ is the distribution density of the ergodic process X, may be replaced by the average of a single realization over a sufficiently long time interval

$$\bar{\chi}=\tilde{\chi}=\lim_{T\to\infty}\frac{1}{T}\int_0^T\chi(t)\,dt. \tag{6}$$

In the future, we will make use of certain properties of the averaging operations of Eqs. (5), (6). Let X and H be ergodic random processes, so that [13, 14]

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$$\overline{\overline{\chi}} = \overline{\chi},\ \overline{\chi + \eta} = \overline{\chi} + \overline{\eta},\ \overline{\overline{\chi}\cdot\eta} = \overline{\chi}\cdot\overline{\eta},$$
$$\overline{\chi^2} = \overline{\chi}^2 + \sigma_\chi^2,\ \overline{\chi\cdot\eta} = \overline{\chi}\cdot\overline{\eta} + \sigma_\chi\cdot\sigma_\eta\cdot r. \quad (7)$$

Here $\sigma_\chi$ is the mean square deviation of the random process X and r is the mutual correlation coefficient of the random processes X and H.

For the subsequent analysis it is convenient to represent the flow parameter oscillations as the sum of averaged and pulsation components

$$\chi = \overline{\chi} + \chi'. \quad (8)$$

Transforming in Eq. (4) to the notation of Eq. (8), we obtain for the pulsation component of the pressure gradient the following expression:

$$-\frac{\partial P'}{\partial z} = \frac{1}{F}\left[\frac{\partial G'_{mix}}{\partial t} + \overline{G}_{mix}\frac{\partial w'_{mix}}{\partial z} + \overline{w}_{mix}\frac{\partial G'_{mix}}{\partial z} + \frac{\partial G'_{mix}w'_{mix}}{\partial z} + \frac{\xi}{2d}\left(\overline{G}_{mix}w'_{mix} + \overline{w}_{mix}G'_{mix} + G'_{mix}w'_{mix} - \overline{G'_{mix}w'_{mix}}\right)\right] \quad (9)$$

In [15, 16] experimental data were used to show that the oscillations of the basic hydrodynamic parameters of a two-phase flow are related to a wave process of structural feature transfer in the flow (motion of bubbles, implements, waves in the wall structure, liquid droplets). The propagation rate of these structural waves c can be uniquely related to the mean mixture velocity $\overline{w}_{mix}$ and the flow volume gas content of the flow $\beta_0$ [16].

Using the relationship

$$\frac{\partial \chi'}{\partial z} = -\frac{1}{c}\frac{\partial \chi'}{\partial t}, \quad (10)$$

we obtain a first-order differential equation for the pressure pulsations at an arbitrary point of the two-phase flow

$$\frac{\partial P'}{\partial t} = \frac{c}{F}\left\{\frac{\partial G'_{mix}}{\partial t} - \frac{1}{c}\left[\overline{G}_{mix}\frac{\partial w'_{mix}}{\partial t} + \overline{w}_{mix}\frac{\partial G'_{mix}}{\partial t} + \frac{\partial G'_{mix}w'_{mix}}{\partial t}\right] + \frac{\xi}{2d}\left(\overline{G}_{mix}w'_{mix} + \overline{w}_{mix}G'_{mix} + G'_{mix}w'_{mix} - \overline{G'_{mix}w'_{mix}}\right)\right\}. \quad (11)$$

Thus, to find the pressure pulsation intensity it is necessary to determine the character of the oscillations in flow rate $G_{mix}$ and velocity $w_{mix}$. To do this, the subsequent analysis uses a heuristic approach of minimization of dissipative energy losses in the flow in question. We are certain that this approach is possible because it has been used successfully in analysis of several averaged hydrodynamic parameters of two-phase flows in [10-12, 15, 17-19].

