range of injection rates we can set $\Psi = \Psi(b)$. Actually, for large values of b the contribution of the first term becomes insignificant and the errors in determining τ_w from $\Psi = \Psi(b)$ reflect little on the accuracy of calculations of the developing pressure gradient. For small b, when the contribution of the first term grows, the accelerations which develop are small and one can take $\Psi = \Psi(b)$.

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INVESTIGATION OF THE PULSATION CHARACTERISTICS OF AN ASCENDING GAS—LIQUID FLOW

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A great deal of attention has been paid recently to the study of the local structure of two-phase gas—liquid flows. This is related to the diversity of the flow modes and the large quantity of parameters and governing characteristics of two-phase flows. Consequently, generalization of the average total parameters (friction losses, heat elimination coefficient) turns out to be difficult. Investigations performed at this time of the local gas—liquid flow characteristics averaged with respect to time [1, 2] must be supplemented by a more detailed investigation of the pulsating flow characteristics to clarify the interaction mechanism between the liquid and gas phase turbulence.

The local gas—liquid flow characteristics averaged with respect to time were investigated in a vertical pipe in [3, 4]. The purpose of this paper is to investigate certain pulsating characteristics of an ascending two-phase flow.

The experiments were performed on the apparatus from [3]. A vertical pipe with 15-mm inner diameter and 5-m length was the working section. A two-phase flow was organized by inserting gas bubbles of identical size in the fluid by using the unit from [4].

Measurements were executed by using an electrochemical method [5, 6]. An electrolyte containing 0.5 N caustic soda and 0.005 N ferri- and ferrocyanide in distilled water was the working fluid. The fluid was kept in a thermostat at 20 ± 0.2°C to maintain the physical properties constant.

A velocity transducer of "frontal point" type of 0.05-mm diameter was used to determine the mean fluid velocity and the fluctuations of its longitudinal component. The transducer

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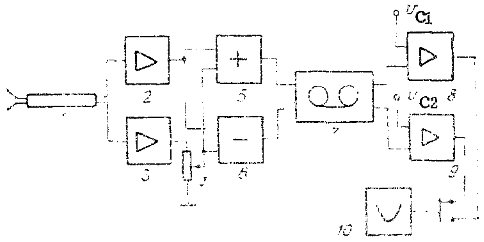

Fig. 1

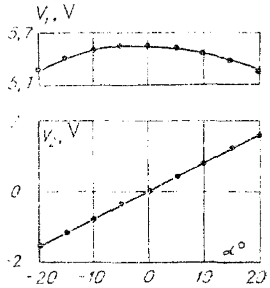

Fig. 2

was calibrated on the tube axis in a laminar flow mode, where the velocity on the axis equalled twice the mean fluid velocity determined from the mass flow rate. The measurement method is described in [6].

A V-shaped electrochemical transducer [7] with maximum sensor dimension 0.2 mm was used to measure the fluctuation intensity of the transverse velocity component. A difficulty associated with the impossibility of distinguishing the transducer current fluctuations caused by the fluid velocity fluctuations from the change in current caused by presence of the gas phase transducer on a part of the surface as the gas bubbles passed through the transducer occurs during operation of a transducer of the type mentioned in a two-phase flow. For this circumstance not to induce great error in the measurement results, the experiments with the V-shaped transducer were conducted for the value $\beta = 0.01$.

The measurement method is analogous to measurements using an X-shaped thermoanemometric transducer [8].

A block diagram of the measuring apparatus is presented in Fig. 1. A signal from the transducer 1 is delivered to the two-channel dc amplifier 2 and 3 where there is a divider 4 at the output of the second channel to balance both channels. Furthermore, the signal was delivered to the adding amplifier 5 and the differential amplifier 6 whose output signals were recorded on the tape of the magnetic recorder 7 of "Schlumberger" type. During reproduction of the recording, the signals were delivered from the tape to the amplifier—limiter 8 and 9, at whose input a compensating voltage U_{C1} and U_{C2} was delivered to bias the mean level. The signal from the amplifier—limiter output was measured by using the quadratic voltmeter 10.

