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LITERATURE CITED

1. A. A. Townsend, Structure of Turbulent Flow with Transverse Shear [Russian translation], IL, Moscow (1959).
2. J. C. Mumford, "The structure of large jet eddies in fully developed turbulent shear flows. Part 1. The plane jet," J. Fluid Mech., 118 (1982).
3. B. Gilbert, "Diffusion mixing in grid turbulence without mean shear," J. Fluid Mech., 100, Pt. 2 (1980).
4. N. V. Aleksenko, V. I. Bukreev, and V. A. Kostomakha, "Nonimpulsive interaction of two isotropic turbulent fields," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1985).
5. L. N. Ukhanova and M. O. Frankfurt, "Experimental study of two-dimensional nonimpulsive jets," Inzh. Fiz. Zh., 47, No. 6 (1984).
6. E. Naudascher, "Flow in the wake of self-propelled bodies and related sources of turbulence," J. Fluid Mech., 22, Pt. 4 (1965).
7. A. S. Ginevskii, K. A. Pochkina, and L. N. Ukhanova, "Laws of propagation of a turbulent jet with zero excess momentum," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6 (1966).
8. J. A. Schetz and A. K. Jakubowski, "Experimental studies of the turbulent wake behind self-propelled slender bodies," AIAA J., 13, No. 12 (1975).
9. J. A. Schetz, E. B. Daffan, and A. K. Jakubowski, "The turbulent wake behind slender propeller driven bodies at angle of attack," AIAA Paper, No. 133 (1977).
10. J. C. Wyngaard, "Measurement of small-scale turbulence structure with hot wires," J. Sci. Instrum., 1, No. 11 (1968).
11. M. Ridjanovic, "Wake with zero change of momentum flux," Doctoral Dissertation, Philosophy, Iowa, USA (1963).
12. V. A. Gorodtsov, "Similarity and weak closing relations for symmetrical free turbulence," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1979).

STUDY OF A DOWNWARD BUBBLY FLOW IN A VERTICAL PIPE

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The structure of a two-phase gas—liquid flow depends to a significant extent not only on the regime parameters, but also on the geometry of the flow — in particular on the orientation of the channel and the direction of motion of the phases. The flow characteristics are significantly influenced by the distribution of the gas phase across the pipe, as was shown in [1, 2], for example. The form of the profile of local gas content depends on a large number of factors: the dimensions of gaseous inclusions, the magnitude of the gradient of liquid velocity, the intensity of turbulent pulsations of velocity, etc. In many regimes in an upward gas—liquid flow the distribution of local gas content has pronounced maxima near the wall of the pipe; in these regimes, there is a substantial increase in the shear stress on the wall [3]. At the same time, the light particles which surface in the presence of a velocity gradient are subjected to a lateral force directed from the wall toward the center of the flow [4]. In connection with this, the characteristics of upward and downward bubbly flows are quite different.

Here we report results of an experimental study of a downward bubbly concurrent flow in a vertical pipe 15 mm in diameter. The two-phase flow was formed by introducing gas into a liquid with a special mixer which made it possible to obtain a gas—liquid flow with roughly the same size of gas bubbles in each case. Meanwhile, the average size could change in different regimes. Measurements were made with the use of the electrochemical method [2]. The working liquid was a solution of 0.5 N caustic soda and 0.01 N potassium ferri- and ferrocyanide in distilled water. The temperature of the liquid was maintained automatically at

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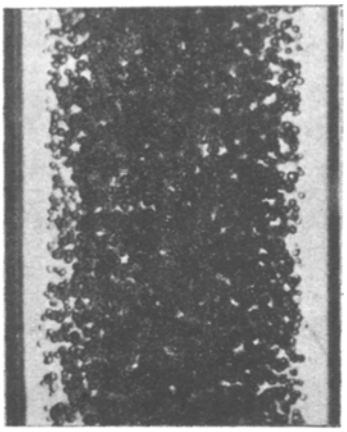

