SPECIAL CHARACTERISTICS OF THE FLOW OF A GAS—LIQUID BUBBLE-TYPE MIXTURE WITH SMALL REYNOLDS NUMBERS

A. P. Burdukov, N. V. Valukina,
and V. E. Nakoryakov

UDC 532.529.5

In [1, 2], as a result of measurements of the hydraulic resistance and the friction in vertical tubes, a region of the flow with anomalously high values of these quantities was disclosed. The measured values of the resistance exceed by an order of magnitude values obtained using appropriate calculating methods. This region of the flow corresponds to bubble-type flow conditions with small reduced velocities of the liquid phase. The above communications do not give a clear explanation of the observed effect. The calculating method proposed in [2], which pretends to take this effect into consideration, does not describe the experimental results of other authors, for example, the results of [1]. In the present work the limits of the existence of this set of conditions were established, and the mean and pulsational characteristics of the friction were measured. It is shown that this region of anomalously high stresses corresponds to laminar and transitional Reynolds numbers. The results of measurement of the pulsations of the friction argue the absence of flow conditions of a gas—liquid mixture without pulsations, even with very small Reynolds numbers. The article proposes the possibility of the development of the "pseudoturbulent" transverse transfer of momentum due to the oscillating motion of the bubbles in the channel. A detailed explanation of an analogous effect in the hydrodynamics of blood was given by Regirer [3].

The unit (Fig. 1) consists of a closed circulating loop with respect to the liquid, made up of a cylindrical sectionalized vertical channel 1 made of Plexiglas, the cylindrical pump 2 made of stainless steel, separator 3, receiving tank 4, thermostat 5, throttling gas 6 and liquid 7 flowmeters, a bubble generator 8, made in the form of a filter made up of Plexiglas disks treated in an abrasive, between which the gas is fed, while the liquid is fed between the external generatrix of the filter and the chamber 9. The size of the bubbles obtained is 50-500 μm. The shear strees is measured using an electrodiffusion method, based on measurement of the rate of an oxidation—reduction electrochemical reaction under diffusion conditions at the surface of a microelectrode, let in flush with the surface of the walls of the tube.

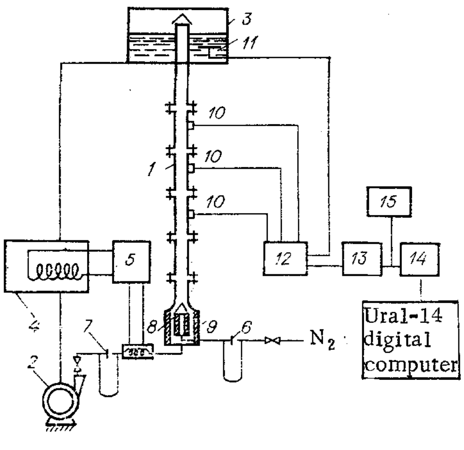

Fig. 1

The electric current of the circuit (polarized pickups — cathodes 10, anode 11) is fed through switch 12 to the electrodiffusion transformer 13, to the analog-digital converter 14, and then to the input of a Ural-14 digital computer or to a recording instrument (for example, a loop oscillograph) 15.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 137-141, July-August, 1975. Original article submitted August 26, 1974.

