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BUBBLE MODE OF FLOW OF A GAS–LIQUID MIXTURE IN A VERTICAL PIPE

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The results of the measurement of the local frictional stress at the wall in an ascending two-phase stream using the electrochemical method are presented.

The need to determine the coefficients of friction and heat transfer in two-phase flows, caused by problems of nuclear power engineering and chemical technology, in particular, has led to the appearance of a large number of investigations of the integral parameters of such flows and the development of a number of semi-empirical and empirical calculation methods based on them [1, 2]. The diversity of forms of flow of two-phase media, however, leads to the fact that there is presently an absence of sufficiently universal calculating methods yielding satisfactory results in the entire range of variation of the flow parameters. The problem of investigating the detailed structure of two-phase flows in order to create mathematical models which more adequately reflect the flow properties becomes urgent in this connection.

Recently, there have appeared a number of reports devoted to measuring the distributions over a channel cross section of the local velocities of the phases and the gas content, as well as the simplest pulsation characteristics of the flow [3-6]. To obtain fuller information about two-phase streams one must, in addition to expanding the range of variation of the parameters, supplement the results of the above-indicated work by the measurement of other important flow characteristics, one of which is the local frictional stress at the wall.

The goal of the present work is to determine the behavior of the coefficient of friction during the ascending flow of a gas–liquid mixture in the bubble mode and at the start of the plug mode using the electrochemical method, which allows one to determine the local shear stress at the pipe wall.

The experiments were carried out on an installation for which a diagram is presented in Fig. 1. The installation consists of a liquid-tight circulation loop having ascending and descending channels of round cross section with an inner diameter of 86.4 mm. All the measurements were made in the ascending section. The channel had transparent inserts of plastic for visual observation.

The liquid was pumped through the loop with a centrifugal pump having a maximum output of 50 m^3/h. The gas was supplied, as shown in Fig. 1c, through the cylindrical section of a porous pipe 40 mm in diameter and 80 mm long located at the entrance to the ascending channel. The liquid and gas were thermostatically controlled at a temperature of 24 ±0.5°C ahead of the entrance to the working section. The flow rates of the liquid and gas were determined with flowmeter diaphragms. The measurements were made in the cross section lying at a distance of 4.750 m (55 diameters) from the point of gas supply. A constant pressure of 1.5 atm. abs. was maintained in the measurement cross section with the help of throttle devices at the outlet of the working section.

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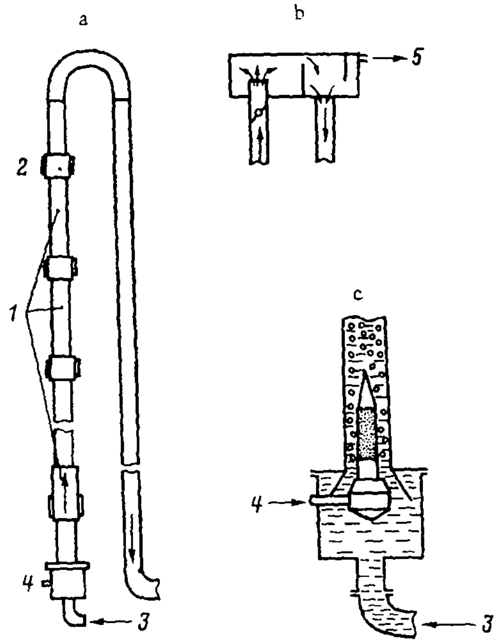

Fig. 1

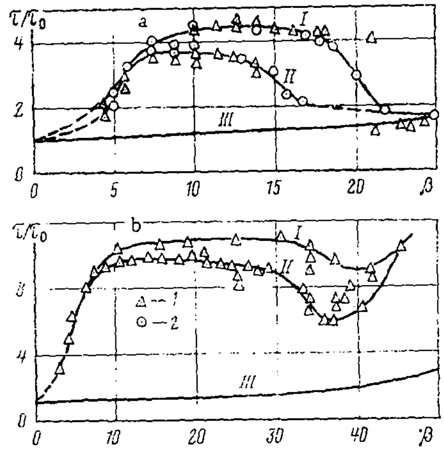

Fig. 2

Fig. 1. Diagram of installation: a) ascending—descending flow; b) ascending flow; c) diagram of gas supply; 1) visualization section; 2) measurement unit; 3) liquid supply; 4) gas supply; 5) gas outlet.