Fig. 1

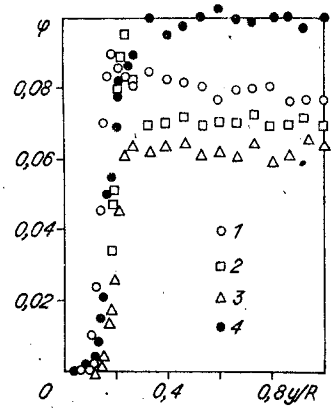

Fig. 2

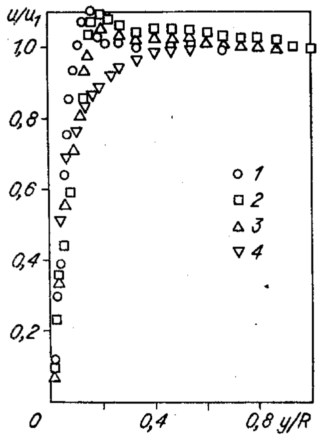

Fig. 3

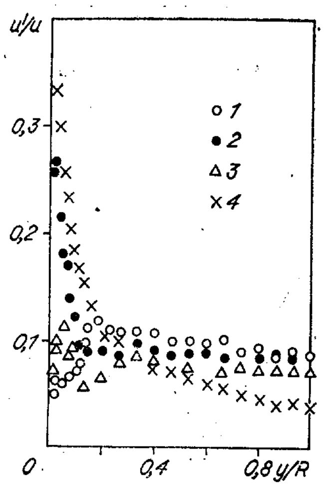

Fig. 4

the level 25 ± 0.2°C. The measurement block, located 4.3 m from the gas inlet, contained eight electrochemical friction transducers. The transducers were arranged uniformly about the perimeter of the pipe. The size of the platinum electrodes of the transducers was approximately 0.02 × 0.3 mm. We measured local gas content and the velocity of the liquid by using an electrochemical transducer of the "frontal point" type. The diameter of the transducer was 0.03 mm on the working end, while the diameter of the platinum electrode was 0.02 mm. The velocity gage could be moved by means of traversing gear with a graduation of 0.01 mm. The transducer currents were amplified by dc amplifiers. The amplified signals were then sent to an ATsP-118 analog–digital converter installed in a KAMAK housing. The output signals of the friction transducers were sent to the ATsP through an eight-channel switch. The signals were analyzed in digital form by an Élektronika-60 computer.

To monitor the size of the gas bubbles in all of the regimes, we photographed the flow. The flow was illuminated by an IFK-20 flash lamp (Fig. 1, where the corrected velocity of the liquid $W_0' = 0.5$ m/sec and the volumetric gas content $\beta = 0.046$). The mean bubble diameter in this regime was 0.44 mm. It is evident from the photograph that a region of pure liquid free of gas bubbles exists near the pipe walls. Such a distribution of the gas phase is typical of a downward flow and was noted in [5] for large-diameter pipes.

Figure 2 shows profiles of local gas content, where 1-4 are, for $W_0' = 0.3$, 0.4, 0.5, and 0.6 m/sec, $\beta = 0.066$, 0.040, 0.046, and 0.077. The quantity R is the radius of the pipe and y is the distance from the wall. The wall region free of gas has a width from 0.5 to 1.5 mm, the exact size depending both on the size of the gas bubbles and, to a greater extent, on the corrected velocity of the liquid. With an increase in W_0', the gas bubbles near the wall begin to undergo oscillatory motion in the transverse direction and come closer to the wall. A region with a roughly constant value of local gas content ϕ is located in the center of the flow. The quantity φ has a distinct maximum at an intermediate radius in several regimes (y = 1.5-2.5 mm). This fact was also noted in [5].

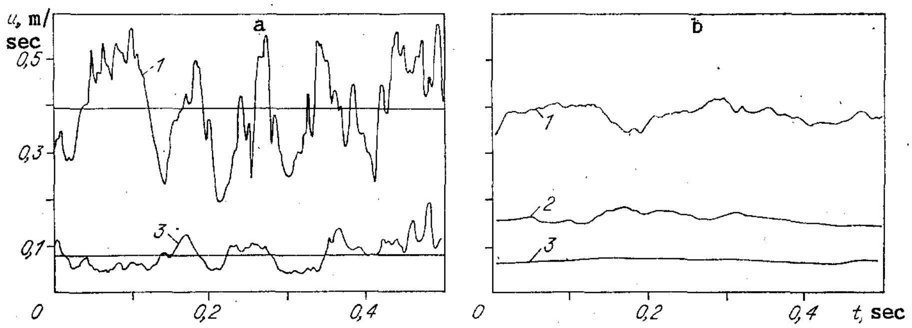

Fig. 5

TABLE 1

W_0', m/sec	β	d_b, mm	$10^{-3}\cdot Re_0$	τ_w/τ_0	τ_w'/τ_w
0,12	0,15	0,44	1,85	15,0	0,08
0,17	0,11	0,54	2,55	5,6	0,07
0,20	0,095	0,38	3,11	3,7	0,07
0,22	0,066	0,44	3,34	1,50	0,05
0,30	0,066	0,47	4,62	1,86	0,05
0,34	0,064	0,50	5,20	1,57	0,05
0,40	0,028	0,79	6,15	0,95	0,13
0,40	0,040	0,63	6,15	1,05	0,04
0,45	0,048	0,80	6,86	0,98	0,06
0,50	0,046	0,44	7,69	0,81	0,08
0,60	0,077	0,55	9,23	0,96	0,25
0,60	0,11	0,85	9,23	1,48	0,13
0,80	0,090	1,46	12,3	1,29	0,32
0,80	0,096	0,63	12,3	1,18	0,31
1,20	0,066	0,64	18,5	1,10	0,34

Figure 3 shows characteristic profiles of the velocity of the liquid phase, where 1-4 correspond to $W_0' = 0.3$, 0.4, 0.5, and 0.8 m/sec; β = 0.046, 0.040, 0.046, and 0.096; u is the local velocity of the liquid, and u_1 is the velocity of the liquid on the pipe axis in the given regime. The central part of the pipe is occupied by a region with a nearly constant velocity. There is a small but distinct velocity maximum 1-1.5 mm from the wall in most regimes. The velocity at this point is as great as 10% more than the velocity on the axis. The drop in velocity from the maximum value to zero at the wall occurs in a fairly narrow region 1-2 mm wide. The exceptions here are the profiles for $W_0' \geq 0.8$ m/sec; in these regimes the gas-content distribution no longer has a distinct region with a constant φ in the center of the pipe. The region of large velocity gradients near the wall is nearly free of gas bubbles, which confirms the presence of a lateral force directed from the wall to the center of the pipe.

