observed that an increase in the rate of fall by two orders of magnitude leads to new results, both qualitatively and quantitatively. Thus, the rate of spreading of the liquid film $25 \cdot 10^{-6}$ sec after the instant of contact is equal to 27 m/sec. This, obviously, may be explained by the fact that an increase in the rate of fall of the drop leads to the development of a cumulative flow at the point where the spherical drop surface impacts the solid surface; that is, in this case the initial rate of spreading of the liquid film is determined not only by the capillary effect but also by the cumulative effect. Because of this, the process of deformation of the drop manifests itself much earlier (approximately 10^{-4} sec after the instant of impact).

The angle of wetting at the start is equal to zero, after which it increases slowly, remaining less than 90° for at least $13 \cdot 10^{-3}$ sec. In our series of experiments it was not possible to determine with sufficient accuracy the angle of wetting owing to the very small thickness of the forward edge of the liquid film.

The author expresses his thanks to V. V. Pukhnachev for turning his attention to the actuality of this problem; he also thanks V. M. Bolosukhin and B. A. Gorbunov for their aid in carrying out the experiments and in their treatment of the results.

LITERATURE CITED

1. V. A. Ogarev, T. N. Timonina, V. V. Arslanov, and A. A. Trapeznikov, "Spreading of polydimethylsiloxane drops on solid horizontal surfaces," J. Adhesion, Vol. 6, No. 4 (1974).
2. O. V. Voinov, "Hydrodynamics of wetting," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5 (1976).

INVESTIGATION OF THE FRICTION STRESS ON A WALL IN A MONODISPERSED GAS – LIQUID FLOW

N. V. Valukina and O. N. Kashinskii

UDC 532.529.5

Despite the fact that a large number of papers (see [1]) is devoted to the measurement of the pressure drop in two-phase gas-liquid flows, at present there are no universal methods of computing the friction stress in such systems which would yield satisfactory results in the whole range of variation of the flow parameters. The bubble flow mode with low gas contents has been investigated least in this respect. Data on the measurement of the friction stress in this mode are presented in [2-5]. At the same time, investigations performed recently of the velocity profiles and local gas content [3, 6, 7] show that the flow configuration in the bubble mode is quite complex, which should naturally be reflected in the behavior of the friction coefficient. As has been shown in [4, 5], at high fluid velocities (more than 3 m/sec) the friction stress at the wall differs slightly from the value computed by means of the homogeneous model [1]. At low flow velocities an anomalous growth in the friction stress occurs in the bubble mode [2, 8, 9], where the measured values differ essentially from the values given by all the known computational methods [8]. In addition to the sharp growth in the tangential stress at the wall, the lack of a unique dependence of the friction stress on the Reynolds number and the discharge gas content is observed at low velocities [8, 9]: the experimental points disclose a significant spread.

A two-phase stream with shallow gas bubbles is a particular case of the flow of a suspension. For small bubble sizes, the gas bubbles can be considered nondeformable in a first approximation; their behavior will hence be analogous in certain respects to the behavior of spherical solid particles in suspensions. Investigations of the effects of solid-particle migration in a fluid flow [10, 11] show that the particle size is an important parameter characterizing the properties of such systems. It is natural to assume that the size of the gas bubbles will exert substantial influence on the flow characteristics in definite modes in gas–liquid flows. At the same time, there are no experimental data in the literature in which the size of the gas bubble was a controllable varying parameter. The purpose of this paper is the experimental investigation of the influence of the gas-bubble size on the characteristics of a monodispersed ascending two-phase flow.

The experiments were performed in the apparatus of [9]. The working section was a vertical tube with a 15-mm inner diameter and 6-m length. The reduced fluid velocity varied between 0.006 and 0.3 m/sec, and the

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 93-98, January-February, 1979. Original article submitted December 29, 1977.

discharge volume gas content varied between 0.5 and 15%. A special gas-bubble generator was fabricated for the tests which would permit obtaining a monodispersed gas–liquid mixture with gas bubbles of controllable size varying between 0.1 and 1 mm. The spread in the bubble size did not exceed 15-20%.