Fig. 2. Dependence of wall shear stress on flow-rate gas content: a) Re = 70,000; b) 20,000; I) purely ascending flow (diagram of Fig. 1b); II) ascending—descending flow (diagram of Fig. 1a); III) function obtained in [1]. τ, τ_0, N/m^2; β, %.

The ascending and descending channels were connected in two schemes (Fig. 1). In the scheme of Fig. 1a, the sections are joined by a bend and the separation of gas from liquid occurs in the tank-separator after the mixture passes through the descending section. With such a scheme it is possible for the descending flow to affect the ascending flow, and therefore in the course of the work the installation was altered in accordance with the scheme of Fig. 1b. In this scheme the ascending and descending sections are joined through a tank with a volume of 80 liters. The separation of the gas, which is vented into the atmosphere, occurs in this tank, while the liquid falls freely through the descending section and then overflows into the lower tank.

The measurements of the wall shear stress were made using the electrochemical method [7, 8]. The end of a platinum plate with a cross section of 0.2 × 2 mm, soldered into a glass tube and ground flush with the wall, served as the pickup. A solution of 0.5 N sodium hydroxide and 0.01 N potassium ferri- and ferrocyanide in distilled water served as the working liquid. The air was supplied from high-pressure tanks through a system of reducers.

The electrochemical friction pickups were calibrated during one-phase fluid flow in the pipe. In the calibration the shear stress was determined from the known liquid flow rate by the Blasius equation. All the shear-stress measurements were made by the system of pickup calibration—measurement—recalibration. In one mode the reproducibility of the pickup current between the calibrations was no worse than 0.5-1%. The accuracy of the measurement of the wall shear stress was 3-5%.

The measurements were made at two values of the Reynolds number (constructed from the reduced velocity and viscosity of the liquid and the channel diameter) — 20,000 and 70,000. A constant liquid velocity was maintained in the experiments while the bulk flow-rate gas content β was varied in the range of 0-25% at Re = 70,000 and up to 50% at Re = 20,000. The bubble, transitional, and the start of the plug modes of flow of the gas—liquid mixture occurred at these values of β.

The measurements made of the frictional stress at the channel wall in the two-phase stream showed the complicated character of the variation of this quantity. The presently widespread methods of calculating two-phase flows [1, 2, 9] yield a monotonic growth of τ with an increase in the flow-rate gas content, with the frictional stress in a two-phase stream differing little from the friction in a one-phase stream at the same liquid flow rate at low values of β (up to ~30%). In our experiments (Fig. 2) we observed a considerable

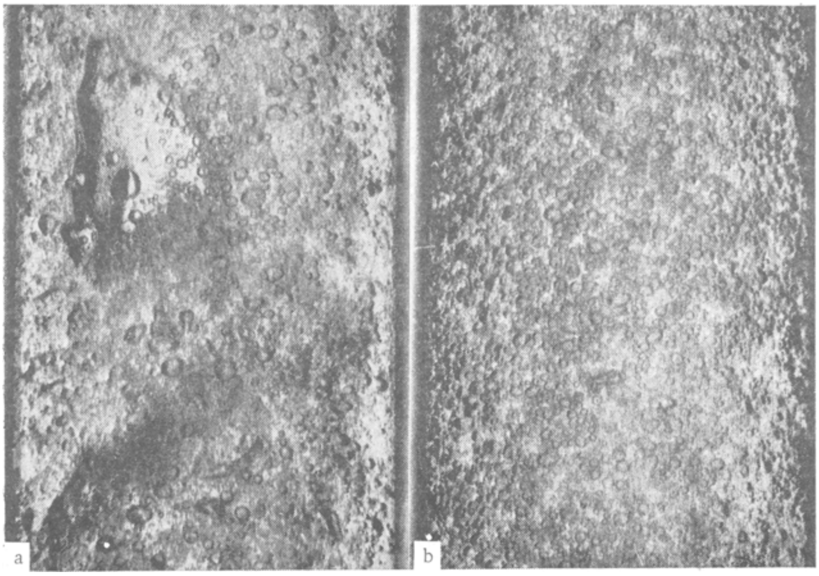

Fig. 3. Photographs of flow in channel: a) mode II; b) mode I.

increase in the frictional stress in comparison with that of a one-phase stream. Moreover, the variation in frictional stress with gas content was not monotonic: a drop in τ with an increase in β occurred in the transitional mode.

