LOCAL GAS CONTENT AND VELOCITY OF THE LIQUID PHASE IN ASCENDING BUBBLE FLOW

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UDC 532.529.5

The results of an experimental investigation of the characteristics of ascending gas–liquid flow in a pipe for gas bubbles of different diameters are given.

Gas–liquid flow in a vertical pipe is characterized by a nonuniform distribution of the gaseous phase over a cross section. This is connected with the presence of a lateral force, under the action of which the bubbles move radially in the pipe. The main contribution is made by the force component connected with the relative motion of a bubble in the liquid stream with a velocity gradient in the radial direction [1-3]. The magnitude of this force depends on the size of the gas bubbles and on their velocity relative to the liquid. Because the velocity of ascent of the bubbles also depends strongly on their size [4], the influence of the size of the gas inclusions on the characteristics of the gas–liquid stream can be very pronounced. As a rule, experimental investigations of gas–liquid flows have been made either without monitoring the size of the gas bubbles [5, 6] or with a single size, which is obtained in the free separation of bubbles from an opening.

The influence of the size of the gas bubbles on the flow characteristics was studied in [7] for a pipe 15 mm in diameter for low values of the Reynolds number. In the present work we investigated gas–liquid flow at high Reynolds numbers in a pipe 86.4 mm in diameter for gas bubbles of different sizes.

The experiments were conducted on an installation described in [6]. A mixer was mounted at the entrance to the working section, making it possible to obtain gas bubbles of one size.

The mixer (see Fig. 1) consists of an annular slit formed by interchangeable outer shells 1, having the same inside diameter d_2 = 86 mm, and interchangeable inner bodies having an outside diameter d_1 of 80 and 70 mm, respectively. Compressed air was supplied to this annular slit through openings 3 with a diameter of 0.2 mm drilled in the outer shell in cross section A–A. The required bubble size, which was determined by photography, was established by selecting the appropriate liquid flow rate $Q_{2\ell}$ in the slit and the outside diameter d_1 of the inner body. The maximum number of openings in cross section A–A was 120, permitting a gas flow of up to $1 \cdot 10^{-4}$ m³/sec. To make investigations at higher gas flow rates we drilled a second row of 120 openings of the same diameter at a distance H = 5.5 mm downstream from cross section A–A.

In order that the average liquid velocity did not change upon approaching the second row of openings, and it influences the bubble size in a definite way, the inner body 2 was made in the form of a cone with a half-angle $\theta = 4°$. Two honeycombs 4 and 5 were placed at the entrance to the annular slit and at the entrance to the inner channel of the mixer to equalize the liquid velocity. The temperatures of the liquid and gas were kept constant and equal to 25 ± 0.5°C. The local gas content ϕ_{en} in the entrance cross section was measured at a distance of ∼300 mm downstream from the mixer exit to estimate the influence of the conditions of supply of the gas. The velocity profile of the liquid phase and the local gas content, and in certain regimes the frictional stress at the wall, were measured in the working section, lying at a distance of ∼4.5 m from the mixer. The measurement procedure and the construction of the sensors were similar to those described in [5, 6]. The measurements were made as follows: First the gas flow rate Q_g and the bubble size were set and then, by varying the liquid rate $Q_{1\ell}$ in the inner channel of the mixer, the reduced liquid velocity w_0' in the working section of the installation was varied. The ranges of variation of the hydrodynamic characteristics of the stream in this research are given in Table 1.

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 2, pp. 181-186, February, 1987. Original article submitted December 12, 1985.

