EXPERIMENTAL INVESTIGATION OF VELOCITY PROFILES IN A HORIZONTAL GAS–LIQUID STREAM

O. N. Kashinskii and P. M. Krokovnyi

UDC 532.529.5

The creation of more refined and universal methods of calculating two-phase streams requires the incorporation of detailed experimental information on the turbulent flow structure. Until recently the investigation of the local characteristics of two-phase flows has been retarded by the absence of reliable methods of diagnostics of these quantities. The advent of such measurement methods as the thermoanemometric, electrochemical, and electrical conduction methods made it possible to proceed to the obtainment and accumulation of experimental data on the local turbulent characteristics of two-phase streams. The structure of an ascending stream has been studied in considerable detail, e.g., in [1–4]. A horizontal gas–liquid stream, which has great importance for technical applications (the combined transport of oil and gas, chemical engineering), has been studied considerably less at this level.

The few attempts to investigate the structure of a gas–liquid stream in a horizontal pipe include [5, 6], in which measurements were made of the local gas content and the average liquid velocities. The distribution of shear stress at the wall of a horizontal pipe during the flow of a two-phase stream was measured in [7]. Since this kind of flow is distinguished by the extreme complexity of the processes of turbulent transfer and interaction of the phases, for an understanding of the stream structure it is necessary to make comprehensive investigations incorporating the measurement of the largest possible number of parameters, including pulsation quantities.

In the present report an investigation is made of the average and simplest pulsation characteristics of a two-phase flow (profiles of the local gas content and velocity of the liquid and of the intensity of turbulent velocity pulsations) in a horizontal pipe.

The local gas content was determined by the electrical conduction method and the liquid velocity by the electrochemical method. The experimental installation is described in [7]. The working section was a horizontal pipe with an inner diameter of 19 mm and a length of 6 m. The reduced velocity of the liquid was varied from 0.25 to 5 m/sec and the flow-rate, volumetric, gas content from 0 to 0.9. The pressure in the working part of the installation was close to atmospheric. A solution of 0.5 N sodium hydroxide and 0.01 N potassium ferri- and ferrocyanide in distilled water was used as the working liquid and nitrogen was used as the gas. The temperature of the liquid and gas at the inlet was kept constant at 25°C and the gas was preliminarily humidified. The measurements were made in the bubble, comb, plug, and projectile modes of flow.

All the measurements were made in a cross section at a distance of 3.8 m (200 diameters) from the point of introduction of the gas, at which the stream can be assumed to be stabilized lengthwise (see [7]). The detector was made by soldering a platinum wire 20 μm in diameter into a glass capillary 50–60 μm in diame-

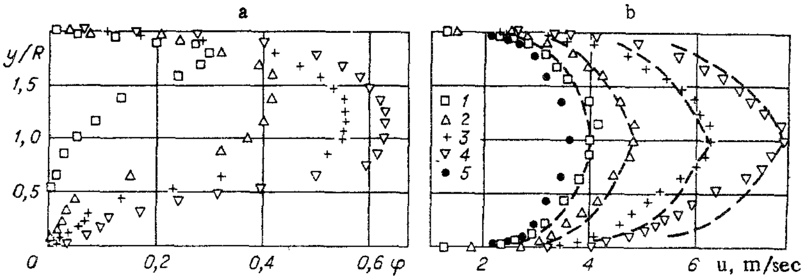

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 74–78, July–August, 1979. Original article submitted August 29, 1978.

TABLE 1

w_0', m/sec	β	Mode of flow
0,5	0,2—0,4	Bubble
	0,6—0,7	Plug
	0,8	Projectile
3	0,07—0,2	Bubble
	0.4—0,5	Projectile

ter. The end of the platinum wire served as the sensor of the detector. Then the detector was glued with epoxy resin into a stainless steel holder 2 mm in diameter, which was moved in the stream by a coordinating device with a scale division of 0.1 mm. Contact with the wall by the detector during its installation in the measurement unit was determined with a cathetometer; the coordinate near the wall was determined by a dial indicator with a scale division of 5 μm. The detector current was amplified with an electrodiffusion transformer. Then the amplified signal was treated in an M-6000 computer, which calculated all the flow characteristics. The measurement apparatus and measuring procedure used are described in detail in [8].

