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APPLICATION OF THE ELECTROCHEMICAL METHOD FOR MEASURING THE FLUID VELOCITY IN A TWO-PHASE BUBBLE FLOW

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A technique for measuring the fluid velocity in a two-phase flow using a combination of the electrochemical method and the conduction method is described. The point of this technique is numerical analysis of complete realizations of signals from the electrodiffusion velocity transducer. The dependence of the results of measurements of local hydrodynamic characteristics of the bubble flow on the level of gas-phase cutting out has been investigated. The measurement data for the local gas content, the fluid velocity, and the velocity pulsations during bubble mixture motion in a tilted channel are presented.

The electrochemical (electrodiffusion) method has found wide application for investigating the flows of liquid and liquid-gas mixtures [1, 2]. The use of friction and velocity transducers permits obtaining information on the flow field both directly on the channel wall and near it. One of the advantages of the method is the possibility of using small-sized point sensors. This appears to be of fundamental importance in studying two-phase liquid-gas flows [1, 3]. In measuring two-phase flows, the operation of the friction transducer does not radically differ from its operation in the one-phase flow. On the contrary, in measuring the fluid velocity, the transducer is alternately in the liquid and the gas phase. In this connection, the problem of phase separation in the transducer arises. A similar problem also arises in using other contact methods of measuring liquid-gas flows, e.g., a hot-wire anemometer or a conduction sensor.

Below, a technique for measuring the fluid velocity in a two-phase flow with the use of a combined method in which the transducer operates in two regimes is described. Here the point is that in taking measurements a numerical analysis of complete realizations of the transducer signals was carried out. The measurement data for the local gas content, the fluid velocity, and the velocity pulsations in the bubble mixture flow in a tilted plane channel are presented.

The bubble flow characteristics were measured in an experimental facility [4]. The operating part of the facility is a rectangular channel with a cross section of 10 $\times$ 100 mm and a length of 1.7 m. Gas was let into the flow through 12 capillaries with an inside diameter of 0.3 mm pasted in an acrylic plastic insert placed on the lower wall. The channel orientation was varied. In the experiments, the tilt angle of the channel θ to the horizontal was varied from -20^o to $+20^o$; $\theta = 0^o$ corresponds to the horizontal position of the channel. Negative values of the angle θ correspond to the upward flow and positive values — to the downward flow. In all regimes, the liquid-gas flow was cocurrent. The distance from the gas inlet to the measuring section was 1300 mm.

As a working liquid a solution of potassium and carbonic sodium ferri- and ferrocyanide in distilled water was used. The liquid temperature was held between 25.3 and 25.5^{o}C. The local gas content and the fluid velocity were measured by a miniature head-point-type velocity transducer [1]. It was a platinum wire of diameter 50 μm welded into a conical glass capillary; the diameter of the working part of the velocity transducer was 0.06 mm. Then the capillary was pasted with epoxy resin in a holder made of a metal pipe 2 mm in diameter. The holder was fastened onto a coordinate device by means of which the transducer could move across the channel. Its front part was conical in shape and the sensor was a cone-shaped end of a platinum wire. The transducer was included in the electric circuit as a cathode and could move from the wall to the axis of the channel. The friction and velocity transducers were located in the measuring unit (Fig. 1). In the present work, only the velocity transducer was used. To measure the lower velocity semiprofiles and the local gas content, the measuring unit was rotated by 180^o.

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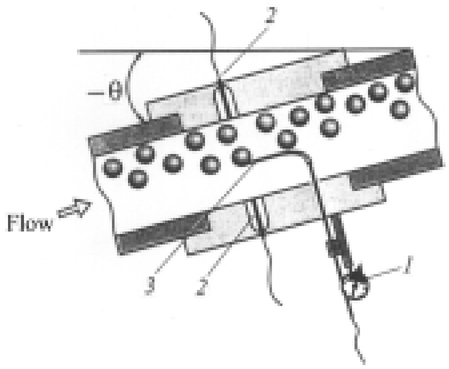


