FRICTION STRESS ON A WALL IN AN ASCENDING PROJECTILE FLOW

O. N. Kashinskii, B. K. Koz'menko,
S. S. Kutateladze, and V. E. Nakoryakov

UDC 532.529.5

The detailed investigations recently conducted on the local characteristics of gas–liquid flow [1, 2] showed the strong dependence of the gas content distribution, liquid and gas phase velocities, intensity of the velocity fluctuations, etc. on the two-phase mixture flow mode.

In addition to the quantities average with respect to time, the direct measurement of the hydrodynamic characteristics at a given point with time is of interest for clarification of the flow mechanism. This is especially important when studying the projectile flow mode, whose structure in liquid connectors and in gas projectiles is substantially different. Utilization of simple models that do not take account of the real flow structure for the computation of the projectile regime is a very rough approximation, and cannot assure acceptable accuracy in determining the flow characteristics in all cases.

An investigation is performed in [3] for the friction stress on the wall and the gas-content in an ascending flow in different flow modes. The simultaneous measurement of instantaneous values of the friction stress on the wall and the fluid velocity at the axis in an ascending projectile flow of a gas–liquid stream in a vertical tube entered the problem of this work. Experiments were performed on the installation described in [4].

A vertical tube of 15-mm inner diameter and 4.5-m length was the working section. Measurements were performed by using an electrochemical method [2, 3]. An electrolyte containing a 0.005 N solution of potassium ferri- and ferrocyanide and 0.5 N caustic soda in distilled water was used as the fluid. Two-phase flow was produced by insertion of air in the fluid flow through an agitator at the entrance to the working section.

As is shown in [2], the greatest deviations between the experimental values for the friction stress on the wall and the computed values according to known dependences are observed for low referred fluid velocities. Hence, measurements in this paper are performed for values of the referred fluid velocity W_0' between 0.12 and 1.2 m/sec. Preliminary measurements showed that a significant drop in the friction stress on the wall occurs at the time of gas projectile passage. Moreover, as is shown in [2] for small W_0' the projectile flow regime is characterized by high values of the relative intensity of the tangential stress fluctuations on the wall. This makes the assumption of the possible existence reverse flows near the wall natural in such modes at specific times. Consequently, a special methodology [5], permitting determination of the magnitude and direction of the instantaneous value of the friction stress on the wall, is applied in the paper.

The measurement diagram is presented in Fig. 1. A double sensor 1 from two platinum plates of 0.02 × 0.3 mm section, framed flush with the wall of the tube, was used to determine the tangential stress. The spacing between the electrodes of the double sensor is around 0.03 mm. The currents in the sensor electrodes were magnified by dc amplifiers 3 and 4, then fed to the primary signal processing circuit 5. The system operating principle is the following. Upon delivery of a voltage to both electrodes of the double sensor, the electrode located lower in the stream is in the diffusion wake of the first electrode, whereupon the value of the current

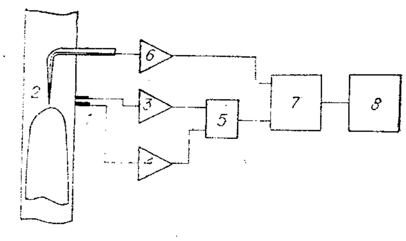

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki Tekhnicheskoi Fiziki, No. 5, pp. 84-89, September-October, 1982. Original article submitted September 30, 1981.