In Fig. 1 we present the results of a measurement of the profiles of the local gas content φ (1a) and the local liquid velocity u (1b) as a function of y/R, where y is the coordinate measured upward from the lower generatrix of the pipe and R is the pipe radius. The reduced liquid velocity w_0' was 3 m/sec while the flow-rate, volumetric, gas content β was varied: 1) $\beta = 0.07$; 2) $\beta = 0.2$; 3) $\beta = 0.4$; 4) $\beta = 0.5$; 5) $\beta = 0$ (a one-phase stream). The modes of flow of a gas–liquid mixture are given in Table 1. The local gas content at a given point was defined as the ratio of the time of occurrence of the gas phase to the entire measurement time. The local liquid velocity was defined as the average value of the instantaneous velocity of the liquid phase over the time corresponding to the time the liquid phase is found at a given point. As seen from Fig. 1, the φ profiles are nonsymmetric in all cases. There is an increased concentration of the gas phase in the upper part of the pipe. In the lower part of the pipe in the region of $y/R \le 0.2$ there is a zone in which the gas content is very low ($\varphi/\beta \ll 1$); liquid containing fine gas bubbles flows here regardless of the conditions in the region with higher values of y/R. In the upper half of the pipe in the plug and projectile modes the profile of gas content is nearly flat at reduced liquid velocities of less than 1 m/sec. At a liquid velocity of 3 m/sec the profile becomes drawn out, analogous to the profiles of gas content in the projectile mode in a vertical pipe [1].

The local velocity profiles of the liquid are also nonsymmetric in the general case, especially at low reduced liquid velocities, with the nonsymmetry increasing with an increase in gas content at a constant reduced liquid velocity, while it increases with a decrease in the liquid velocity at a constant gas content. However, the point of maximum velocity lies close to the axis in all modes, although it is shifted somewhat above it. At a reduced liquid velocity of 3 m/sec the velocity profiles become almost fully symmetric. As seen in Fig. 1b, the velocity profiles in the projectile mode are somewhat less full than in a one-phase stream with the same value of the velocity at the axis (dashed lines). Such behavior of the liquid velocity in the projectile mode is also characteristic of an ascending two-phase stream [1].

The quantity $u(1-\varphi)$ characterizes the average value of the instantaneous, local, liquid velocity averaged not over the time of occurrence of the liquid phase at a given point but over the entire measurement time. This is a kind of local flow-rate velocity, determining the amount of liquid transferred through a given point per unit time. Profiles of $u(1-\varphi)$ at reduced liquid velocities of 0.5 and 3 m/sec are shown in Fig. 2a, b, respectively. Values of the flow-rate gas content: a: 1) $\beta = 0.2$; 2) $\beta = 0.4$; 3) $\beta = 0.6$; 4) $\beta = 0.8$; b: 1) $\beta = 0.07$; 2) $\beta = 0.2$; 3) $\beta = 0.4$; 4) $\beta = 0.5$. The distributions of $u(1-\varphi)$ are essentially nonsymmetric. Only the profiles with small values of β, which corresponds to the bubble mode when the gas–liquid mixture can roughly be taken as homogeneous, are close to symmetric in some measure. In the other modes there is a considerable increase in the local flow-rate velocity from the upper generatrix of the pipe to the lower. At large values of the gas content there is a very considerable increase in $u(1-\varphi)$ in the lower part of the pipe. This corresponds to the fact that in the projectile and plug modes the large bubbles and projectiles are concentrated above while below there is a liquid layer containing small bubbles. It is through just this layer that a large part of the liquid flow is carried. It is interesting that the magnitude of the given effect does not decrease with an increase in the reduced liquid velocity. With an almost fully symmetric profile of the local liquid velocity u (see Fig. 1) there is still considerable nonuniformity in the rates of transfer of the liquid