Since the characteristics of transducers of the type measured have not been investigated in detail, the transducer was calibrated according to the mean velocity before the experiment, analogously to the calibration described above for the "frontal point" transducer, and the transducer also underwent angular calibration by using apparatus from [7]. Typical angular calibration curves are presented in Fig. 2, where V_1 and V_2 are the output voltages, respectively, of the adding and differential amplifiers, α is the angle between the normal to the transducer and the stream direction, and the curves are constructed for a 0.07 m/sec fluid velocity. It is seen that the sum V_1 is practically independent of the angle α in the range of angles $\alpha = \pm 25°$, while the difference V_2 depends linearly on α. The transducer sensitivity factors relative to the longitudinal and transverse velocity fluctuations were determined from the calibration results, and later used in processing the measurement results.

Typical oscillograms of the transducer signal in a two-phase flow are presented in Fig. 3. The upper signal is the voltage of the adding amplifier V_1 and the lower is from the

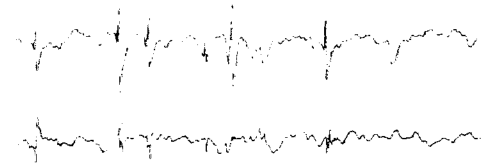

Fig. 3

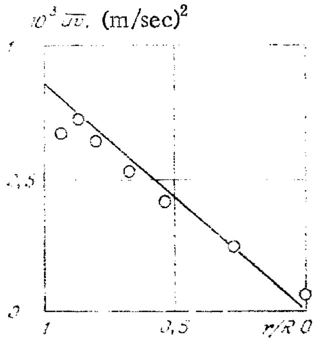

Fig. 4

differential amplifier V_2. Abrupt jumps in the voltage correspond to the times of finding the transducer in the gas phase. Moreover, the sections of the signal adjacent to the jumps can correspond to the times when part of the transducer electrode is in the gas phase. In order to make minimal measurement error because of the jumps mentioned, the following method was used to process the signal. The voltages U_{C1} and U_{C2} and the amplifier–limiter gains were regulated in such a manner that the signal corresponding to turbulent fluctuations occupied almost the whole dynamic range of the amplifiers 8 and 9, and the maxima of this signal were close to the limiting levels but did not reach it. As the transducer goes into the gas phase a sharp change occurs in the signal level; however, the amplifiers do not allow the signal to exceed the limitation level. Consequently, a possible error in the measurement of the rms value of the fluctuations does not exceed $V_0\varphi/e$, where V_0 is the limitation level, e is the rms value of the output voltage of amplifier 8 or 9, and φ is the local gas content at this point. Taking into account that it is possible to make $V_0/e <$ 2.5 by a suitable selection of the gains and compensating voltages of the amplifier–limiters, we obtain that the error in measurement caused by the absence of a special method of blocking the transducer signal during passage of the gas phase does not exceed 2.5 φ. The local value of the gas content for $\beta = 0.01$ did not exceed 0.04. The maximal error in measurement due to the presence of gas bubbles in the stream was therefore <10%.

To check the correctness of the measurements, the correlation between the longitudinal u and transverse v components of the velocity fluctuations in a single-phase stream was measured in conformity with the recommendations [8]. The results are presented in Fig. 4, where R and r are, respectively, the tube radius and the running radius. Measurements were performed for the Reynolds number value $9 \cdot 10^3$. The line corresponds to the linear dependence $\overline{uv} = v_*^2(r/R)$ (v_* is the dynamic velocity), from which the deviations of the experimental points are within the limits of measurement error; the points are the measurement results.

The measured profiles of the longitudinal component of the fluid velocity fluctuations in a two-phase stream u' (U is the velocity on the tube axis) are shown in Fig. 5, where 1 is Re = 9000, $\beta = 0$; 2 is Re = 9000, $\beta = 0.01$; 3 is Re = 4250, $\beta = 0.01$; 4 is Re = 1720, $\beta = 0.01$; 5 is Re = 1720, $\beta = 0.1$; 6 is Re = 1000, $\beta = 0.01$. The size of the gas bubbles in the two-phase flow was 1 mm in all the experiments.