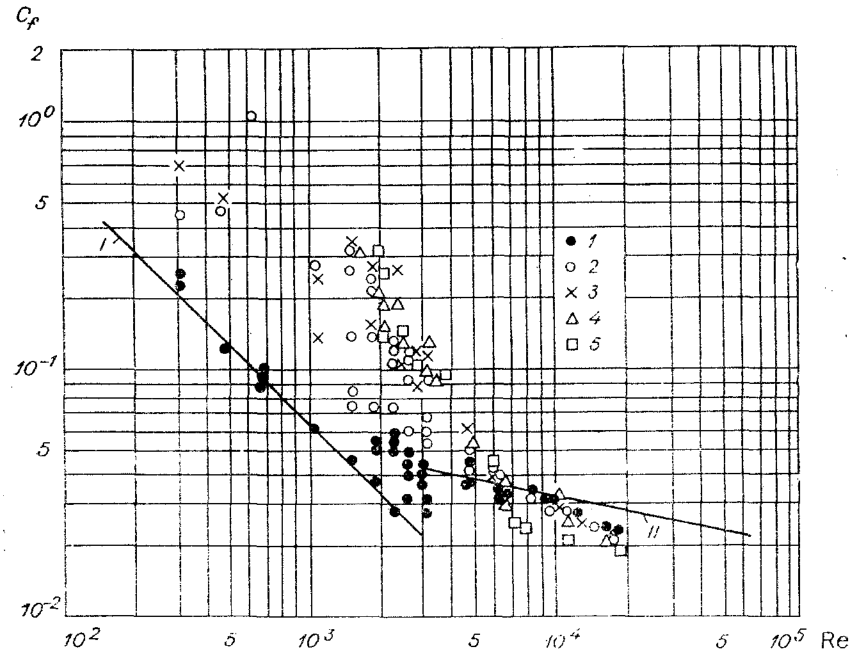

Fig. 2

The experimental section is a vertical tube with an inside diameter of 15 mm and a length of 6 m, made in the form of sections with blocks of micropickup cathodes, arranged along the length of the tube at different distances from the inlet.

The pickup (a cathode, made of platinum wire with a diameter of 50-500 μm or platinum foil measuring 50 × 500 μm) is welded to a cylinder made of chemically stable glass, which is fastened by an adhesive to a holder made of stainless steel, and then the whole block is machined as a unit; the pickup is ground using special grinders and powders. The pickup block is mounted on the wall in such a way that the pickup plate has its narrow edge along the flow. Particular attention is paid to seeing that there are no protrusions between the wall of the tube and the pickup block.

The experiments were made using a $(0.1\text{-}1)\cdot 10^{-2}$ normal solution of red and yellow blood salt ($K_3Fe(CN)_6$ and $K_4Fe(CN)_6 \cdot 3H_2O$) in 0.5-N background solution of NaOH in distilled water.

A detailed description of the electrodiffusion method of measuring friction can be found in [1]. With large values of the voltage between the cathode and the anode in the electrolyte composition used, excluding the migration of ions in an electric field, the diffusion equation in the diffusion layer at the control electrode has the form

$$u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=D\frac{d^2c}{\partial y^2},$$

$$c(x>0,\ 0)=0,\ c(x,\ \infty)=c_\infty.$$

Since the profile of the velocity within the limits of the diffusion layer is linear $U = (\tau/\mu)y$, the solution of the equation given yields a direct connection between the current and the friction. The friction was calculated using a formula obtained from the diffusion equation,

$$\tau=\frac{1.87\mu I^3}{F^3L^2h^3c_\infty^3D^2}\text{ — for flat}$$

$$\tau=\frac{3.16\mu I^3}{F^3d_0^5c_\infty^3D^2}\text{ — for round}$$

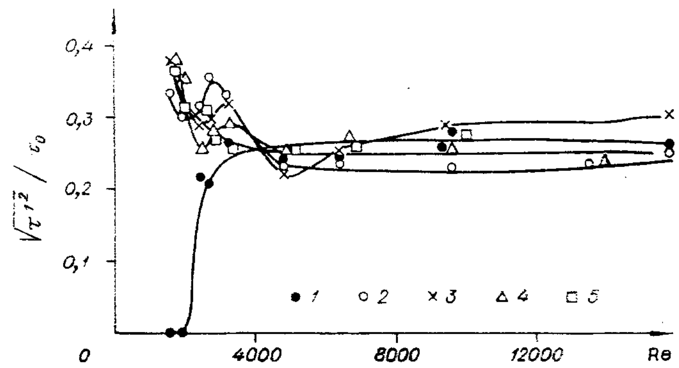

Fig. 3

pickups. Here μ is the dynamic viscosity; I is the limiting current at the pickup; F is the Faraday number; L is the dimension of the pickup along the flow; h is the width of the pickup; c_∞ is the concentration of ions of the oxidizer in the volume; D is the diffusion coefficient.