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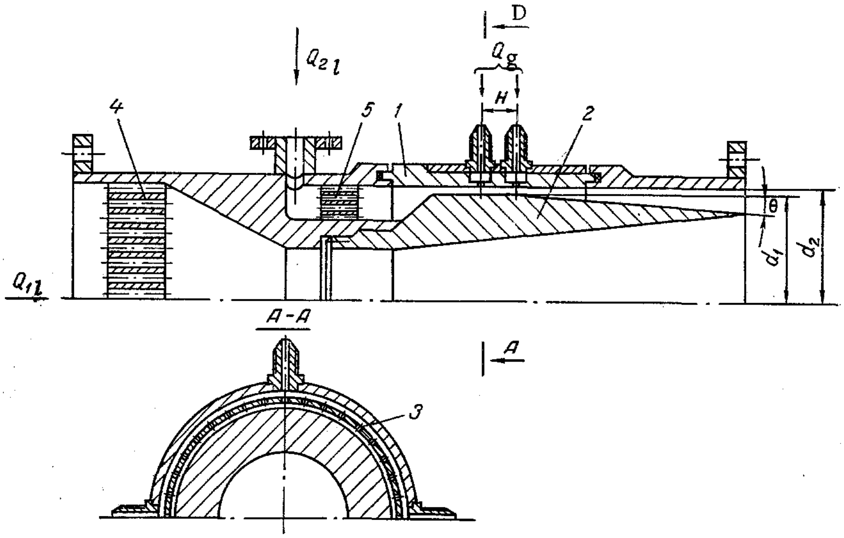

Fig. 1. Diagram of the mixer.

TABLE 1. Parameters of Experimental Regimes

β					
w_0'					$Q_g \cdot 10^3$
0,425	0,53	0,64	0,74	1,06	
0,017 0,036 0,084	0,014 0,03 0,069	0,012 0,025 0,058	0,01 0,02 0,05	0,007 0,015 0,036	0,044 0,094 0,23

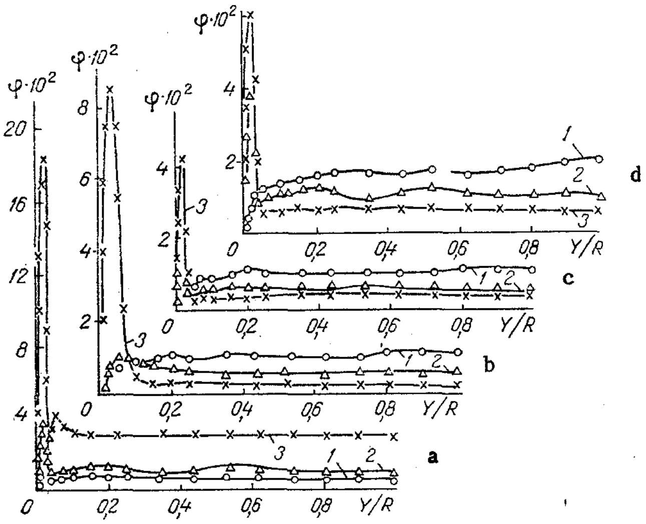

Fig. 2. Distributions of local gas content in a pipe cross section: a) $w_0' = 0.74$; $d_b = 1$: 1) $\beta = 0.01$; 2) 0.02; 3) 0.05; b) $w_0' = 0.425$, $\beta = 0.017$: 1) $d_b = 1$; 2) 1.5; 3) 2; c) $Q_g = 0.044 \cdot 10^{-3}$, $d_b = 1$: 1) $w_0' = 0.425$; 2) 0.74; 3) 1.06; d) $Q_g = 0.094 \cdot 10^{-3}$, $d_b = 1$: 1) $w_0' = 0.425$; 2) 0.74; 3) 1.06.