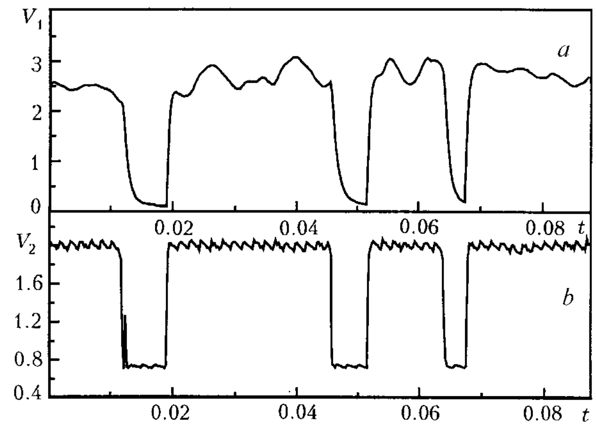


Fig. 1. Measuring unit: 1) coordinate device; 2) friction transducer; 3) velocity transducer.

Fig. 2. Transducer signal in the two-phase bubble flow: a) low-frequency component; b) high-frequency component (phase signal).

In the general case, for the "head-point"-type transducer the calibration dependence has a form analogous to the known "King law" for the hot-wire anemometer:

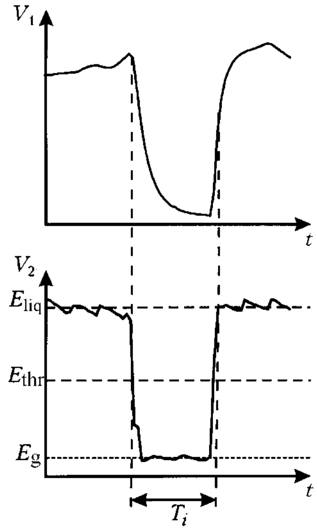
$$I = A + Bu^{1/2} \ .$$

In the present work, calibration of the velocity transducer was carried out in a one-phase flow just before and immediately after measurements in order to exclude the influence of the transducer instability on experimental data. The signal averaging time at each point during calibration was 10 sec. The calibration dependence was constructed by points under laminar and turbulent conditions, excluding the transient condition, and approximated by a straight line in coordinates $I = u^{1/2}$.

In the case of operation in a liquid-gas flow, the transducer current depends on both the fluid velocity and pulsations and the change of the liquid and gas phases on the sensor. In the liquid-gas mixture, the transducer electrode is alternately in the liquid phase and the gas phase. In the first case, its indications correspond to the instantaneous values of the liquid phase velocity. At these instants, the velocity transducer operates as in the one-phase flow. When in the gas phase, the electric circuit of the transducer opens and its current sharply decreases. The current does not drop to zero due to the capacitive discharge of the double electric layer through the input resistance of the measuring scheme.

In taking measurements in liquid-gas flows, it is necessary to clearly resolve the moment the transducer sensor passes through the interphase. The moments of interphase transitions in the signal of the electrodiffusion velocity transducer are rather sharp. However, the upper level of the signal ("liquid level") changes with time in accordance with the fluid velocity dynamics. To more reliably resolve the moments the phases change, the technique of [5] combining the electrochemical method and the conduction method was used. In the first regime, the transducer indication is determined by the fluid velocity alone, and in the second one — the regime of transducer conduction — the transducer indication is independent of the fluid velocity and has two fixed values corresponding to the cases where the transducer is in the liquid phase or in the gas phase.

In realizing this technique, direct-current bias voltage with a radio-frequency voltage of frequency 250 kHz imposed on it was applied to the transducer. Then the transducer current was split into low-frequency and high-frequency components by respective filters. Then both signals were amplified and the high-frequency signal was also detected and smoothed. The thus-obtained signals were sent to the digitizer and recorded in the computer memory. The signals were interrogated with a frequency of 4 kHz (for each channel), and the measurement time at one point was 100 sec. The data file capacity was 4 Mb. The typical records of transducer signals in the case of operation in the two-phase flow are shown in Fig. 2.