Figure 4 shows results of measurement of the intensity of the longitudinal component of the liquid-velocity pulsations (1-3 correspond to $W_0' = 0.3$, 0.4, and 0.5 m/sec; β = 0.066, 0.040, and 0.046; 4 — $W_0' = 0.4$ m/sec, single-phase flow). Turbulence of liquid velocity u'/u in the central part of the pipe is greater than in a single-phase flow, which is related to the perturbing effect of the gas bubbles resulting from the relative rate of surfacing of the bubbles. The behavior of the pulsations near the wall, where there are no bubbles, is interesting. The values of u'/u in this region are considerably lower than in the single-phase flow. There is a particularly large drop toward the pipe wall at $W_0' = 0.3$ m/sec. An increase in W_0' is accompanied by an increase in u' near the wall, and with an increase in liquid velocity the distribution of the intensity of the liquid-velocity pulsations approaches the corresponding distribution in the single-phase flow. We should also note that in the region occupied by the gas phase, u'/u changes little and amounts to 0.07-0.11. Thus, the gas phase has a damping effect in a downward two-phase flow and acts to reduce turbulent pulsations of the liquid.

Table 1 shows results of measurement of the mean value and the intensity of shear-stress fluctuations on the wall. Here, τ_w is the shear stress on the wall in the two-phase flow; τ_0, shear stress on the wall in a single-phase flow with a velocity equal to W_0'; $Re_0 = W_0'D/\nu$ (D is the diameter of the pipe and ν is the velocity of the liquid); τ_w' is the RMS value of the intensity of the shear-stress fluctuations on the wall; τ_w'/τ_w is the "degree of turbulence" on the wall; τ_w' and τ_w were determined by averaging the readings about the pipe (at eight points). The quantity τ_0 was calculated from the known flow rate of the liquid by using the Blausius formula for $Re_0 \geq 2.2 \cdot 10^3$ and the Hagen–Poiseuille law for lower values of Re_0. It is evident that at subcritical Reynolds numbers, τ_w may significantly exceed the value of τ_0 for laminar flow in the pipe. At $Re_0 > 2.2 \cdot 10^3$, τ_w may be either greater or somewhat less than the single-phase value of τ_0. It should also be noted that in several regimes τ_w'/τ_w is considerably less than the values 0.33-0.36 characteristic of developed turbulence in a single-phase pipe flow. The quantity τ_w'/τ_w correlates well with the values of u'/u near the wall.

Figure 5 shows characteristic records of the behavior of liquid velocity near the wall over time (a is for the single-phase flow, $W_0' = 0.5$ m/sec; b is for the two-phase flow, $W_0 = 0.5$ m/sec, $\beta = 0.046$; 1-3 are for y = 0.5, 0.2, and 0.1 mm). It is evident that there is a sharp reduction in the rate of fluctuation in the two-phase flow compared to the one-phase flow.

It follows from Figs. 2 and 3 that a downward bubbly flow can be regarded as a rod flow having a core with constant values of velocity and local gas content. The behavior of the flow is very similar to the flow of a nonimpulsive liquid [6]. The presence of a core with a constant velocity results in an increase in τ_w compared to the single-phase flow, even if the effective viscosity in the wall region is equal to the laminar viscosity. This effect maximizes the reduction in shear stress on the wall due to the suppression of turbulent pulsations. To all appearances, the stabilizing effect of the gas phase is determined by the fact that the velocity pulsations introduced into the liquid flow have a negative sign (the velocity of the liquid near the bubbles is lower than the mean velocity of the liquid at the given point). It should also be noted that this effect is not seen in an upward bubbly flow. In this case, the introduction of a gas phase always leads to an increase in the intensity of liquid pulsations.

LITERATURE CITED

1. R. A. Herring and M. R. Davis, "Structural development of gas–liquid mixture flows," J. Fluid Mech., 73 (1976).
2. V. E. Nakoryakov, O. N. Kashinsky, et al., "Local characteristics of upward gas–liquid flow," Int. J. Multiphase Flow, 7 (1981).
3. A. P. Burdukov, N. V. Valukina, and V. E. Nakoryakov, "Features of the flow of a bubbly gas–liquid mixture at low Reynolds numbers," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1975).
4. J. Happel and G. Brenner, Hydrodynamics at Low Reynolds Numbers [Russian translation], Mir, Moscow (1976).
5. B. G. Ganchev, V. A. Nizovtsev, and V. G. Peresad'ko, "Downward bubbly flows with a low velocity of the phases," in: Jet Boundary Flows [in Russian], ITF, Novosibirsk (1984).
6. R. Baird, W. Stewart, and E. Lightfoot, Transport Phenomena [Russian translation], Khimiya, Moscow (1974).