The flow power dissipated due to friction per unit channel length ($\partial N/\partial z$) is proportional to the product of the flow velocity times the longitudinal pressure gradient generated by friction forces, and defined by the last term on the right side of Eq. (1). Taking the ratio of this power to the power dissipated by friction in an ideal pulsation-free homogeneous flow $(\partial N/\partial z)_{hom}$, after the transformations described in [10-12], we obtain a dimensionless energy parameter characterizing energy dissipation in the pulsating two-phase flow:

$$E = \frac{\left(\frac{\partial N}{\partial z}\right)}{\left(\frac{\partial N}{\partial z}\right)_{hom}} = \frac{G_1^3 + (1+\gamma_0)^2 G_2^3 + (3+2\gamma_0)G_1^2 G_2 + (1+\gamma_0)(3+\gamma_0)G_1 G_2^2}{(\overline{G}_1)^3 + (1+\gamma_0)^2(\overline{G})^3 + (3+2\gamma_0)(\overline{G}_1)^2(\overline{G}_2) + (1+\gamma_0)(3+\gamma_0)\overline{G}_1(\overline{G}_2)^2}. \quad (12)$$

Application of the technique of minimizing dissipative energy losses referred to above reduces to a search for flow parameters which produce the smallest possible value of the averaged energy parameter $\overline{E}$ for specified mean flow rate values $\overline{G}_1$ and $\overline{G}_2$, and also the parameter $\gamma_0$.

Applying the averaging operation of Eq. (5) to Eq. (12) and considering Eq. (7), we obtain

$$\overline{E} = 1 + \{K_1^2(1-x_0)^2(3+2x_0\gamma_0) + K_2^2(1+\gamma_0)(3+2x_0\gamma_0+\gamma_0) + 2rK_1K_2(1-x_0)x_0(3+2\gamma_0+2x_0\gamma_0+x_0\gamma_0^2)\}\{(1-x_0)^3 + (1+\gamma_0)^2x_0^3 + (1-x_0)^2x_0(3+2\gamma_0) + (1-x_0)x_0^2(3+\gamma_0)(1+\gamma_0)\}^{-1}. \quad (13)$$

Here $x_0 = \overline{G}_2/(\overline{G}_1 + \overline{G}_2)$ is the flow mass gas content; $K_i = \sigma_{G_i}/\overline{G}_i$, $i = 1, 2$, are variation coefficients; while r is the mutual correlation coefficient of the above phase flow rates.

Minimizing the quadratic form (13) for parameters r, $K_1$, and $K_2$ with consideration of the limiting inequalities

$$-1 \leqslant r \leqslant 1,$$
$$0 \leqslant K_1 \leqslant K_{max},$$
$$0 \leqslant K_2 \leqslant K_{max}, \quad (14)$$

we obtain the following results.

1. The phase flow rate correlation coefficient $r = -1$. Physically, this means that pulsations in liquid and gas flow are "out of phase" and related as follows

$$\frac{G_2'}{\sigma_{G_2}} = -\frac{G_1'}{\sigma_{G_1}}. \quad (15)$$

2. The phase flow rate variation coefficients are related to the mass gas content in the following manner:

for $0 \leqslant x_0 \leqslant x_{lim_1}$,

$$K_1 = \frac{x_0 [3 + 2x_0\gamma_0 + \gamma_0 (2 + x_0\gamma_0)]}{(1 - x_0)(3 + 2x_0\gamma_0)} K_{max}, \; K_2 = K_{max}; \quad (16)$$

for $x_{lim_1} \leqslant x_0 \leqslant x_{lim_2}$

$$K_1 = K_{max}, \; K_2 = K_{max}; \quad (17)$$

for $x_{lim_2} \leqslant x_0 \leqslant 1$

$$K_1 = K_{max}; \; K_2 = \frac{(1 - x_0)[3 + 2x_0\gamma_0 + \gamma_0 (2 + x_0\gamma_0)]}{x_0 (1 + \gamma_0)(3 + 2x_0\gamma_0 + \gamma_0)} K_{max}. \quad (18)$$

Here $x_{lim_1}$ and $x_{lim_2}$ are the limiting values of mass gas content

$$x_{lim1} = \frac{\sqrt{3(\gamma_0 + 1)(\gamma_0 + 3)} - 3}{\gamma_0 (\gamma_0 + 4)}, \quad (19)$$

$$x_{lim2} = \frac{(1 + \gamma_0)\sqrt{3(3 + 2\gamma_0)} - (3 + 2\gamma_0)}{\gamma_0 (4 + 3\gamma_0)}.$$

In [12] these values were related to transitions from bubble to charge flow and from charge to disperse-ring flow.

