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CHARACTERISTICS OF A FLOW OF MONODISPERSE GAS–LIQUID MIXTURE IN A VERTICAL TUBE

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The results of measurement of the wall shear stress, and the void and liquid-velocity profiles in an ascending two-phase flow containing gas bubbles of uniform size are given. It is shown that the bubble size has a significant effect on the flow structure and characteristics.

The need to investigate the fine structure of two-phase flows is due to the complex motion of the phases and to the large number of parameters that affect the characteristics of such flows. Several experimental studies [1-3] have shown that there may be different local void distributions over the tube cross section, which must obviously affect other characteristics of the flow (velocity profile, wall shear stress, heat- and mass-transfer coefficients). Bubbly flow, which is often encountered in engineering applications, has been most poorly investigated so far. The presently available and very few measurements of the friction factor in these conditions [4-6] indicate the presence of a region of sharp increase in the wall shear stress in comparison with single-phase flow at low values of void fraction. The relations $\tau/\tau_0(\beta)$ were not identical in the different investigations and in a number of cases a single relation could not be obtained even in the same experiment [5, 6]. It follows from this that in a particular region of parameters we do not have sufficient knowledge of the

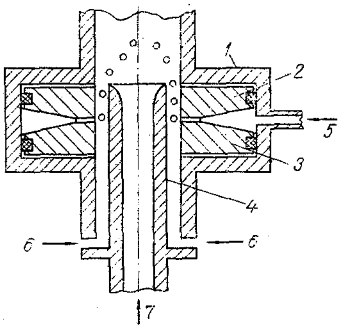

Fig. 1. Generator of calibrated gas bubbles: 1) case; 2, 3) rings; 4) insert; 5) gas input; 6) slit liquid input; 7) central liquid input.

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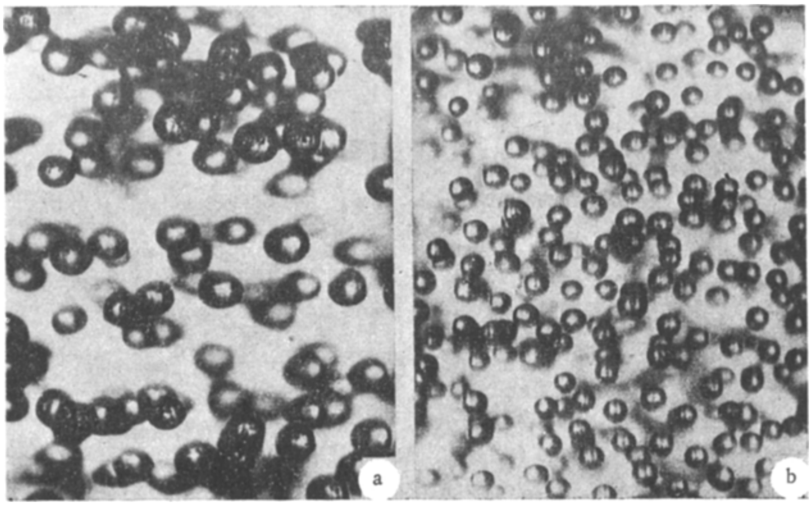

Fig. 2. Photographs of two-phase flow: a) d = 1 mm; b) d = 0.5 mm.

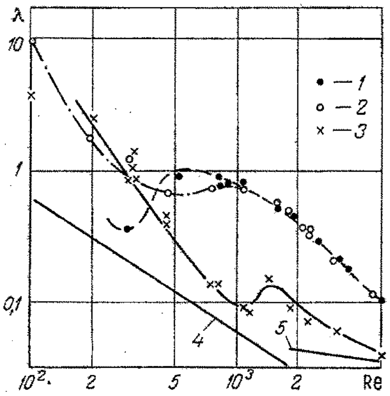

Fig. 3. Friction factor in monodisperse gas–liquid flow with β = 10%: 1) d = 0.1; 2) 0.5; 3) 1 mm; 4) Hagen–Poiseuille law; 5) Blasius law.

reduced velocities of the liquid and gas for determination of the flow characteristics. An important parameter of gas–liquid fluxes is the diameter of the gas bubbles, on which the nature of the flow past the bubbles largely depends, and their motion relative to the liquid. Determination of the effect of bubble size on the characteristics of a two-phase flow requires the conduction of experiments with gas bubbles of calibrated diameter. As far as we know, there have been no systematic investigations of this kind.