 0021-8944/82/2305-0668$07.50

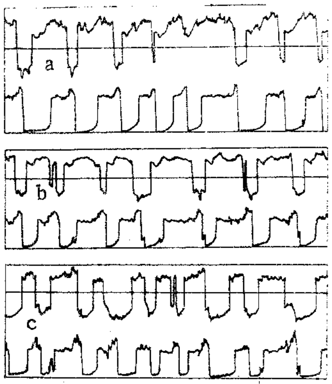

Fig. 2

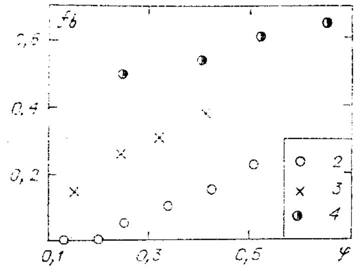

Fig. 3

of the second electrode is less than for the first, although they are under identical hydrodynamic conditions. For a change in the stream direction, the lower value of the current corresponds to the first electrode. The primary processing circuit 5 compares the signals from the amplifiers 3 and 4 and delivers that signal to the output whose value is greater, hence, the output voltage of the amplifier 3 is inverted. A sensor of the "frontal point" type [2] with 0.04-mm diameter is used as velocity sensor 2. The velocity sensor current is magnified by using the amplifier 6. Then the signals from the circuit 5 and the amplifier 6 were recorded on the tape recorder 7. Its digital processing on an M-6000 type electronic computer 8 was used in reproducing the signal. The following flow characteristics were calculated: The local gas content on the axis φ_1; the reverse flow coefficient f_b; the mean tangential stress on the wall τ_W; the mean intensities of the positive and negative tangential stress components on the wall τ_+, τ_-; and the mean fluid velocity on the tube axis u_1.

The characteristics mentioned were determined in the form:

$$\varphi_1 = \frac{1}{T}\sum_i T_i, \quad f_b = T_-/T,$$

$$\tau_+ = \frac{1}{T_+}\int\limits_{T_+}\tau(t)\,dt, \quad \tau_- = \frac{1}{T_-}\int\limits_{T_-}\tau(t)\,dt,$$

$$\tau_W = \frac{1}{T}\int\limits_{T}\tau(t)\,dt, \quad u_1 = \frac{1}{T(1-\varphi_1)}\int\limits_{T}u(t)\,dt,$$

where $\tau(t)$, $u(t)$ are the instantaneous values of the tangential stress on the wall and the velocity on the axis at the time t, T is the measurement time, T_+, T_- are the times of forward and backward flow existence near the friction sensor ($T_+ + T_- = T$), and T_i is the duration of the i-th bubble.

The stream directly behind the measurement section was photographed in all the regimes investigated. The mean length of the gas projectile l was determined from the photographs.

Calibration of the sensors for the tangential stress on the wall and the velocity was performed in single-phase flow in a tube, hence the velocity sensor was on the axis. Two calibration dependences were determined, respectively, for the sensor of the tangential stress on the wall for the first and second electrodes in independent operation. Both electrodes were connected simultaneously during the measurement, however, as has been mentioned above, the reading was always taken off that electrode which was first in the stream, i.e., the shielding influence of the other electrode was excluded.

To determine the true gas content φ, the local gas content profile was measured by using the velocity sensor described above. The values obtained for the local gas content were integrated over the tube section.

Examples of the simultaneous recording of the friction and velocity sensor currents on a loop oscilloscope are presented in Fig. 2 (a) $W_0' = 0.6$ m/sec, $\varphi = 0.36$; b) $W_0' = 0.3$ m/sec, $\varphi = 0.24$; c) $W_0' = 0.12$ m/sec, $\varphi = 0.25$). The upper oscillogram for each regime corresponds to the friction sensor signal, and the lower to the velocity sensor signal. When the friction sensor signal is above the zero line, the instantaneous value of the friction on the wall is positive, which corresponds to upward fluid motion near the wall. The friction sensor signal segments below the zero line correspond to times of backward flow (the fluid moves downward near the wall). The velocity sensor signal has downward troughs, corresponding to the times when the sensor is in the gas. The time axis is from right to left. Divisions on the lower zero line corresponds to 0.2-sec time segments. The signal scales along the vertical axis are arbitrary.