The friction stress at the wall was measured in a section 2.5 m from the inlet (150 calibers). The tangential stress was determined by using an electrochemical method [9, 12]. The working fluid was a solution of 0.5 N caustic soda and 0.01 N potassium ferri- and ferrocyanide in distilled water. The friction sensors were the endfaces of a platinum plate of 0.1×1.5 mm cross section embedded flush with the wall. The sensors were carefully fitted to the inner surface of the tube and were ground with a fine abrasive cloth.

The mean value of the sensor current and the rms values of the current pulsations were measured to determine the tangential stress at the wall. The sensor signal was amplified by using a wideband dc amplifier. The mean value of the amplifier output voltage was measured by using an integrator consisting of a V2-23 voltmeter and a Ch3-32 frequency meter. This system permitted obtaining the mean value of the stress with a 100-sec averaging time. The rms value of the amplifier output voltage pulsation was determined by using a special quadratic voltmeter with a 1 Hz to 5 kHz passband, which was used because of the low-frequency nature of the sensor current pulsations. The tangential stress τ was determined by means of the measured mean value of the sensor current I and the mean value of square of the current pulsations $\overline{i^2}$ by using the formula

$$\tau = A(I^3 + 3I\overline{i^2}), \tag{1}$$

where A is a coefficient determined during calibration. The sensors were calibrated in the laminar flow of pure liquid in the tube. The value of the tangential stress during the calibration was determined by means of the known fluid discharge by the Hagen–Poiseuille formula. The described scheme for performing the measurements permitted obtaining the local value, averaged with respect to time (100 sec is the averaging time), of the friction stress on the wall. The error in measuring τ did not exceed 5-7%.

A characteristic feature of the flow for low values of the Reynolds number $\mathrm{Re} < 5000$ was the significant asymmetry in the flow. Visually this was manifest in a nonuniform distribution of the gas bubbles over the circumference of the tube in one section. It would be natural to assume that asymmetry in the tangential stress distribution along the perimeter should be a consequence. Hence, six identical friction sensors were mounted uniformly around the circumference in one cross section in the measuring section. The current of all six sensors was measured successively in one mode and then the local values of the friction stress were computed for each by means of (1). The diagrams of the tangential stress on the wall were, as a rule, nonsymmetric, and the ratio of the maximum value of τ to the minimum value reached 3-4 in one section in a number of cases. This asymmetry in the distribution of τ around the circumference was random in nature and was not ordinarily reproduced upon repetition of the measurements in the very same mode. Despite the fact that the working part of the apparatus was carefully erected vertically, the asymmetry occurred in a majority of modes. It should be noted that the gas-liquid flow emerging from the bubble generator into the beginning of the working section was sufficiently uniform; the asymmetry developed only at a certain spacing from the inlet.

The tangential stress values at the wall, presented below, are the result of averaging values of τ for all six sensors located in one cross section. The mean values of τ obtained in this manner were reproduced to an accuracy no worse than 10-15% upon repetition of the measurements in the given mode.

Results of measuring the friction stresses at the tube wall are presented in Figs. 1-3 for the ascending flow of a gas–liquid mixture as a function of the Reynolds number for different discharge gas contents and bubble sizes. The drag coefficient λ and Reynolds number were determined by the following formulas, respectively:

$$\lambda = 8\tau/\rho u^2, \quad \mathrm{Re} = uD/\nu,$$

where u is the mixture velocity determined by the formula

$$u = w_0' + w_0'',$$

and w_0', w_0'' are the reduced liquid and gas velocities, ρ is the liquid density, ν is the liquid viscosity, and D is the tube diameter.

