FRICTIONAL STRESS AT THE WALL IN AN ASCENDING GAS – LIQUID FLOW

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The determination of the coefficients of friction and heat and mass exchange in a turbulent two-phase flow is a very important problem today both from the purely scientific point of view and for many technical applications. The main difficulty in solving this problem is the large number of parameters affecting the structure of the two-phase flow. A knowledge of the flow rates of liquid and gas is not sufficient for determining even the average characteristics of the two-phase flow. The structure of the flow, and consequently the properties of the turbulent transfer, will also be affected by the distribution of phases over the cross section of the channel, the compressibility of the gaseous phase, the gravitational forces, and the detailed structure of the processes on the gas–liquid interface.

The traditional approach to the problem of studying the characteristics of two-phase flows is to distinguish specific flow regimes [1, 2], the most important of which in a vertical tube are the bubble regime, the plug regime, and the dispersed-annular regime, with subsequent calculation according to various models, which are usually applicable to one of the regimes. This scheme gives satisfactory results only if two conditions are satisfied: first of all, if some equilibrium structure is established fairly rapidly, and secondly, if all the flows in one regime are similar. Experimental data available today indicate that these conditions are by no means always satisfied. An equilibrium flow structure indepdndent of the inlet conditions, as was shown in [3], is established only at considerable distances from the inlet and at large liquid-flow velocities (> 3 m/sec). Numerous measurements made recently on certain local characteristics [4-8] indicate that qualitatively similar distributions of the gas content will be found only in the plug regime, whereas in the bubble regime there is no such similarity and the flow situation is much more complicated.

An understanding of the mechanism of the two-phase flow requires complex investigations including the measurement of as many flow characteristics as possible, such as the local gas content, the liquid and gas velocities, the tangential forces at the wall, and the pulsation characteristics. Among the most detailed studies of this kind are the measurements in [9, 10], the first of which is basically methodological in nature. In these studies there was no determination of such an important flow characteristic as the local frictional stress at the wall; furthermore, the range of liquid velocities was very narrow. Earlier investigations of the frictional stress in two-phase flows [11-13] give no information on the internal structure of the flow.

In the present study we conducted a detailed investigation of the characteristics of an ascending two-phase flow in a tube with small flow velocities (up to 2 m/sec). The frictional stress at the wall was measured by the electrochemical method, and the gas-content profiles by the electrical-conductivity method.

The experiments were carried out on an apparatus shown in schematic form in Fig. 1. The two-phase flow was set up by feeding a liquid with a dispersed gaseous phase into the stream. Circulation of the liquid was established by means of a centrifugal pump 1 with a maximum flow rate of 50 m^3/h and a pressure of 6 gauge atmospheres. The liquid from the pump passed through a flow-metering diaphragm 2 connected with a U-shaped differential manometer 3 and through a regulating gate 4 and then entered the working segment 5. After the working segment the gas–liquid mixture entered the return channel 7, and then the separator 9. In the separator the liquid and gas were separated, the liquid going into the collection tank 10, from which it returned to the pump. The gas from the separator outlet was discharged into the atmosphere. In order to maintain the required pressure in the measurement section, the flow at the outlet of the return channel was throttled by means of a gate 8. The gas system consisted of high-pressure tanks 11, reducers 12 and 15, a filter 13, and a flow-metering diaphragm 14.

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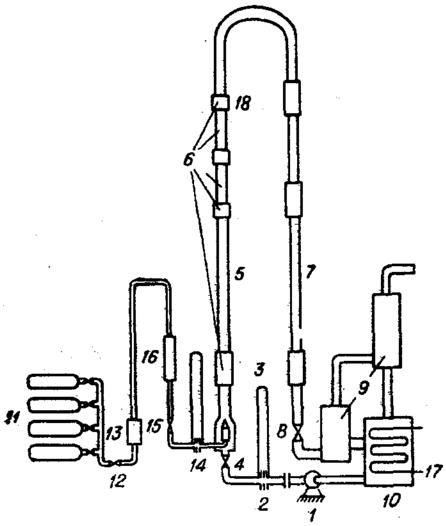

Fig. 1

The working segment consisted of a vertical tube with an inner diameter of 86.4 mm and a length of 6.5 m. The gas was fed in through the lateral surface of a porous tube 40 mm in diameter and 80 mm long, which was set up at the inlet to the working segment. Because it had a high resistance, the porous tube could not be used for regimes with a high value of reduced gas velocity. For that case the gas was fed through a nozzle with an aperture diameter of 20 mm, set up on the axis of the working segment.