Analysis of the signal as a random process and calculation of the spectral density of the flow of mass over to the spectral density of the pulsations of the friction were carried out using relationships for the frequency characteristics, given in [1].

A scheme for analysis of the experimental results, using a centralized system for the collection and analysis of information, is given in [4].

The results of experiments on measurement of the mean friction and the standard deviation of the pulsations of the friction with a mass flow of the gas β = 0-0.1 (1) $\beta = 0$; 2) $\beta = 0.005$; 3) $\beta = 0.025$; 4) $\beta = 0.045$; 5) $\beta = 0.07$) are given in Figs. 2, 3. The data on c_f with $\beta = 0$ are in satisfactory agreement with the well-known dependence of Blasius I for laminar, and Nikuradze II for turbulent, flow conditions. As the characteristic velocity in Figs. 2, 3 there is taken the velocity of the mixture $W = W'_0 + W''$; the viscosity is taken equal to the viscosity of the liquid, and the density equal to the density of the liquid.

It is surprising that, with small gas contents, with low values of Re there is a strong effect of the gas contents on the mean and pulsational characteristics of a two-phase flow. In the region of large Reynolds numbers the gas content has practically no effect on these characteristics and the mixture can be regarded as homogeneous, obeying the laws governing the flow of a one-phase liquid.

In actuality, in the region Re > 5000, the friction practically coincides with the data of Nikuradze, and the relative standard deviation of the pulsations of the friction $\sqrt{\overline{\tau'^2}}/\tau_0 =$ 0.3, which is in agreement with known data for one-phase flows [5-8].

In the case of small Re numbers, the mean friction with small gas contents is several times greater than the friction with the flow of a one-phase liquid; this effect is particularly marked with very small Reynolds numbers.

It can be seen from Fig. 3 that the value of the relative mean-square pulsation of the friction also varies in a unusual manner. With Re < 1900, in a one-phase liquid $\sqrt{\overline{\tau'^2}}/\tau_0 = 0$, with $\beta \simeq 0.01$ $\sqrt{\overline{\tau'^2}}/\tau_0 = 0.35$-$0.38$, approaching a value equal to 0.3 in the region of one-phase flow.

In previous work on measurement of the hydraulic resistance with the flow of a gas–liquid mixture in vertical tubes [1, 2] there has been observed the existence of a region with anomalously high values of the resistance with small gas contents and small reduced velocities of the liquid phase. Figure 4 gives the results of the experiments of different authors. The data in Region II are well described by known dependences [4-6]; I is the region where the friction behaves anomalously, not obeying these dependences. The data in the region of an anomalously high stress are not correlated in the coordinates of Fig. 4, and there are no methods which permit calculating the friction under these conditions with a sufficient

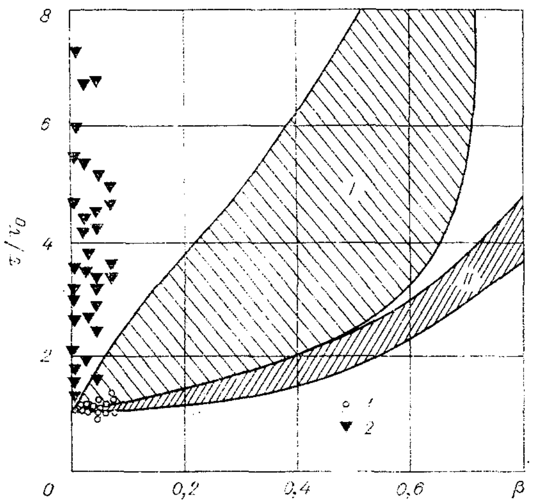

Fig. 4

degree of accuracy. Figure 4 gives the results of experiments (1) Re > 3200; 2) Re < 3200). A comparison of Figs. 2 and 4 brings out the obvious fact that the so-called "anomalous" region is demarcated by values of the Reynolds numbers corresponding to laminar and transitional flow conditions.