The aim of the present work was to investigate the effect of bubble diameter on the characteristics of two-phase flow in a vertical tube.

The experiments were carried out in the rig shown schematically in [6]. The working section consisted of a vertical tube with internal diameter 15 mm and length 5 m. A gas-bubble generator, described below, was mounted at the inlet of the working section. The range of reduced liquid velocities was 0.6 cm/sec to 0.3 m/sec, which corresponds to Reynolds numbers (based on the reduced velocity and viscosity of the liquid) from 100-5000. The discharge volumetric void fraction β varied from 0.5-15%.

A special generator, which enabled us to inject gas bubbles of constant diameter into the flow, was mounted at the inlet of the working section. It was similar in design to the device used for a similar purpose in [7]. A diagram of the gas-bubble generator is shown in Fig. 1. Two metal rings with internal diameter equal to the tube diameter were fitted in a case. The contiguous faces of the rings were ground and then

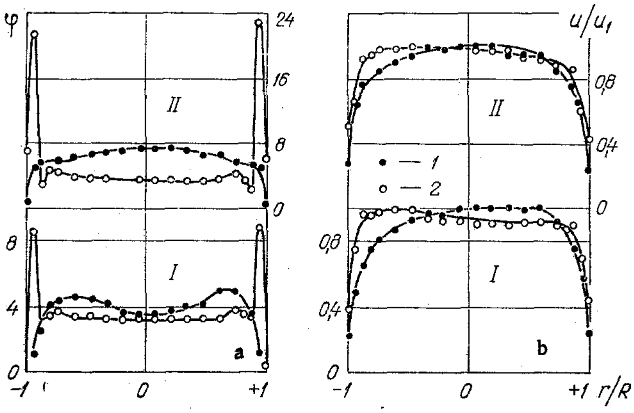

Fig. 4. Profiles of local void fraction (a) and liquid velocity (b) for β = 10%; I) Re = 990; II) Re = 2280; 1) d = 1; 2) d = 0.5 mm; r, R in m; u, u_l in m/sec; φ in %.

identical grooves of 0.05-mm depth were made in the face of the bottom ring. The grooved ring could be changed; the number of grooves varied from 1-180. Tightening of the rings produced a set of equal holes through which the gas was injected into the flow. The gas bubbles were injected into the annular slit between the inner surface of the rings and the outer surface of a coaxial insert. The liquid was fed separately through the slit and through the insert. The flow of liquid through the slit was constant during the series of experiments. This, and also the equal sizes of the holes, ensured that the gas bubbles all had the same diameter. When the gas emerged from the hole equal bubbles were obtained in a very wide range of variation of gas flow through the hole. Hence, a change in reduced gas velocity in the two-phase flow was usually effected by alteration of the number of holes by replacement of the grooved ring by another one. The reduced liquid velocity was changed by regulating the flow through the central hole of the insert without altering the flow through the annular salt. Gas bubbles of different diameter were obtained by a change in the slit width, and also by regulation of the flow through the slit.

The described device enabled us to obtain a gas–liquid flow with the above-indicated range of variation of reduced liquid velocity and void fraction and gas-bubble diameters of 0.1-1 mm. The spread of the diameters did not exceed 15-20%, so that the obtained gas–liquid mixture could be regarded with satisfactory accuracy as monodisperse. The mean bubble diameter was determined from flashlight photographs of the flow. Typical photographs are shown in Fig. 2.

The hydrodynamic characteristics were measured by the electrochemical method [6, 8]. The working liquid was a solution of 0.5 N sodium hydroxide and 0.005 N potassium ferri- and ferrocyanide in distilled water. The experiments were conducted at a constant liquid temperature of 20°C. To measure the wall shear stress we used sensors consisting of platinum plates of cross section 0.1 × 1 mm embedded flush with the wall. To measure the liquid velocity and local void fraction we used blunt-nosed velocity probes of diameter 30 μm.