The working liquid used was a solution of 0.5 N sodium hydroxide and 0.01 N potassium ferri- and ferrocyanide in distilled water. The gas used was nitrogen. The temperature of the liquid and gas at the inlet was kept constant (24 ± 0.5°C). For thermostating the gas, an electric heater 16 with regulatable power was included in the gas line. The liquid was thermostated by means of a heat exchanger 17 placed in the tank through which the cooling water was pumped (the water was turned on and off automatically by the temperature-regulating circuit).

The method used for measuring the frictional stress at the wall, the local gas content, and the liquid velocity are described in [14]. All the measurements were made at the cross section 18, which was 4750 mm (55 tube diameters) from the gas input point. The friction sensor dimensions were 0.1 × 1.5 mm (for measuring average values) and 0.02 × 0.3 mm (for measuring pulsed quantities). The sensors measuring the local gas content and the velocity had an electrode diameter of 20 μm and an insulated diameter of 40 μm. The measurements by the electrochemical method were made according to a calibration-measurement-recalibration scheme. The calibration was carried out with pure liquid flowing in the tube. The pressure at the measurement cross section was kept constant (0.5 gauge atmosphere).

For visual observation of the flow, a number of transparent plastic inserts 6 were included in the working segment.

The measurements were made at reduced liquid velocities W_0' ranging from 0.44 to 2.05 m/sec and volumetric gas-content values β from 0 to 80%. Both bubble and plug regimes of flow existed in the tube.

In the region with a bubble regime of flow, in the indicated range of parameters, we observed that the tangential stress τ at the wall was a multiple-valued function of W_0' and β. For fixed values of the reduced liquid velocity and unchanged mixer construction, there were two flow regimes with sharply different characteristics. The different flow structures were clearly visible in photographs. In one of the states (regime I) the bubbles were fairly uniform in dimension and moved mainly in a vertical direction. The other state (regime II) was characterized by a large dispersion of bubble dimensions and the appearance in the center of the channel of irregularly shaped formations, which constituted the initial stage of the development of the plugs. The bubbles moved in a much more disorderly fashion, especially entering the vortex path behind the large bubbles. When the apparatus was turned on, either one or the other regime appeared initially and continued for some time (from a few minutes to 1-2 h), then the flow structure changed fairly rapidly to the other regime, after which there could be a return to the first regime. Many repetitions of the experiments showed that the change from one regime to the other is a random process.

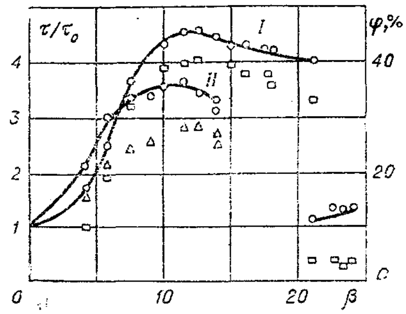

Fig. 2

Figure 2 shows the results of the measurement of the tangential stress at the wall in the region of unstable flow for $W_0' = 0.785$ m/sec. The circles show the values of τ/τ_0, where τ_0 is the frictional stress at the wall when pure liquid flows past it at an average velocity of W_0'.

The points lying on curves I and II are those for regimes I and II, described above. It can be seen that for small values of β (5-10%) there is a sharp increase in the tangential stress at the wall in comparison with the single-phase flow, and values of τ in the two-phase flow that correspond to regimes I and II for the same β may differ by a factor of 1.5. For smaller liquid velocities this difference may be even greater. At $\beta = 21\%$ there is a sudden change of the flow to the fully developed plug regime, accompanied by a sharp drop in τ.

At the same time as measuring τ, we measured the local gas content φ at points whose distances from the wall were y = 0.5 mm and 1 mm (the rectangles and triangles, respectively, in Fig. 2). The choice of the y values was based on the fact that the function $\varphi(y)$ has a maximum near these points in regimes I and II, respectively. The behavior of φ for a fixed value of y is completely analogous to the behavior of the frictional stress at the wall. When the change to the fully developed plug regime takes place, the distribution of the local gas content changes sharply, the gas moves away from the wall to the central part of the tube, and this leads to a sharp drop in φ near the wall.