Also a peculiarity of flow with the above-indicated parameters was the presence of a certain instability and, as a consequence of this, the absence of a one-to-one dependence $\tau(\beta)$ at a constant liquid velocity. The character of the flow behavior was investigated in more detail at a Reynolds number of 70,000. Simultaneously with the measurements we made visual observations of the flow pattern directly ahead of the cross section in which the electrochemical pickup was mounted.

The results of the measurements of the wall shear stress are presented in Fig. 2. At Re = 70,000 and $\beta < 7\%$ the measured values of τ grew monotonically with an increase in β, with the experimental points lying along one curve when the measurements were repeated many times. But the existence of two bubble modes of flow, characterized by essentially different values of the wall shear stress (curves I and II in Fig. 2a), took place upon an increase in the gas content and up to the transition to the plug mode of flow. Both modes were stable and could exist for quite a long time. The occurrence of one flow mode or another depended on some uncontrolled random factors in the turning on of the experimental installation. In some cases modes I and II existed for several hours while in others a reorganization from one mode to the other occurred, with the duration of this transitional process being varied: from 1-2 min to 1 h. The new mode formed after the reorganization also might not be fully stable, and in a number of cases the reverse reorganization of the flow occurred.

Stream photographs taken at the start and end of the process of transition from one mode to the other are presented in Fig. 3. Mode II occurred first (Fig. 3a). This is not a purely bubble mode: bubbles of large diameter, comparable with the channel size, appear at the center of the channel; a considerable scatter in bubble sizes is observed in addition. Mode I (Fig. 3b) is a purely bubble mode and all the bubbles have close sizes; the mean bubble size is less than that in mode II.

The given phenomenon occurred when the ascending and descending channels were joined in accordance with both schemes (Fig. 1a, b). In neither case was the preferred development of one or the other mode observed.

The flow in the region of a transition from the bubble to the plug mode of flow (β = 18-22% at Re = 70,000 and 33-40% at Re = 20,000) is very complicated. A monotonic drop in the frictional stress to the value corresponding to the developed plug mode occurred in the installation built in accordance with the scheme of Fig. 1a, regardless of whether the movement was along line I or II. When the ascending and descending channels were separate (Fig. 1b), the protraction of the bubble mode up to β = 21% with a subsequent sharp breaking off of the flow to developed plug flow took place in a number of cases (when the points lay along line I with an increase in β). A one-to-one dependence $\tau(\beta)$ at a constant liquid velocity was again observed in the plug mode. It should also be noted that with a decrease in β the transition from the developed plug mode to the bubble mode could take place along either line I or II.

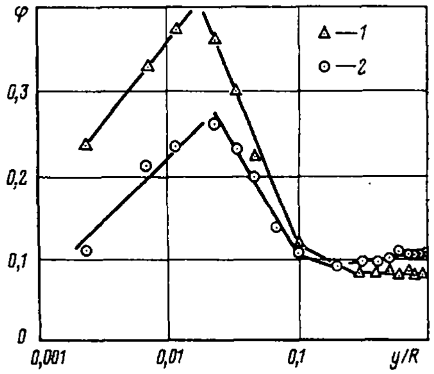

Fig. 4. Profiles of local gas content: 1) mode I; 2) mode II. y, R, m.

The frictional stress at Re = 20,000 was measured only on the installation built in accordance with the scheme of Fig. 1b, since in the scheme of Fig. 1a at the given liquid velocity in the descending channel plugs of great length (more than 1 m) formed which moved very slowly upward and broke upon reaching the top bend, which produced strong low-frequency oscillations (with a period of several tens of seconds) in the liquid flow rate. This made it impossible to conduct measurements.

The character of the behavior of $\tau(\beta)$ at Re = 20,000 (Fig. 2b) was qualitatively the same as that at the higher Reynolds number. At $\beta > 10\%$ the experimental points spread out into layers, and this had a random nature with possible transitions from one state to the other. The flow behavior was the most stable at β = 30-37%. The transition to the developed plug mode with a considerable decrease in the frictional stress at the wall occurred in a narrow region of values of β = 32-37%. A sharp rise in τ occurred at higher gas contents.

We tested whether or not the phenomena described above are a consequence of the instability of operation of the gas-bubble generator, owing, e. g., to incomplete ventilation of the pipe pores through which the gas was introduced into the stream. For this purpose the tests were repeated with preliminary ventilation of the porous pipe for 1-1.5 h (during which the working section of the porous pipe was above the liquid level) and with subsequent supply of liquid without turning off the gas, with preliminary turning on of the liquid and subsequent supply of the gas, and with interruptions in the gas supply of different durations. No effect of the initial state of the gas-bubble generator was noticed.