The gas-bubble diameter for Figs. 1-3 was 1, 0.5, and 0.1 mm, respectively. The different symbols correspond to the different volume discharge gas-contents β [1) 0.5, 2) 1, 3) 2, 4) 5, 5) 10, 6) 15%]. The solid lines 7 and 8 denote the Hagen–Poiseuille and Blasius formulas, respectively, for laminar and turbulent flow modes of a pure liquid in the tube, respectively.

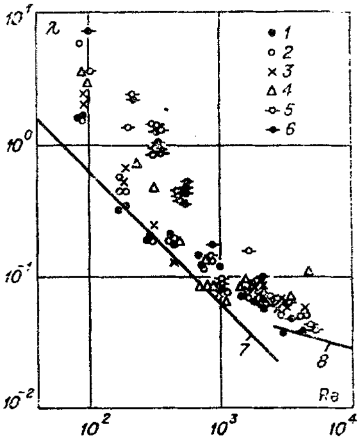

Fig. 1

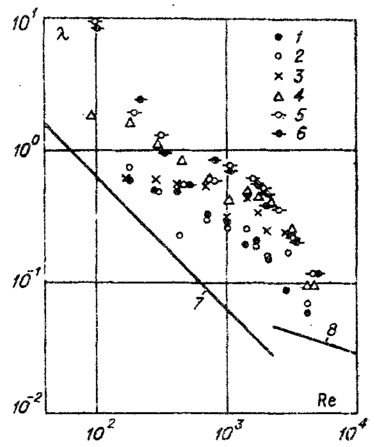

Fig. 2

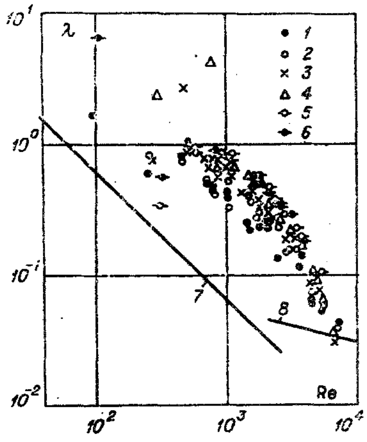

Fig. 3

The friction stress in the two-phase flow was considerably higher in almost all the modes than in the pure liquid flow despite the low values of the gas content. The nature of the change in λ(Re) is different for different bubble sizes. For d = 1 mm (see Fig. 1), the greatest value of λ/λ_0, where λ_0 is the value of the drag coefficient in a pure liquid flow with the same value of the Reynolds number, is reached for Re = 80-100. As the flow velocity grows, the dependence λ(Re) approaches the corresponding dependence for a single-phase flow. A quite definite stratification of the points corresponding to the different gas contents holds; as β grows, the ratio λ/λ_0 increases. The dependence λ(Re) is smooth in the Reynolds number range corresponding to the transition flow mode in a single-phase stream (Re = 2000-4000), where the value of λ is greater than in a turbulent single-phase flow at the same Re. As the Reynolds number increases further the points approach the Blasius dependence.

The dependence λ(Re) for bubbles of smaller size (d = 0.5 and 0.1 mm, see Figs. 2 and 3), differs substantially from the dependence for the bubbles of smaller size. There is an abrupt rise in λ in the 700 < Re < 5000 range, where the ratio λ/λ_0 reaches the values 10-15 in this range. Stratification of the point in β holds only for gas contents less than 2%. For β = 5-15% the dependences λ(Re) practically merge for different β. The ratio λ/λ_0 diminishes, tending to one, as the Reynolds number approaches 5000. For d = 0.1 mm in the domain Re < 700, the flow was strongly asymmetric and unstable. This caused a large spread in the points in these modes: The quite definite regularities were not traced here. In the 100 < Re < 700 range, the behavior of λ(Re, β) for the bubbles of size 1 and 0.5 mm is qualitatively similar: The ratio λ/λ_0 diminishes as Re grows and stratification in β holds.