Figures 3-5 show the results of the measurements of τ/τ_0 for different liquid velocities in a broader range of gas-content values; they also show the data of [15] for a tube with a diameter of 15 mm, and of [16] for a tube with a diameter of 86.4 mm [1) data of [15] for bubble regime; 2) data of [15] for plug regime; 3) data of [16]; 4) results obtained by the authors]. The solid curve is the graph of the function given in [11]:

$$\tau/\tau_0 = (1 - 0.833\beta)^{-1.53}. \tag{1}$$

The experiments whose results are shown in Figs. 3-5 were carried out in [15, 16] and in the authors' study with approximately the same values W_0' (Fig. 3: [15] – $W_0' = 0.51$ m/sec, [16] – $W_0' = 0.432$ m/sec, authors' experiments – $W_0' = 0.44$ m/sec; Fig. 4: [15] – $W_0' = 0.81$ m/sec, authors' experiments – $W_0' = 0.785$ m/sec; Fig. 5: [15] – $W_0' = 1.18$ m/sec, [16] – $W_0' = 0.956$ m/sec, authors' experiments – $W_0' = 1.06$ m/sec). The points 5 in Fig. 5 are the authors' data for $W_0' = 2.05$ m/sec.

It can be seen that for liquid velocities of $W_0' \leq 1$ m/sec the behavior of τ for small β looks the same as in Fig. 2. For small β we have a sharp increase in τ to some value τ_1 which is the maximum for the bubble regime, and τ_1 increases with increasing W_0'. The range of gas-content values at which the bubble regime exists becomes narrower as W_0' increases. Furthermore, for small values of β the function $\tau(\beta)$ is not single-valued.

For $W_0' = 2.05$ m/sec the nature of the variation of $\tau(\beta)$ changes substantially. There is no sharp increase in τ for small values of β, and the further increase in β is accompanied by a monotonic increase in τ; the experimental points are in good agreement with formula (1). The function $\tau(\beta)$ is no longer multiple-valued.

As we pass to a fully developed plug regime, there is a sharp decrease in τ, and at $W_0' \geq 0.7$ m/sec the experimental points are in good agreement with (1). However, at $W_0' = 0.44$ m/sec the values of τ obtained in the experiment are higher than those for (1).