It follows from the structure of Eqs. (16)-(18) that the parameter which defines the pulsation processes is the magnitude of the greatest possible value of the phase flow rate variation coefficient $K_{max}$. To determine this value we utilize the condition of absence of reverse flows of liquid and gas, found experimentally in [2]. In the case under consideration this condition can be expressed as

$$|G_i'| \leqslant \overline{G}_i; \; i = 1, \; 2. \quad (20)$$

Moreover, to find the value of $K_{max}$ it is necessary to know either the time dependence of the phase flow rate $G'_1(t)$ or $G'_2(t)$, or the pulsation distribution density of these flow rates $\tilde{p}(G'_1)$ or $\tilde{p}(G'_2)$. These functions are not known a priori, and cannot be directly determined experimentally at present.

However, as follows from analysis of experimental data (Fig. 1), the pulsations of the flow parameters have the form characteristic of the superposition of a harmonic process and a random noise [14]. In connection with this fact, it is useful to consider two limiting cases.

1. The phase flow rate pulsations are a harmonic process with a random initial phase. With consideration of Eq. (15), such oscillations may be described mathematically by

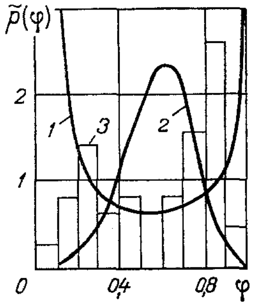


Fig. 1

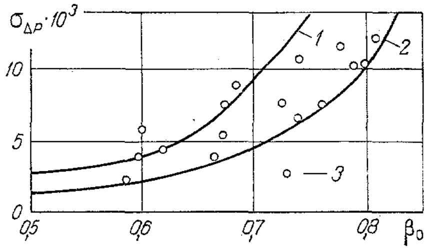


Fig. 2

Fig. 1. Distribution density of pulsations in true volume gas content: 1, 2) calculation with models of harmonic and chaotic phase flow rate oscillations; 3) experimental distribution histogram, P = 0.1 MPa, $\bar{w}_0$ = 0.55 m/sec.

Fig. 2. Mean-square intensity of pulsations in longitudinal pressure drop versus flow volume gas content: 1, 2) calculations for harmonic and chaotic models of flow rate oscillation; 3) experimental data [16], P = 0.16-0.2 PMa, $\bar{w}_0$ = 2.0-2.5 m/sec, $\sigma_{\Delta p}$, MPa.

$$G_1' = \sqrt{2}\, K_1 \bar{G}_1 \sin 2\pi f_0 t,$$
$$G_2' = -\sqrt{2}\, K_2 \bar{G}_2 \sin 2\pi f_0 t. \tag{21}$$

Using Eqs. (20), (21) to define the value of the greatest possible phase flow rate variation coefficient, we obtain $K_{max} = 1/\sqrt{2}$.

2. The pulsations in the liquid and gas flow rates are a purely chaotic process. The normalized autocorrelation function of such a process is a δ-function, and the distribution density, as follows from the central limit theorem of probability theory [13, 14], must be close to the density of a normal distribution law

$$\tilde{p}(G_i') = \frac{1}{2\pi K_i \bar{G}_i} \exp\left(-\frac{G_i'^2}{2K_i^2 \bar{G}_i^2}\right), \quad i = 1, 2. \tag{22}$$

Using the "three sigma" rule of [13], for the condition of practical impossibility of reverse phase flows we obtain $K_{max} = 1/3$.

The conclusions made relative to the phase flow rates $G_i$ permit us to use Eq. (3) to determine the character of oscillations in the total flow $G_{mix}$ and the velocity $w_{mix}$ of a two-phase flow as functions of the flow regime parameters.

When the model of harmonic pulsations of phase flow rates is used, Eq. (11) can be integrated. In this case the intensity of the pressure pulsations, i.e., the value of the mean-square deviation, is found from Eqs. (6), (7).

When purely chaotic pulsations are considered, we use well-known relationships for integration of random functions [13], which also permit determination of the pressure pulsation intensity.