Visual observations of the flow configuration showed that the nature of the differently sized bubble motion is distinct. This is manifested most clearly for Re < 2000. Bubbles with d = 0.1 and 0.5 mm tend to be concentrated near the wall, forming a near-wall layer with a high value of local gas content. The trajectory of small bubble motion is almost rectilinear; lateral pulsations of the bubble velocity are not noticeable visually. Therefore, the small size bubbles behave analogously to floating solid particles to some extent. As is known [11], particles whose density is less than the liquid density migrate to the wall in ascending motion. The

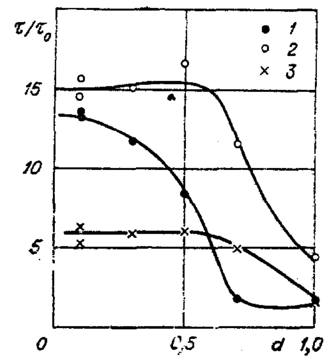

Fig. 4

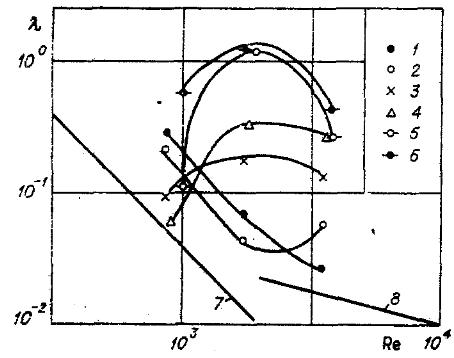

Fig. 5

presence of gas circulation within the bubble will naturally change the conditions at the interface; however, the nature of the migration remains qualitatively the same as for solid particles. With a good approximation the bubbles of this size can be considered undeformable; in this case the magnitude of the Laplace pressure within the bubble apparently turns out to be significantly higher than the intensity of the turbulent pressure pulsations in the liquid so that these latter cannot cause noticeable changes in the bubble shape.

The flow configuration alters substantially with the passage to bubbles with d = 1 mm. The motion trajectory of these bubbles ceases to be rectilinear and a strong displacement in the lateral direction with an amplitude commensurate with the channel diameter occurs with the ascent. Consequently, the 1-mm-size bubbles are not concentrated near the wall, but are distributed uniformly over the whole channel section. Such a nature of the bubble motion is explained by the fact [13] that bubble deformation starts to be felt for these sizes. In this case the deflection from the spherical shape turns out to be slight, however, and is not seen clearly in the photograph.

The process of bubble interaction with turbulent velocity and pressure pulsations in the fluid is quite complex for the same reason that all the velocity pulsations in a liquid are caused only by the perturbing effect of the bubbles at Reynolds numbers less than the critical number for a single-phase flow. The smaller the bubble size, the less the intensity of the pulsations they cause in the liquid. A growth in the pulsation intensity occurs as the size increases, and at a certain critical size d_* the pressure pulsations in the flow become commensurate with the quantity σ/d, where σ is the surface tension, which results in a deviation from the spherical bubble shape. Bubble deformation results in the appearance of intense lateral bubble velocity pulsations (the "spiraling" process starts), which raises the intensity of the liquid velocity still more. Therefore, the passage from one local gas content distribution over the tube section (the gas is concentrated near the wall) to another (uniform distribution over the cross section) should occur in a sufficiently narrow range of variation of the bubble diameter.

Measurements of τ were performed for d = 0.3 and 0.7 mm in order to obtain a more complete picture of the influence of d on the magnitude of the friction stress on the wall in certain modes. The relative value of the tangential stress on the wall τ/τ_0 (τ_0 is the magnitude of τ in a single-phase flow for the same liquid velocity) is presented in Fig. 4 as a function of the bubble size d for $\beta = 10\%$ and different Reynolds numbers [1) Re = 700, 2) Re = 1600, 3) Re = 3200]. As is seen from Fig. 4, the dependence of τ/τ_0 on the size is quite strong. A diminution in τ occurs with the increase in d. It is interesting to note that the critical size varies with the change in liquid velocity. The greatest values of τ/τ_0 and the most definite dependence on the size hold at Re = 1600 for 0.5 mm < d < 1. For Re = 3200 the diminution in τ with the change in d is considerably smoother.