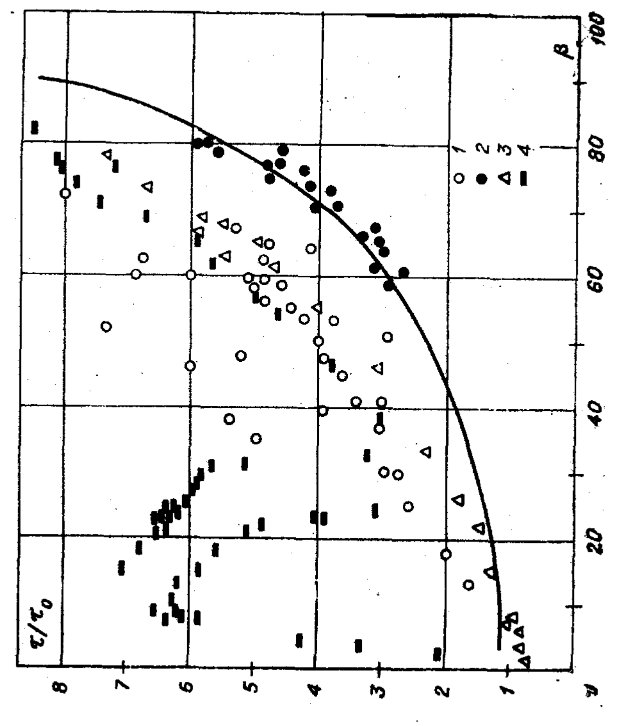

Fig. 3

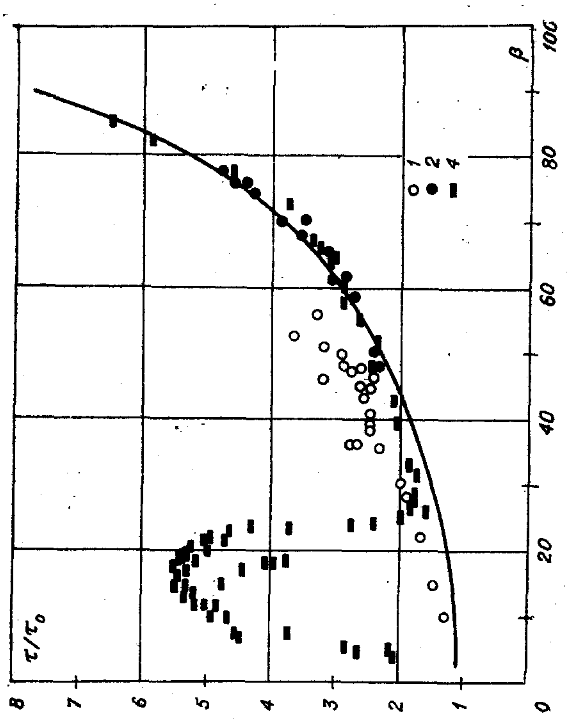

Fig. 4

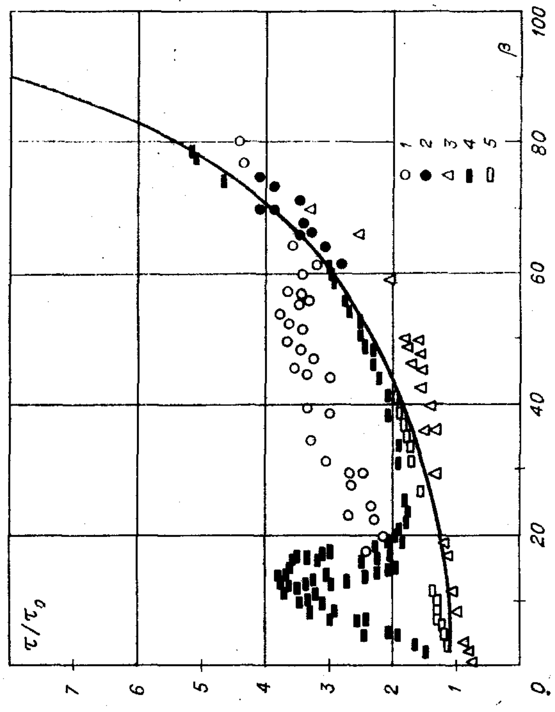

Fig. 5

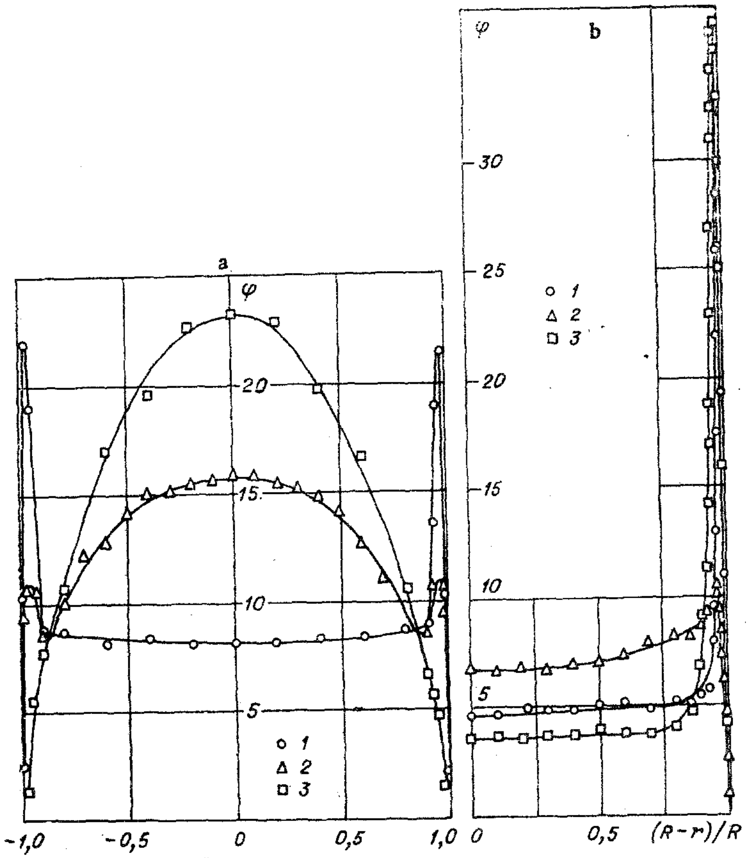

Fig. 6

The data of [16], obtained in a tube of the same diameter, are in satisfactory agreement with the data obtained by the authors in the fully developed plug regime. In the bubble regime, however, there is no such agreement between the data. The reason for this is that in [16] the method used for the gas feed was different – the gas was blown in through a nozzle 20 mm in diameter. The flow structure in the bubble regime was radically different: The gas exited from the nozzle in the form of large bubbles, and there was no concentration of gas near the wall. Thus, for $W_0' < 1$ m/sec the flow depends to a large extent on the initial conditions. For the data of [15], obtained in a tube of much smaller diameter, there is only qualitative agreement in the behavior of $\tau(\beta)$ in the bubble regime. The boundaries of the region in which the bubble regime exists and the maximum values of τ are very different quantitatively from the results obtained by the authors. The measured profiles of the local gas content in the different regimes are shown in Fig. 6. The data in Fig. 6a were obtained for a single value of the reduced liquid velocity, 0.57 m/sec, and different values of outgoing gas content: 1) $\beta = 12.6\%$; 2) $\beta = 16.4\%$; 3) $\beta = 19.6\%$. The profiles of φ for different values of β differ considerably in shape. For small β values we have sharp maxima of the local gas content near the walls of the tube. This distribution of φ corresponds to a pure bubble regime of flow. In the fully developed plug regime ($\beta = 19.6\%$) the gas-content profile is parabolic in shape, with one maximum at the center of the tube. In the transitional regime between bubble and plug flows, we may observe φ profiles which are, in a sense, a combination of the first two, with three maxima (near the wall and at the center of the tube). It should be noted that the gas-content profiles so obtained are qualitatively quite analogous to those given in [9, 10].