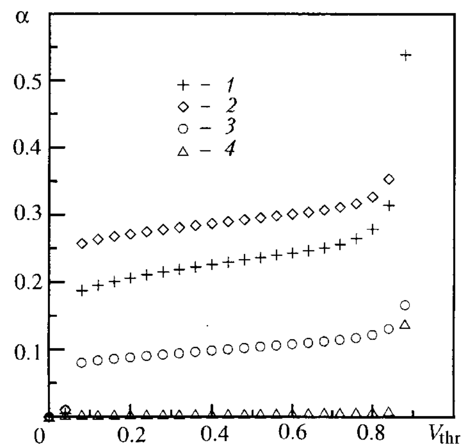


Fig. 3. Signal at the passage of one gas bubble though the transducer.

Fig. 4. Measured local gas content as function of the cutting-out level at W_{liq} = 0.6 m/sec; β = 0.05; θ = -10^o: 1) y = 0.5; 2) 1.1; 3) 2; 4) 3 mm.

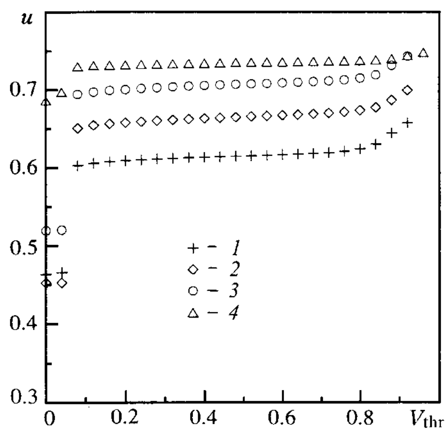
Figure 3 gives a fragment of the signal record corresponding to the passage through the transducer of one gas bubble. The phase signal has two levels: liquid E_{liq} and gas E_g. They depend only on the presence on the transducer of a given phase and are not associated with the fluid velocity. A high-frequency component caused by the insufficient filtration is imposed on the liquid level. On the whole, the phase signal turns out to be completely identical to the signal of the resistive local transducer used in the conduction method [6, 7]. The transition from the liquid level to the gas level and vice versa is not instantaneous, and the signal fronts have a finite duration. This is due to both the finite size of the transducer electrode and the complex process of passage through the interface transducer.

The basic point determining the accuracy of measurements of the liquid-gas flow characteristics is the choice of the criterion of cutting out the signal portions corresponding to the gas phase. For the conduction transducer signal (or the high-frequency signal illustrated in Figs. 2 and 3), this problem reduces to the choice of the cutting-out threshold. Its corresponding voltage is shown in Fig. 3 as E_{thr}. Once the threshold value has been chosen, it is easy to determine the time T_i of passage through the transducer of the ith gas bubble. It is also marked in Fig. 3. The local gas content at a given point is determined as

$$\alpha = \frac{\sum_i T_i}{T} .$$

It is more convenient to use the relative cutting-out threshold $V_{thr} = (E_{thr} - E_g)/(E_{liq} - E_g)$. The value of E_{thr} is 1 for the liquid phase and 0 for the gas phase.

Since the conduction transducer signal is other than rectangular, the value of the measured gas content depends on the value of the chosen threshold. This relation is shown in Fig. 4 for one regime (W_{liq} = 0.6 m/sec, $\beta = W_g/(W_{liq} + W_g) = 0.05$, $\theta = -10^o$) and several values of the transverse coordinate y. Taking into account that in the present work we entered in the computer memory the realizations of all signals during measurements, the curves were constructed by individual records of duration 100 sec as a result of their numerical treatment. It is seen that with increasing threshold value V_{thr} the measured value of the local gas content increases, which, taking into account the shape of the phase signal, is quite natural. The best choice of the cutting-out level is a value maximally close to the liquid level, i.e., to V_{thr} = 1. Actually this level cannot exceed a value of 0.8–0.85 due to the fact that a high- frequency noise, which can cause measurement errors at higher values of V_{thr}, is imposed. The problem of choosing the cutting-out level is always present in measurements by the conduction method. In [6], for example, it is also recommended to choose a threshold value maximally close to the liquid level.