Combining the results in one formula, we obtain

$$\sigma_p = \rho_1 \bar{w}_0 \bar{w}_{mix} \sqrt{\left[a\left(\frac{c}{\bar{w}_{mix}} - 1\right) - b\right]^2 + q_1 (ab)^2 + q_2 \left(\frac{c\xi}{4\pi d f_0}\right)^2 \left[(a-b)^2 + \frac{(ab)^2}{8}\right]}, \tag{23}$$

where

$$a = (1 - x_0) K_1 - x_0 K_2; \tag{24}$$

$$b = \frac{x_0 K_2 (1 + \gamma_0) - (1 - x_0) K_1}{1 + x_0 \gamma_0}; \tag{25}$$

where the coefficients $q_1$ and $q_2$ are equal to 0.5 and 1 in the harmonic model and to 2 and 0 in the chaotic pulsation model; $\bar{w}_0 = \bar{G}_{mix}/F\rho_1$ is the circulation velocity.

An evaluation of the intensity of pulsations in the longitudinal pressure drop in the flow is also of significant practical interest

$$\sigma_{\Delta P} = \sqrt{\overline{[P'(z) - P'(z=0)]^2}}. \tag{26}$$

Introducing the concept of a longitudinal (along the z axis) correlation coefficient:

$$r_P = \frac{\overline{P'(z)\,P'(z=0)}}{\overline{P'^2}}, \tag{27}$$

after obvious transformations we obtain

$$\sigma_{\Delta P} = \sigma_P \sqrt{2(1 - r_P)}. \tag{28}$$

The dependence of the correlation coefficient $r_P$ upon z was studied in [4, 5]. It was shown that at sufficiently high z (of the order of 1 m) the value of $r_P$ tends to zero. In this case Eq. (28) takes on the following form:

$$\sigma_{\Delta P} = \sqrt{2}\,\sigma_P. \tag{29}$$

Figure 2 shows a comparison of calculated (using Eqs. (23)-(29)) and experimental data, the latter presented in [16], on the value of the mean-square intensity of longitudinal pressure drop pulsations.

The technique developed also permits calculation of the intensity of pulsations in the true volume gas content of the two-phase flow

$$\sigma_\varphi^2 = \overline{\varphi^2} - (\overline{\varphi})^2, \tag{30}$$

where

$$\overline{\varphi} = \lim_{T\to\infty} \frac{1}{T} \int_0^T \varphi dt = \int_{-\infty}^{\infty} \varphi \tilde{p}(G_2') dG_2'; \tag{31}$$

$$\overline{\varphi^2} = \lim_{T\to\infty} \frac{1}{T} \int_0^T \varphi^2 dt = \int_{-\infty}^{\infty} \varphi^2 \tilde{p}(G_2') dG_2'. \tag{32}$$

The instantaneous values of the true gas content in the first homogeneous approximation can be expressed in terms of instantaneous values of the phase flow rates with the formula

$$\varphi = \beta = \frac{G_2}{G_2 + G_1(1 + \gamma_0)^{-1}}. \tag{33}$$

With use of the model including harmonic pulsations of the phase flow rates, Eqs. (31)-(33) give the following results:

$$\overline{\varphi} = \beta_0 \frac{K_2 + h - K_2\sqrt{1 - 2h^2}}{h\sqrt{1 - 2h^2}}, \tag{34}$$

$$\overline{\varphi^2} = \frac{\beta_0^2}{h^2}\left[\frac{(1 + 4K_2^2)h^2 + 2K_2h^3 - K_2^2}{(1 - 2h^2)^{3/2}} + K_2^2\right]. \tag{35}$$

Here $h = (1 - \beta_0)K_1 - \beta_0 K_2$.

It should be noted that Eq. (34) for $\overline{\varphi}$ coincides with the expression for true volume gas content presented in [11, 12] and confirmed for vapor and gas–liquid flows in tubes and channels at sufficiently high Froude numbers.

When a flow with chaotic oscillations of the phase flow rates and the distribution density (22) is considered, the improper integrals in Eqs. (31), (32) cannot be determined analytically, so they were calculated numerically with a computer.