The local-gas-content profiles shown in Fig. 6b were measured for β values close to each other but for different reduced liquid velocities: 1) $W_0' = 0.44$ m/sec, $\beta = 7.5\%$; 2) $W_0' = 2.05$ m/sec, $\beta = 8.6\%$; 3) $W_0' = 0.79$ m/sec, $\beta = 7.6\%$. The profile corresponding to $W_0' = 2.05$ m/sec is substantially different from the profiles for smaller values of W_0': The distribution of gas content over the cross section is much more uniform. The gas-content maximum near the wall is preserved but much less marked. For smaller liquid velocities ($W_0' < 1$ m/sec) the values of φ near the wall reach 0.3-0.4, as a result of which there is a reduction in φ in the central part of the tube. It is interesting to note that the height of the maximum of φ near the wall and the value of the gas content at the center of the tube are not monotonic functions of the velocity.

A comparison of the local gas-content profiles with the distributions of $\tau(\beta)$ indicates that the sharp increase in τ the bubble regime for small gas-content values is due to the presence of sharp gas-content maxima near the wall of the tube. The bubbles in the wall layer have in this case an ascending velocity relative to the liquid that is comparable with the local liquid velocity at any given points, and apparently they strongly deform the profile of the liquid velocity, increasing the velocity gradient at the wall. The drop in τ with increasing β that takes place when there is a transition from the bubble to the plug regime is due to the reduction of the φ maxima near the walls and the removal of the gas toward the center of the tube. The model given in [11] can be used only in the case when the distribution of the gas concentration over a cross section of the tube is nearly uniform. Unfortunately, the studies conducted by the authors did not include a simultaneous measurement of the frictional stress at the wall and the flow structure, although the effects of increasing friction at low gas-content values [15, 17] and the appearance of φ maxima near the wall in this regime [3, 10] are well known.

The only attempt to describe the behavior of $\tau(\beta)$ in the bubble regime for small liquid velocities was made in [18]. In the calculation method, based on an analysis of stratified annular flow, Ueda [18] artifically introduced relations obtained from an analysis of the experimental data of [17]. The calculation method so obtained describes the experimental data of [17] satisfactorily. However, when it is applied to our results, there is a very large discrepancy between the calculated and experimental values of τ; this may be attributed to the limited possibility of extending the results of [18] to tubes of considerably larger diameter.

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