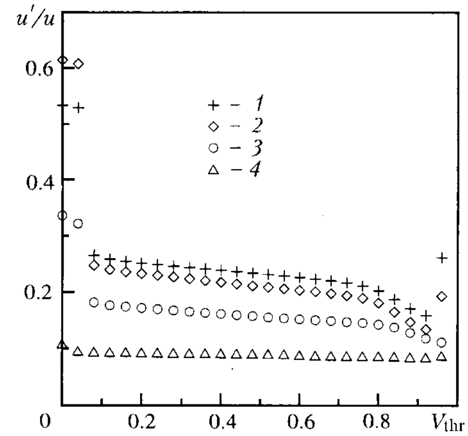


Fig. 5. Measured fluid velocity as a function of the cutting-out level at W_{liq} = 0.6 m/sec; β = 0.1; $\theta = -20^o$: 1–4) same notations as in Fig. 4.

Fig. 6. Measured velocity pulsations as a function of the cutting-out level at W_{liq} = 0.6 m/sec; β = 0.05; $\theta = -10^o$: 1–4) same notations as in Fig. 4.

The choice of the cutting-out threshold also influences the measured values of the fluid velocity and velocity pulsations. The dependences of the mean velocity u and the rms value of velocity pulsations u' are given in Figs. 5 and 6. It is seen that there exists a certain relation between the measured value of the mean velocity and V_{thr}; however, it is weaker than for the gas content. On the whole, the level of cutting out influences the accuracy of measurement of the mean velocity but slightly. The dependence of the intensity of velocity pulsations on the cutting-out level is somewhat stronger. This is due to the fact that at a low cutting-out level the part of the signal corresponding to the gas phase is recognized as fluid velocity pulsations.

As the level of the cutting-out threshold V_{thr} is increased, there is an increase in the measured values of the local gas content and the fluid velocity while the intensity of velocity pulsations decreases.

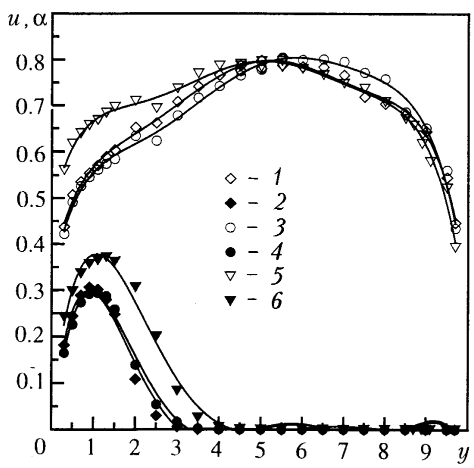
To measure the hydrodynamic characteristics of the bubble flow, we chose a value of the cutting-out threshold of V_{thr} = 0.8. It is close to the liquid level but is below the level that can be influenced by the noises imposed on the high-frequency signal in the liquid phase. Due to the fact that the dependences of the gas content and velocity on the cutting-out threshold are linear in the range of V_{thr} from 0.2 to 0.8, it is easy to extrapolate the obtained results to the liquid level at V_{thr} = 1. However, this will change the result compared to the values for V_{thr} = 0.8 but slightly.

The measurement data for the fluid velocity and the local gas content are given in Fig. 7. Light points denote the fluid velocity and dark ones — the gas content. The y-coordinate was measured from the upper wall of the channel, so y = 5 mm corresponds to the channel center and y = 10 mm is the lower wall coordinate.

The cross-section distribution of the gas phase strongly depends on the channel tilt angle. In the upward flow, the peak of the gas content at the upper wall is clearly defined at a distance of the order of the mean radius of the bubble. When the tilt angle is changed to the downward flow, the bubble-layer thickness in the vicinity of the upper wall of the channel sharply increases. An increase in the expendable gas content does not lead to a qualitative change in the picture; only the peak height and the bubble layer width increase.

One of the factors causing a deformation of the gas-content profiles on going from negative tilt angles to positive ones is the presence of lateral forces acting on the bubble in the direction perpendicular to the wall. The sign of these forces depends on the sign of the relative velocity of emergence of the bubble. At negative tilt angles of the channel the bubbles move faster than the liquid. The lateral force in this case presses the bubble to the wall, as it does in the upward bubble flow in a vertical pipe [3]. At positive tilt angles, when the flow becomes descending, the relative velocity sign changes. In this case, the lateral force should push the bubble off the wall, i.e., work against gravity. This leads to an increase in the bubble-layer thickness. At even larger tilt angles bubbles may depart from the wall, as is observed in the downward bubble flow in a vertical pipe [8].