The distribution of the true gas content in the measurement cross section was measured for a more detailed study of the flow structure. The quantity φ was determined by the electrical-conductivity method [3, 6]. The measurements were made at Re = 70,000. At first the measurement of the true gas content at two fixed points at distances of 0.5 and 1 mm from the wall were made in parallel with the measurement of the frictional stress. The behavior of φ near the wall greatly resembles the behavior of τ/τ_0. Higher values of the gas content (up to 40%) near the wall occur in the bubble mode of flow; during reorganization of the mode of flow from mode I to mode II the value of φ near the wall drops sharply (the gas goes from the wall to the center of the pipe). An analogous pattern of radial distribution of φ was obtained in a number of other reports [5, 6]; however, the data of these authors were obtained for stable bubble and plug modes of flow.

In one of the tests the reorganization of the flow structure took place very slowly, so that the total radial profiles of the true gas content could be measured before and after the reorganization (Fig. 4). It is seen that in mode I the value of φ near the wall is considerably higher than at the point lying on curve II at the same β. At the same time, the opposite pattern occurs in the central part of the pipe. It should also be noted that the φ profile corresponding to curve II has three maxima (two near the wall and one weak one at the center of the pipe), which is also characteristic for the transition to the plug mode. For a point lying on curve I the central part of the φ profile is flat.

The results presented show that under the conditions under which the measurements were made there is a strong dependence of the structure of the two-phase flow on the initial conditions (in particular, such a parameter as the dispersion of the initial size of the gas bubbles can prove important). Such behavior is evidently inherent to flows at low liquid velocities since, as shown in [6], at a liquid velocity of 3 m/sec the same equilibrium flow structure forms, regardless of the conditions of introduction of gas into the pipe. The presence of the described effects at low liquid velocities is connected with the fact that in the overall balance of the energy of turbulent flow the free energy of the phase interface is comparable with the energy of turbulent pulsations of the liquid, so that even small changes in the dimensions of the gas bubbles make a significant contribution to the balance of the energy of two-phase flow and can significantly alter its structure. A detailed investigation of the profiles of the liquid velocity and the intensity of the turbulent pulsations is now being conducted for a future investigation of the flow in the indicated range of the parameters.

NOTATION

τ, wall shear stress; τ_0, wall shear stress in one-phase flow; β, bulk flow-rate gas content; φ, local true gas content; R, pipe radius; y, distance from wall; Re, Reynolds number, constructed from reduced velocity and viscosity of the liquid.

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HEAT EXCHANGE IN FILM CONDENSATION OF STATIONARY VAPOR ON A VERTICAL SURFACE

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New experimental data are presented on the condensation of chladone-21 on vertical tubes over a wide range of Reynolds numbers and are compared with theoretical results.

The heat exchange when a pure stationary saturated vapor condenses on a vertical surface was first considered by Nusselt [1] in the case of laminar flow of a film of condensate. He obtained the following relation for the mean heat-transfer coefficient α for condensation on a vertical plate of height L:

$$\alpha = 0.943\sqrt[4]{\lambda^3\rho'(\rho' - \rho'')\,rg/\mu\Delta tL}\,. \tag{1}$$

In dimensionless form Eq. (1) can be written as

$$(\alpha/\lambda)\,(\nu^2/g)^{1/3} = 0.925\mathrm{Re}^{-1/3}. \tag{2}$$

Nusselt made a number of assumptions in deriving Eq. (1), the correctness of which was confirmed by later investigations. A review of the work on this question can be found in [2]. It has been established that for laminar flow of a film of condensate there is no need to introduce any additional corrections to (1) when $\mathrm{Pr} \geq 1$, and $K \geq 5$, since they lie within the limits of experimental accuracy. Here $\mathrm{Pr} = \nu/a$, $K = (r/c)\Delta t$ are the Prandtl and Kutateladze criteria.

However, Eq. (1) has an extremely limited area of application since purely laminar flow of a film of condensate only occurs for very small Reynolds numbers of the film $\mathrm{Re} = qL/\mu r = G/\nu$.

For $\mathrm{Re} \sim 5$ waves are formed in the flowing film which intensify the heat transfer. Attention was first drawn to this in [3]. In [4] for Reynolds numbers of the film characterizing the beginning of wave formation, the following relationship was proposed:

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