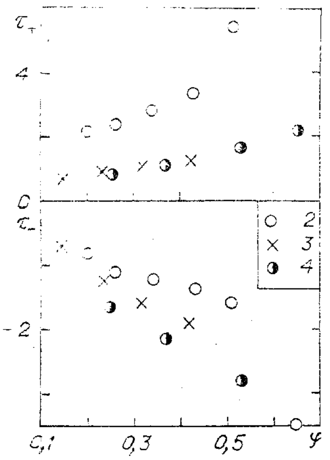

Fig. 4

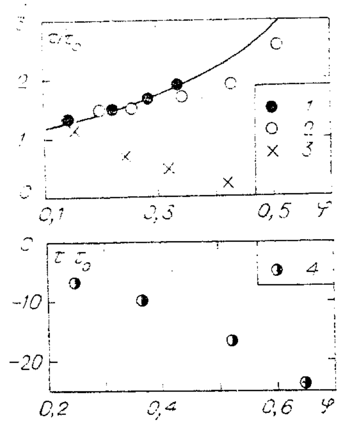

Fig. 5

As a rule, the friction stress on the wall changes sign at the times the gas projectiles are found. The duration of the backward flows and the intensity of the friction sensor signal depend strongly on the reduced fluid velocity. If backward flows hold only upon the passage of the longest projectiles for $W_0'=0.6$ m/sec, then each projectile is accompanied by the appearance of backward flows for $W_0'=0.3$ and 0.12 m/sec. At the same time, there are no backward flows in practice for $W_0'=1.2$ m/sec up to $\varphi=0.33$. As is seen from the oscillograms, a change in flow direction occurs a certain time after passage of the projectile leading edge, where this time diminishes as the reduced fluid velocity diminishes. A reverse flow surge occurs a certain distance behind the projectile trailing edge.

The forward and backward flow signal intensities are approximately identical for $W_0'=0.3$ and 0.6 m/sec, at the same time an explicit predominance of the backward flow intensity holds for $W_0'=0.12$ m/sec.

The backward flow coefficient f_b defined above is presented in Fig. 3 as a function of the true gas content. As the gas content grows, a natural increase in f_b occurs since the projectile length grows. The quantity f_b depends quite strongly on W_0' and diminishes as the latter increases. The notation in Figs. 3-5 is: 1) $W_0'=1.2$ m/sec; 2) $W_0'=0.6$ m/sec; 3) $W_0'=0.3$ m/sec; 4) $W_0'=0.12$ m/sec.

The intensities of the forward and backward friction stress components on the wall are presented in Fig. 4. As φ increases, growth of the absolute values of τ_+ and τ_- occurs. A strong dependence of these quantities on the reduced fluid velocity is also observed: if τ_+ grows as W_0' increases, then τ_- diminishes (in absolute value).

Results of measuring the mean value, with respect to time, of the friction stress on the wall τ_W in the standard coordinates τ_W/τ_0 (τ_0 is the friction stress on the wall in a single-phase flow for the same value of W_0') versus φ, are presented in Fig. 5. Here the dependence from [6] $\tau_W/\tau_0=(1-\varphi)^{-1.53}$ is superposed. Satisfactory agreement of the measurement results with this dependence holds only for $W_0'=1.2$ m/sec; the experimental points are located below for lower values of the reduced fluid velocity. If the dependence $\tau_W(\varphi)$ qualitatively has the same form for $W_0'=0.6$ m/sec, then a drop in τ_W with the growth of φ will hold for lower values of W_0'. It should be noted that an analogous tendency in the behavior of $\tau_W(\varphi)$ is observed for small W_0' in [7], where the presence of backward flows is shown qualitatively for small values of the fluid velocity in a two-phase flow in a vertical tube. Let us note that the friction stress on the wall has a negative value and a large absolute value as compared to τ_0 in all regimes when $W_0'=0.12$ m/sec.

Let us execute a qualitative comparison between the results presented above and the flow pattern as a gas projectile moves, rising in a vertical tube [8]. A stationary fluid flow, forming an annular film on the inner tube surface, occurs in the coordinate system coupled to the forward part of the bubble. If friction forces on the wall and on the liquid–gas interface are neglected, then the fluid flow occurs only under the effect of gravity. The backward flow occurs when the free fall velocity of the liquid film becomes greater than the velocity of coordinate system motion (or the projectile velocity). For a projectile velocity of 1 m/sec (which corresponds approximately to the regime in Fig. 2b), we obtain the length 0.05 m for the acceleration section; the friction stress on the wall changes sign at such a distance from the beginning of the projectile. Taking account of the friction stress on the wall can only diminish the cited estimate of the distance to the point of the flow surge since the force acting from the wall on the fluid film is directed downward up to this point.