Measurements of the characteristics of the two-phase flow showed that at constant values of Re and β the structure of the flow and, hence, its characteristics depend significantly on the bubble diameter. Figure 3 shows the relation between the friction factor (calculated from the measured values of τ) and the Reynolds number for a two-phase flow with β = 10%. It is apparent that in the general case the values of λ are higher than in a single-phase flow. The nature of the behavior of λ(Re) is different for different bubble diameters: when d = 1 mm λ decreases monotonically with increase in Re, approaching the value in a single-phase flow.

For d = 0.1 and 0.5 mm there is a sharp increase in λ when Re > 700. This difference in the behavior of the friction factor is due to the different void distribution over the tube cross section. Figure 4a shows local void profiles for a regime with bubble diameters equal to 1 and 0.5 mm. It is apparent that when d = 1 mm the void distribution over the tube radius is almost uniform. There is a maximum in the central part of the tube or two weak maxima far from the walls. Reduction of the bubble diameter leads to alteration of the structure: the gas becomes concentrated near the walls, and the profiles of φ have two sharp maxima near the walls and an almost constant value at the tube center. The void fraction near the walls in the case of an ascending flow of two-phase mixture has been determined in many investigations [1-3]. Such a distribution is due to the fact that when the motion of the bubble is similar to motion of an ascending solid sphere (which is the case when the bubbles are small) it migrates to the wall. In fact, as visual observations showed, bubbles of diameter less than 0.5 mm move mainly in a straight line and at a small distance from the point of entry of the gas are concentrated near the tube wall. With further increase in diameter the distortion of the bubbles becomes appreciable (Fig. 2), the nature of the flow round them changes, with the result that the motion ceases to be linear and the bubbles begin to move in a trajectory in the form of a helix whose diameter is comparable with the channel diameter. This rules out concentration of the bubbles near the wall and the gas is distributed more uniformly over the whole cross section of the tube. The bubble diameter at which the motion changes its nature lies in the range 0.6-1 mm. In this range of diameters the flow structure is significantly altered, which leads to quite different relationships between the friction factor and the Reynolds number. Hence, the concept of effective viscosity cannot be applied to this two-phase flow.

The presence of the gas phase in the flow leads to great distortion of the liquid velocity profiles in comparison with single-phase flow in a tube. The velocity profiles (Fig. 4b) become much more filled in comparison with the laminar flow profile and become similar to impact flow. A characteristic feature of the profiles in the region of small Reynolds numbers is the asymmetry that is present in the general case. This was not due to any defects of the experimental apparatus, such as nonuniform admission of the gas round the circumference or to off-vertical alignment of the channel. The asymmetry was random and could vary evenly over the height of the channel. The velocity profiles shown in Fig. 4 are typical of the considered flow. It should be noted that in spite of the asymmetry of the profile, it is apparent that the velocity profiles for $d = 0.5$ mm are more filled than for $d = 1$ mm, but the difference in the degree of filling is slight. Thus the main mechanism distorting the velocity profile is the definite turbulence produced in the flow by the presence of the gas phase. A secondary factor is the effect of increased void fraction near the walls on the velocity profile. In the considered flow the presence of void maxima leads to greater distortion of the wall part of the liquid velocity profile and, accordingly, to a sharp increase in the wall shear stress. In the center the velocity and void distributions for different bubble diameters are almost uniform, which is also the case in flows with large Reynolds numbers [3].

NOTATION

τ	is the wall shear stress;
τ_0	is the wall shear stress for single-phase flow;
β	is the discharge volumetric void fraction;
φ	is the local void fraction;
λ	is the friction factor;
u	is the local liquid velocity;
u_1	is the maximum liquid velocity;
Re	is the Reynolds number;
R	is the tube radius;
r	is the radius of measurement point;
d	is the mean diameter of gas bubbles.

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