In the range of Reynolds numbers corresponding to the transition mode in a pure liquid, the behavior of $\lambda(\mathrm{Re})$ for d = 0.7 mm (Fig. 5, where the notation corresponds to Figs. 1-3) is qualitatively distinct even for different gas contents. For $\beta = 0.5$-2% these bubbles behave as "large-scale" bubbles, i.e., λ/λ_0 tends to the dependence for a single-phase flow. For large values of β they start to behave as "fine" bubbles, the ratio λ/λ_0 grows significantly and depends strongly on Re. In this Reynolds-number range, the picture of the bubble interaction with the liquid pulsations is still more complicated since the turbulent processes occurring are not determined uniquely by the perturbing effect of the bubbles, but can be damped out or developed depending on the flow mode.

Therefore, the behavior of the stress at the wall in a flow with gas bubbles of different size is determined, for low Reynolds numbers, by two main processes which are closely interrelated: by the different nature of the gas-content distribution over the tube section and by the additional turbulence caused by the perturbing effect of the gas phase. The size of the gas bubbles and the distribution function of the bubble size are important parameters which strongly affect the characteristics of a gas–liquid flow.

LITERATURE CITED

1. G. F. Hewitt and N. S. Hall-Taylor, Annular Two-Phase Flows, Pergamon (1971).
2. A. Inoue and S. Aoki, "Fundamental studies on pressure drop in an air–water two-phase flow in a vertical pipe," Bull. JSME, 14, No. 70 (1971).
3. A. Serisawa, I. Kataoka, and I. Mishiyoshi, "Turbulent structure of air–water bubble flow," Int. J. Multiphase Flow, 2, No. 3 (1975).
4. M. R. David, "The determination of wall friction for vertical and horizontal two-phase bubble flows," Trans. ASME, Ser. D, J. Basic Eng., 96, No. 2 (1974).
5. E. M. Kopalinsky and R. A. A. Bryant, "Friction coefficients for bubble two-phase flow in horizontal pipes," AICE J., 22, No. 1 (1976).
6. R. A. Herringe and M. R. Davis, "Structural development of gas–liquid mixture flows," J. Fluid Mech., 73, Part 1 (1976).
7. M. Kh. Ibragimov, V. P. Bobkov, and N. A. Tychinskii, "Investigation of the behavior of the gas phase in the turbulent flow of an air–water mixture in channels," Teplofiz. Vys. Temp., 11, No. 5 (1973).
8. Investigation of Turbulent Flows of Two-phase Media [in Russian], Nauka, Novosibrisk (1973).
9. A. P. Burdukov, N. V. Valukina, and V. E. Nakoryakov, "Flow features of a gas–liquid bubble mixture at low Reynolds numbers," Prikl. Mekh. Tekh. Fiz.. No. 4 (1975).
10. G. Segre and A. Silberberg, "Behavior of macroscopic rigid spheres in Poiseuille flow," J. Fluid Mech., 14, Part 1 (1962).
11. P. Vasseur and R. G. Cox: "The lateral migration of a spherical particle in a two-dimensional shear flow," J. Fluid Mech., 78, Part 2 (1976).
12. I. F. Mitchell and T. J. Hanratty, "A study of turbulence at a wall using an electrochemical wall shear stress meter," J. Fluid Mech., 26, Part 1 (1966).
13. S. S. Kutateladze and M. A. Styrikovich, Hydrodynamics of Gas–Liquid Flows [in Russian], Énergiya, Moscow (1976).