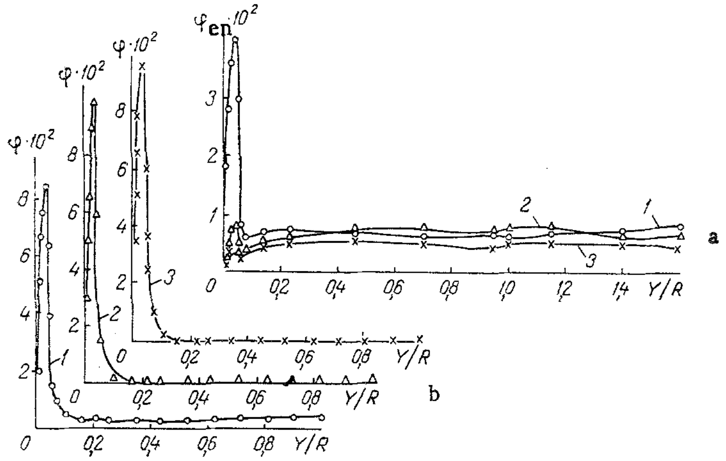

Fig. 3. Influence of the gas content ϕ_{en} at the channel entrance (a) on the distribution of local gas content (b) in the working section of the installation: $Q_g = 0.044\cdot10^{-3}$, $d_b = 2$: 1) $w_0' = 0.425$; 2) 0.74; 3) 1.06.

From Fig. 2a it is seen that for a bubble diameter $d_b = 1$ mm with $w_0' = 0.74$ m/sec, variation of the flow-rate gas content from 0.01 to 0.05 leads to an increase in the gas content near the wall and the appearance of rather pronounced maxima in the distribution of the local gas content ϕ.

Similar results were obtained for $d_b = 1.5$ and $d_b = 2$ mm. This fact indicates that a gradual saturation of the boundary region with gas occurs, and the peak of gas content is separated from the wall by an amount equal to the bubble radius. An increase in the bubble diameter leads to a similar increase in gas content near the wall with a constant flow-rate gas content β (Fig. 2b). This indicates that the hydrodynamic lateral force acting on the bubbles and leading to a concentration of gas near the wall in ascending flow increases with an increase in bubble diameter. The gas concentration near the wall increases similarly with an increase in the reduced velocity of the liquid (Fig. 2c and d). This is connected with an increase in the gradient of liquid velocity near the wall and hence in the lateral force acting on the bubbles.

As was noted above, the variation of w_0' with constant d_b and β was accomplished by varying the liquid flow rate $Q_{1\ell}$. In turn, this leads to a different distribution of gas content ϕ_{en} at the channel entrance, which naturally must be reflected in the distribution of gas content in the working section. But, as can be seen from Fig. 3, in the working section the distribution of ϕ had clearly expressed maxima of gas content near the wall in all cases, whereas the distribution of gas content at the channel entrance had one only for $w_0' = 0.425$ m/sec.

This again confirms the conclusion that an increase in the reduced liquid velocity w_0' causes a strong increase in the hydrodynamic lateral force acting on a bubble, leading to the almost complete migration of the bubbles from the core of the stream to the channel walls. The ratio of the gas contents in the peak of gas content near the wall and in the same cross section at the center of the channel serves as an index of this. For example, for $d_b = 1.5$ mm, $\beta = 0.015$, and $w_0' = 1.06$ m/sec we have $\phi_{peak}/\phi_c >> 100$.

From Fig. 4 it is seen that for constant liquid and gas flow rates, an increase in the bubble diameter from 1 to 2 mm leads to greater filling of the velocity profiles of the liquid phase. The greatest deformation of the velocity rofiles occurs in those regimes where there are well-expressed maxima of gas content; the velocities in the boundary region have inflection points or even small local maxima at an intermediate radius. This occurs because the bubble layer near the wall has a higher velocity than the liquid velocity at the given point and entrains some liquid with it. The presence of such local maxima of liquid velocity was noted earlier only on descending bubble flow [8], and was not observed in ascending flow. From all appearances, this is connected with the fact that in the previous investigations the size of the gas bubbles was not monitored accurately enough. When gas bubbles of different sizes, the behavior of which differs, are present in the stream, the above-indicated pattern