As is seen from Fig. 5, the measured values of u' in the developed turbulent flow mode (points 2, 3) are close to the corresponding values in a two-phase flow. The intensity of the longitudinal velocity component in the central part of the tube is somewhat higher than in a single-phase flow because of the additional perturbations caused by the relative motion of the gas bubbles. Near the wall the values of u' are practically identical for Re = 9000 in two-phase and single-phase flows, while u' is even somewhat less in a two-phase flow for Re = 4250. This effect of the attenuating influence of the gas bubbles on fluid turbulence

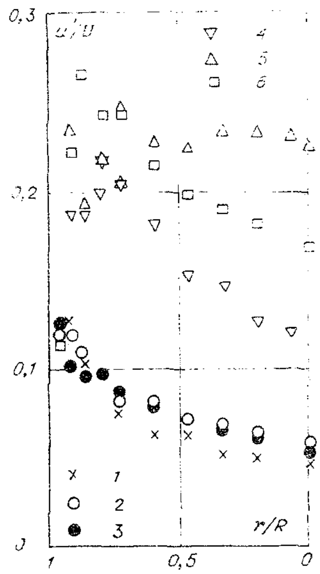

Fig. 5

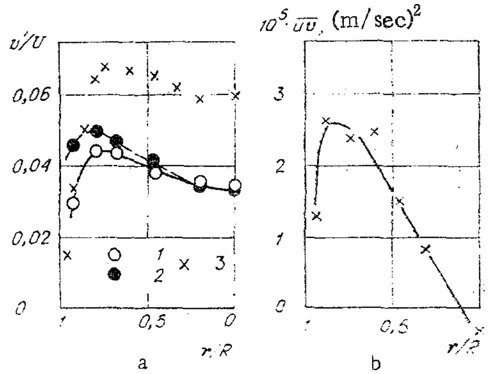

Fig. 6

is analogous to that described in [2]. On the whole, for low gas contents in the developed turbulent mode, the influence of the presence of the gas phase on the fluctuation characteristic of the fluid is slight.

The results of measuring u' for Reynolds numbers corresponding to the laminar flow mode (points 4-6) exhibit a significantly higher level of longitudinal fluid velocity fluctuations compared to the developed turbulent flow. For $\beta = 0.01$ the u' profiles are qualitatively similar to turbulent single-phase flow; a strong dependence on the Reynolds number is observed. This is perfectly natural since the local slip coefficient diminishes for the gas bubbles as the fluid velocity increases, and the relative magnitude of the gas-phase perturbation of the fluid diminishes correspondingly also. The u' profiles are strongly dependent on the discharge gas content. For $\beta = 0.1$ (points 5) the u' distribution differs substantially from all the rest. In this case, a practically constant value of u' holds in the central part of the tube. An analogous distribution of the degree of turbulence in a number of modes was noticed in [2].

Profiles of the transverse fluid velocity component fluctuations are presented in Fig. 6a, where 1 has Re = 4250, $\beta = 0$; 2 has Re = 4250, $\beta = 0.01$; 3 has Re = 1000, $\beta = 0.01$. It is seen that in a developed turbulent mode the v' profile in a two-phase stream differs slightly from the single-phase profile. A certain rise in the intensity of the transverse fluctuations exists near the wall, while the values of v' in the single- and two-phase streams are in agreement in the central part of the tube. Let us also note that the values of u' and v' at the center of the tube are similar in the identical turbulent flow modes, and the flow is almost isotropic. For Re = 1000 the values of v' are ~1.5 times greater than the corresponding values in the developed turbulent mode, although the qualitative nature of the curve is retained. However, in this case a substantial anisotropy of the fluctuations holds even in the center of the tube. The ratio here is ∿3. Despite the subcritical value of the Reynolds number, the correlation $\overline{uv}$ differs from zero (Fig. 6b, Re = 1000, β = 0.01) and has qualitatively the same form as in turbulent flow. Since the velocity of bubble displacement in the transverse direction is approximately an order of magnitude less than the relative velocity of buoyancy, the transverse bubble motion cannot cause such a high value of v'. Visibly, after each bubble passes into the fluid, local flow turbulization occurs, which cannot, however, cause the development of a fully turbulent mode since the Reynolds number is below the critical value for the tube. This turbulization causes a "pumping" of part of the longitudinal fluctuation energy into the transverse and the origination of Reynolds stresses. Therefore, the occurrence of a flow quite similar to developed turbulence even at the subcritical number is possible during continuous insertion of strong perturbations in a fluid flow. The appearance of additional turbulent viscosity specifies a fuller velocity profile in these regimes [3, 4].

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