The channel-cross-section distribution of the fluid velocity is essentially nonsymmetric (Fig. 7). The profile shape in the upper half of the channel somewhat deforms when the tilt angle and the expendable gas content change. In the lower half of the channel, in the region of one-phase flow, the velocity profiles also differ from the one-phase



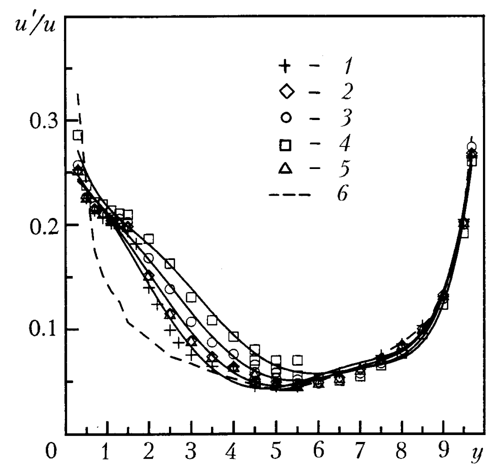


Fig. 7. Velocity (1, 3, 5) and local gas content (2, 4, 6) profiles (W_{liq} = 0.6 m/sec): 1, 2) β = 5%, $\theta = -10^{\circ}$; 3, 4) 5 and 0; 5, 6) 10 and –20.

Fig. 8. Fluid velocity pulsations (W_{liq} = 0.6 m/sec, β = 0.05): 1) $\theta = 20^{\circ}$; 2) –10; 3) 0; 4) 10; 5) 20; 6) one-phase flow.

one and depend on the tilt angle of the channel. This is due to two factors: the fluid flow rate redistribution between the upper and lower halves of the channel and the nonzero value of the velocity coordinate derivative at the center of the channel. As is shown in [2], at tilt angles of the channel of 30 to 50° with the horizontal, velocity profiles filled to a greater extent compared to the one-phase ones are observed. The trend towards velocity-profile deformation in the horizontal layer is the same as in [9].

Figure 8 shows the dependence of the relative velocity pulsations at different points of the channel cross section on the tilt function. The obtained values of u'/u in the vicinity of the channel wall did not exceed the characteristic values of pulsations in the turbulent one-phase flow (30%), decreasing towards the channel center. Comparison of the experimentally measured relative pulsations of the fluid velocity in the one-phase flow with the data obtained at $\beta = 0.5$ demonstrate the perturbing action of a bubble cluster on the flow characteristics in the upper part of the channel. At $y < 5$ mm, a stratification of the values of velocity pulsations for various tilt angles of the channel is observed, whereas in the lower part they practically agree.

Thus, in this work we have developed an electrochemical method for measuring the local gas content and the fluid velocity in a two-phase liquid-gas flow. Numerical analysis of concurrent records of the low-frequency and high-frequency components of the electrochemical velocity transducer signal permits more reliable measurements of the local hydrodynamic characteristics of liquid-gas flows under various conditions.

NOTATION

I, transducer current, A; A, B, calibration coefficients (constants), A, $\text{A}\sqrt{\text{sec/m}}$; u, fluid velocity, m/sec; V_1, velocity transducer voltage, V; V_2, conduction transducer velocity, V; E_{liq}, voltage corresponding to the liquid level; E_{g}, voltage corresponding to the gas level, V; E_{thr}, voltage corresponding to the cutting-out level, V; T_i, time of the ith bubble passage through the transducer, sec; T, total measurement time, sec; t, current time; V_{thr}, relative cutting-out threshold; α, local gas content; β, expendable volume gas content; W_{f}, reduced fluid velocity, m/sec; W_{liq}, reduced gas velocity; m/sec; θ, tilt angle of the channel, deg; u, rms value of velocity pulsations, m/sec; y, coordinate, mm; u'/u, relative pulsations of the fluid velocity. Subscripts: liq, liquid; g, gas; thr, threshold.

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