The data presented are convincing evidence that it is impossible to speak of purely laminar flow conditions of a bubble-type mixture, even with very small Reynolds numbers. Flow in this case is accompanied by a high relative level of the pulsations of the friction and is distinguished by high values of the shear stresses at the solid wall. Within the limits of the accuracy of the calculation, the spectrum of the pulsations of the friction is continuous.

A possible reason for these phenomena may be the oscillating motions of the bubbles at the solid surface, accompanied by a transfer of momentum in a transverse direction. The characteristic scale of the motion is obviously determined by the size of the bubbles, the value of the gas constants, and the shear stress at the solid surface. Such motions of the bubbles are observed visually, even with Re < 1000, and can undoubtedly lead to a radical change in the character of the flow.

An analogous explanation of the effect of an increase in the rate of transfer of small particles (clots in blood) in the presence of large deformed particles (erythrocytes) was first given by Regirer [3].

On the basis of what has been said, the flow conditions of a bubble-type mixture in the region of small Reynolds numbers can be called "microturbulent" bubble conditions. It can be seen from Fig. 2 that the friction coefficient is no longer determined by the Reynolds number alone. If the concepts expounded above are valid, then the friction coefficient must depend on the gas contents and a parameter, including the mean bubble size.

For a correct correlation of the results and a deeper understanding of the nature of the process, experiments on measurement of the friction and recording of the sizes of the bubbles and visualization of the picture of their motion are needed. Experiments on measurement of the distribution of the reduced velocity and of the pulsations of the velocity over the cross section of the channel can make a significant contribution to an understanding of the mechanism of "microturbulent" transfer of momentum.

LITERATURE CITED

1. V. E. Nakoryakov, A. P. Burdukov, B. G. Pokusaev, V. A. Kuz'min, V. A. Utovich, V. V. Khristoforov, and Yu. V. Tatevosyan, Investigations of Turbulent Flows of Two-Phase Media [in Russian], Izd. Inst. Teplofiz. Sibirsk. Otd. Akad. Nauk SSSR, Novosibirsk (1973).
2. T. Ueda, "On the upward flow of gas—liquid mixtures in vertical tubes," Bull. JSME, 10, No. 42 (1967).
3. S. A. Regirer, "Questions of the hydrodynamics of blood circulation," in: The hydrodynamics of Blood Circulation [Russian translation], Izd. Mir, Moscow (1971).
4. The Electrodiffusion Diagnosis of Turbulent Flows [in Russian], Izd. Inst. Teplofiz. Sibirsk. Otd. Akad. Nauk SSSR, Novosibirsk (1973).
5. E. M. Khabakhnasheva, B. V. Perepelitsa, E. S. Mikhailova, V. V. Orlov, V. M. Karsmen, and G. I. Efimenko, "Method and results of investigations of turbulence at the wall under heat-transfer conditions and with a high level of pulsations," in: Heat and Mass Transfer [in Russian], Vol. 1, Izd. Energiya, Moscow (1968).
6. A. A. Armand and E. I. Nevstrueva, "Investigation of the mechanism of the motion of a two-phase mixture in a vertical tube" Izv. VSES. Teplotekh. Inst. Im. F. E. Dzerzhinskii, No. 2 (1950).

7. R. W. Lockart and R. E. Martinelly, "Proposed correlation of data for isothermal two-phase, two-component flow in pipes," Chem. Eng. Progr., 45, No. 1 (1949).
8. I. F. Mitchell and I. J. Hanratty, J. Fluid Mech., 26, Part 1 (1966).