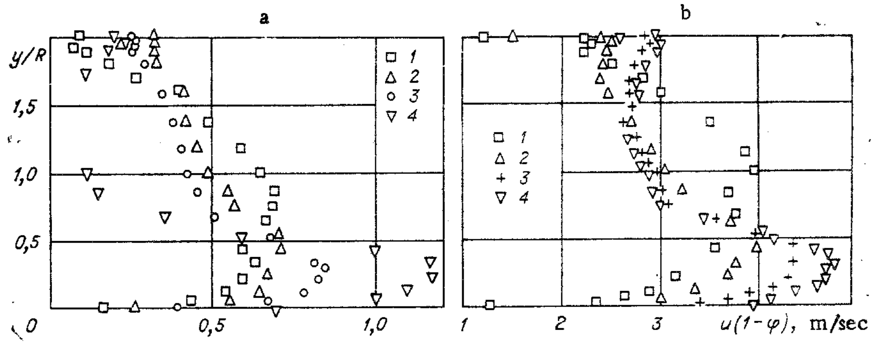

Fig. 2

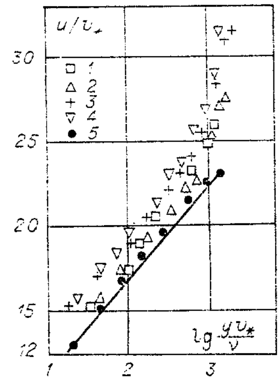

Fig. 3

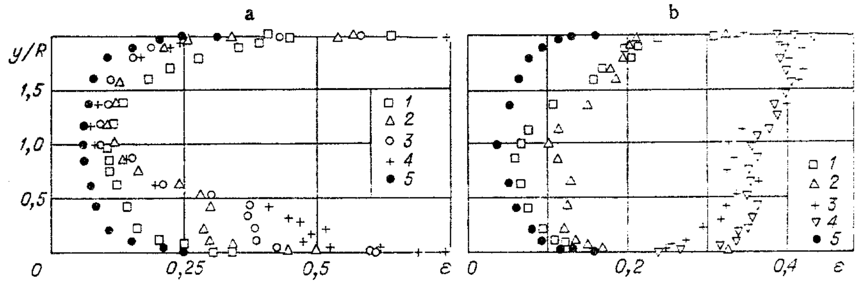

Fig. 4

and gas phases over the pipe cross section. It should be noted that in [5, 9] precisely the quantity $u(1-\varphi)$ is understood as the average velocity of a gas–liquid stream; the velocity profiles obtained are qualitatively similar to those presented in Fig. 2.

It is interesting to analyze the liquid velocity profiles obtained in the universal semilogarithmic coordinates (a "wall law") $u/v_* = f(yv_*/\nu)$, where ν is the kinematic viscosity of the liquid, while the dynamic velocity v_* was determined from the measured value of the shear stress at the wall at the given point, also determined by the electrochemical method [7]. In Fig. 3 we present an analysis in these coordinates of the local liquid velocity for $w_0' = 3$ m/sec and the following values of the flow-rate gas content: 1) $\beta = 0.07$; 2) $\beta = 0.2$; 3) $\beta = 0.4$; 4) $\beta = 0.5$; 5) $\beta = 0$. The standard dependence for a one-phase flow [10],

$$u/v_* = 5.75 \lg (yv_*/\nu) + 5.2, \tag{1}$$

is denoted by a solid line. As seen from Fig. 3, in a two-phase stream the analysis in "wall-law" coordinates does not give a single dependence. The points in Fig. 3 depart from the curve (1) by 5-20%, with the departure growing monotonically with an increase in gas content. In the analysis of the local flow-rate velocity in these coordinates a clear separation into layers is absent, although a departure from (1) still occurs.