For $W_0'=0.12$ m/sec the projectiles have a large length, the friction stress on the wall changes sign rapidly and, furthermore, the film draining down along the tube wall should be stabilized in thickness and ve-

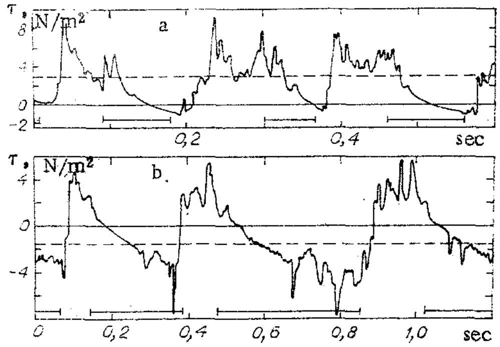

Fig. 6

locity under the effect of the friction force on the wall. The tendency towards stabilization of the value of τ_- is seen in Fig. 2c.

The oscillograms presented in Fig. 2 yield only a qualitative representation of the behavior of $\tau(t)$ because of the strongly nonlinear dependence of the sensor current on the friction stress. Examples of records of τ as a function of the time, restored by using the calibration dependences, are presented in Fig. 6 for the regimes: a) $W_0^{\prime}=0.6$ m/sec, $\varphi=0.34$; b) $W_0^{\prime}=0.12$ m/sec, $\varphi=0.65$ (τ, N/m^2 and t in sec). The time axis is from left to right. The mean values of τ_W in these experiments are denoted by dashes. The time of gas projectile passage in a given section are denoted by solid line segments. After the passage of the projectile nose sections, a monotonic drop in the friction stress on the wall occurs, which can be accompanied by a sign change for τ. This drop is sufficiently smooth, as corresponds to a change in the velocity of the fluid film motion under the effect of gravity, and is continued until the passage of the projectile tail section. Then a quite abrupt rise in the friction follows, with a corresponding change to the positive. Even after the passage of the projectile, a reverse flow direction near the wall can exist for a certain time interval. At the same time, there is a noticeable rise in the fluid velocity immediately behind the projectile, as is seen in Fig. 2. This is visibly associated with the presence of a vortex of toroidal shape behind the projectile, which contains the trapped gas bubble, as a rule.

An interesting feature of the flow at the times before the passage of the projectile tail section are the sufficiently large negative excursions of τ. These excursions exist only in the domain of negative τ values and indicate flow instability in the film near the projectile tail, the reason for this instability still remains unclear.

When creating more perfect flow analysis methods, the complex structure of a gas–liquid stream in the projectile regime requires a separate analysis of the flow in the liquid bridge and at the times of gas projectile passage since the latter, as has been shown above, can introduce a significant contribution to the mean values of the friction coefficients on the wall.

LITERATURE CITED

1. A. Serizawa, I. Kataoka, and I. Michiyoshi. "Turbulence structure in air–water bubbly flow," Int. J. Multiphase Flow, 2, 235 (1975).
2. V. E. Nakoryakov et al., "Local characteristics of upward gas–liquid flows," Int. J. Multiphase Flow, 7, 63 (1981).
3. S. S. Kutateladze (ed.), Investigation of Turbulent Flows of Two-Phase Media, [in Russian], Izd. Inst. Teplofiz. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1973).
4. A. P. Burdukov, N. V. Valukina, and V. E. Nakoryakov, "Flow features of a gas–liquid bubbly mixtures at low Reynolds numbers," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1975).
5. O. N. Kashinskii, V. A. Malkov, and V. A. Mukhin, "Investigation of the initial stage of boundary-layer separation by an electrodiffusion method," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 8, Issue 2 (1976).
6. A. A. Armand, "Resistance in two-phase system motion along horizontal pipes," Izv. VTI, No. 1 (1946).
7. G. Cognet, M. Lebouche, and M. Souhar, "Utilisation des techniques électrochimiques pour la mésure de frottement pariétal dans les écoulements diphasiques," Houille Blanche, No. 5 (1978).
8. G. K. Batchelor, Introduction to Fluid Dynamics, Cambridge Univ. Press (1967).