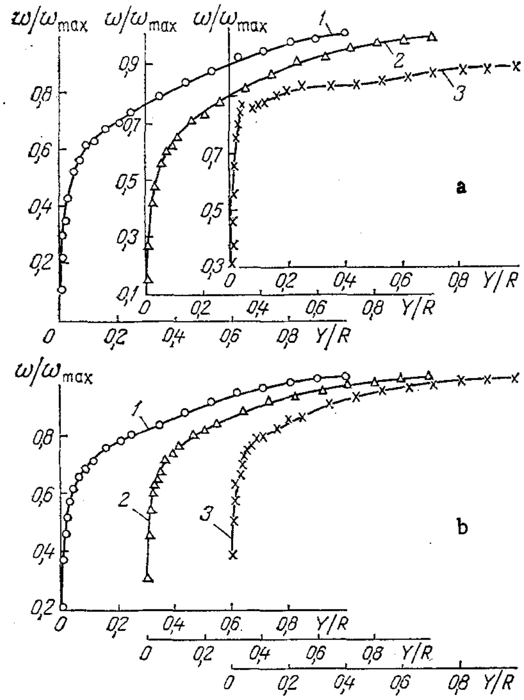

Fig. 4. Distributions of the dimensionless velocity of the liquid phase, $Q_g = 0.044 \cdot 10^{-3}$, $w_0' = 0.425$ (a) and 0.74 (b): 1) $d_b = 1$; 2) 1.5; 3) 2.

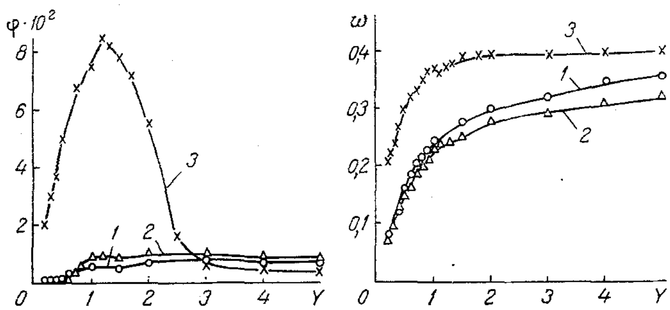

Fig. 5. Distributions of liquid velocity and local gas content in the wall region, $Q_g = 0.044 \cdot 10^{-3}$, $w_0' = 0.425$: 1) $d_b = 1$; 2) 1.5; 3) 2.

is masked by other effects. For example, for small bubbles the velocity of migration toward the wall is low and very great length is needed to completely clear the stream core of the gaseous phase. It should be noted that in previous investigations ϕ_{peak}/ϕ_c did not exceed 10.

The reduced velocity of the liquid also has considerable influence on the characteristics of bubble flow. When it increases, the ratio of the velocity of bubble ascent to the liquid velocity decreases, leading to less deformation of the liquid velocity profile. As can be seen in Fig. 5, with an increase in w_0' the inflection points in the velocity profile become less pronounced, while the profile itself becomes less full, despite the fact that the wall maxima in gas content increase. As was shown in [5, 6], in the limit with high w_0' the influence of the gaseous phase on the flow becomes insignificant.

The presence of sharp maxima of the gas content near the wall leads to a considerable increase in the frictional stress at the wall, which can exceed the value for a one-phase stream by a factor of two to three even for $\beta = 0.05$. The frictional stress at the wall is also affected significantly by d_b.

Thus, the size of the gas bubbles is a significant parameter determining the characteristics of gas–liquid bubble flow in a developed turbulent regime.

NOTATION

w_0', reduced liquid velocity, m/sec; w_0'', reduced gas velocity, m/sec; $Q_\ell = Q_{1\ell} + Q_{2\ell}$, total volumetric flow rate of liquid, m^3/sec; $Q_{1\ell}$, volumetric flow rate of liquid in the inner channel of the mixer, m^3/sec; $Q_{2\ell}$, volumetric flow rate of liquid through the annular slit of the mixer, m^3/sec; Q_g, volumetric flow rate of gas through the mixer, m^3/sec; $\beta = Q_g/(Q_\ell + Q_g)$, flow-rate gas content; w, local velocity of liquid in the gas–liquid stream, m/sec; w_{max}, maximum velocity of liquid at the center of the channel in the gas–liquid stream, m/sec; d_b, bubble diameter, mm; θ, aperture half-angle of the conical part of the inner body of the mixer, deg; Y, distance from the wall, mm; R, channel radius, mm; ϕ, local gas content. Indices: en, conditions at the channel entrance; ', ", parameters pertaining to the liquid and gaseous phases, respectively.

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