The presence of a gas phase in the stream can markedly alter the distribution of turbulent pulsations of the liquid velocity. In Fig. 4 we present measured values of the degree of turbulence $\varepsilon = \sqrt{\overline{u'^2}}/\bar{u}$ in the two-phase stream: a) $w_0' = 0.5$ m/sec; 1) $\beta = 0.2$; 2) $\beta = 0.4$; 3) $\beta = 0.6$; 4) $\beta = 0.7$; b) $w_0' = 3$ m/sec; 1) $\beta = 0.07$; 2)

$\beta = 0.2$; 3) $\beta = 0.4$; 4) $\beta = 0.5$. Points 5 correspond to one-phase flow. As seen from Fig. 4, the presence of a gas phase in the stream promotes greater turbulization of the liquid phase. One should also note the nonlinear variation of the profiles of the degree of turbulence as a function of β, which confirms the "two-layer" structure of the liquid phase in the plug mode. In a liquid plug (upper part of the profile of Fig. 4a) the distribution of the degree of turbulence has the same character as in a one-phase stream. At the base (lower part of the profile) one observes separation of the values of the degree of turbulence into layers as a function of the degree of disturbance, introduced mainly by the liquid plug. And the degree of disturbance increases with an increase in the velocity of the plugs, which in turn depends on the increase in β. In addition, there is a second inflection point, which corresponds to the boundary of the region of disturbance introduced by the gas plugs.

At $w_0' = 3$ m/sec the profiles of ε have the following features. In the bubble mode ($\beta = 0.07$) the degree of turbulence grows in comparison with a one-phase stream only in the upper part of the channel where most of the bubbles move. Moreover, the profiles of ε have a very specific character when $\beta = 0.4$-0.5 (developed projectile mode). In this mode, evidently, the large gas bubbles, in bursting through the liquid, cause very strong turbulization of the liquid over the entire cross section.

The authors thank F. E. Kushnir for assistance provided in making the present investigation.

LITERATURE CITED

1. A. Serizawa, I. Kataoka, and I. Michiyoshi, "Turbulence structure of air–water bubbly flow," Int. J. Multiphase Flow, 2, No. 3 (1975).
2. R. A. Herringe and M. R. Davis, "Structural development of gas–liquid mixture flows," J. Fluid Mech., 73, No. 1 (1976).
3. A. P. Burdukov, B. K. Koz'menko, and V. E. Nakoryakov, "Distribution of velocity profiles of the liquid phase in a gas–liquid stream at low gas contents," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1975).
4. A. P. Burdukov, N. V. Valukina, and V. E. Nakoryakov, "Properties of the flow of a gas–liquid bubble mixture at low Reynolds numbers," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1975).
5. A. A. Armand, "Resistance to the motion of two-phase systems through horizontal pipes," Izv. Vses. Teplotekh. Inst., No. 1 (1946).
6. G. P. Isupov and V. A. Mamaev, "An experimental investigation of turbulent separate flow of a gas–liquid mixture in a horizontal pipe," Neft. Khoz., No. 6 (1968).
7. P. M. Krokovnyi, V. E. Nakoryakov, B. G. Pokusaev, and V. A. Utovich, "An experimental investigation of a horizontal two-phase stream by the electrodiffusion method," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1973).
8. A. P. Burdukov, O. N. Kashinskii, V. A. Malkov, and V. P. Odnoral, "Diagnostics of the principal turbulent characteristics of two-phase streams," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1979).
9. V. A. Mamaev and G. P. Isupov, "The velocity profile in gas–liquid plug flow," Neft. Khoz., No. 12 (1969).
10. J. C. Rotta, The Turbulent Boundary Layer in an Incompressible Liquid [Russian translation], Leningrad (1967).