Results of analytical and numerical calculations of the mean square values of pulsations in gas content $\sigma_\varphi$ for P = 0.16 MPa for the cases of sinusoidal and chaotic oscillations of phase flow rates are shown in Fig. 3. Also shown are experimental data obtained by gamma scintillation of an air–water flow in a vertical tube 20 mm in diameter at P = 0.16 MPa and

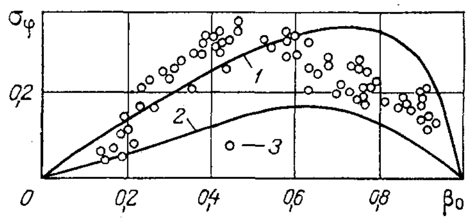


Fig. 3. Mean-square intensity of pulsations in true volume gas content versus flow rate volume gas content: 1, 2) calculation with models of harmonic and chaotic phase flow rate oscillations, respectively; 3) experimental data, P = 0.1 MPa, $\bar{w}_0$ = 0.5-1.5 m/sec.

$\bar{w}_0$ = 0.5-1.5 m/sec. The radiation source was the isotope Am-241 with activity of 0.55 Ci. The high level of gamma quantum count, the scintillation radiation detector, and secondary apparatus provided reliable fixation of the density of the two-phase flow in the tube with a time constant of 20-30 msec, which is an order of magnitude less than the observed periods of the pulsations φ. The experimental values of $\sigma_\varphi$ were determined by processing oscillograms of the flow density pulsations using mathematical statistics methods [14] on a computer.

It is evident from Fig. 3 that just as for pulsations of the longitudinal pressure drop, the experimental values of $\sigma_\varphi$ are located for the most part between the two calculated lines corresponding to harmonic (upper curve) and chaotic (lower curve) laws of phase flow rate change with time.

Thus, the technique developed herein permits calculation of upper and lower limits for the numerical values of such pulsation hydrodynamic characteristics of two-phase flows in channels as $\sigma_P$, $\sigma_{\Delta P}$, and $\sigma_\varphi$, a knowledge of which is often required in engineering practice to evaluate the intensity of vibrations in heat exchanger construction as well as pulsations in temperature and other parameters of two-phase flows.

## NOTATION

z, coordinate in direction of flow; t, time; T, period of averaging; d and F, diameter and cross-sectional area of flow channel; ξ, friction coefficient; P, pressure; ρ, density; $\gamma_0 = (\rho_1 - \rho_2)/\rho_2$, reduced mixture density; $w_0$, circulation velocity; $w_{mix}$, mixture velocity; G, mass flow rate; c, speed of structural wave propagation; β, volume gas content; $\beta_0 = \bar{G}_2/[\bar{G}_2 + \bar{G}_1(1 + \gamma_0)^{-1}]$, flow rate volume gas content; $\tilde{p}$, distribution density; K, variation coefficient; r, correlation coefficient; σ, mean square deviation; $f_0$, phase flow rate oscillation frequency; N, flow power; E, energy parameter. Indices 1, 2, mix correspond to liquid, gas, and mixture; tilde and overbar symbols denote averaging over probability and time; primes denote pulsation components.

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# REDUCTION OF HYDRODYNAMIC DRAG AND SIZE OF POLYMER PARTICLES

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The influence of the size of polymer particles and their number in the deformed fluid volume on the Thoms effect is examined in an example of biopolymers of surface extractions of water animals.

The reduction of turbulent fluid drag upon the insertion of admixtures of certain polymers is of national-economic interest. However, despite the numerous attempts of researchers, there is no theory of this phenomenon at this time [1], and the physicochemical aspects of both the mechanism of the action and the nature of the particles — the hydrodynamic activity carriers — have been inadequately studied. The clarification of the fundamental aspects of the mechanism of the process, of the most important parameters governing the hydrodynamic activity of macromolecular admixtures, is needed for a practical application of parameters in order to reduce the hydrodynamic drag of liquid media.

Since the hydrodynamic activity of polymers can be considered as the result of polymer particle interaction with turbulent formations of the medium, one of the fundamental parameters governing its interaction is the size of these particles.

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