MEASUREMENT OF THE TURBULENT FLOW STRUCTURE OF SUBMERGED JETS OF POLYMER SOLUTIONS

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Measurements are made of the average and pulsation velocities, the energy spectra, and the coefficients of turbulent diffusion during the flow of submerged jets of water and solutions of polyethylene oxide, Na—CMC, and guar gum.

Work conducted recently on the study of the properties of the turbulent flow of weak polymer solutions [1-2] has revealed important drawbacks of the measuring devices which are generally used in Newtonian hydromechanics: the thermoanemometer and the Pitot tube. It is known that measurements of turbulent characteristics are more difficult in ordinary dropping liquids than in gases. In thermoanemometric measurements the flow of polymer solutions can cause a reduction in sensitivity and the appearance of anomalous signals not caused by turbulent pulsations and determined by the passage of associations near the sensitive element of the pickup [4]. Measurements with a Pitot tube encounter difficulties connected with the impossibility of making measurements with heads of small diameter because of blockage of the inlets, which greatly limits the measurements especially in the boundary region. At present only two methods of measuring the average and pulsation velocities are known which do not have the enumerated drawbacks: laser Doppler anemometry [5, 7] and the stroboscopic method [3]. However, the first method, which is probably the most promising for the future, is inaccessible at present because of the complexity of the measurement of pulsation velocities. The second method, which is well recommended in the study of boundary turbulence in polymer solutions, does not yet permit the conducting of correlation and spectral measurements. Many of the drawbacks of thermoanemometry are removed to a considerable degree by the electrodiffusion method, although its application is limited by laboratory test beds where an electrolyte of special composition is used as the working liquid. The many years of experience in work with the Pitot tube in Newtonian liquids, the comprehensively studied properties of its application, including measurements in turbulent streams of polymer solutions, and the success in creating miniature pressure transducers of high sensitivity and low inertia — all this lay at the basis of the development of a device for measuring pulsation velocities of liquid media: a Pitot tube with a piezoceramic transducer [10]. However, the use of this instrument in the shear turbulent flow of polymer solutions which differ in viscoelasticity and in the presence of associations, requires caution and the careful selection of the dimensions of the pickup depending on the properties of the polymer solution. Wells [8] and Rodriguez [9] first used a Pitot tube with a piezoceramic transducer to measure the turbulent intensity and energy spectra in purely viscous liquids and polymer solutions. On the basis of an analysis of the equation of motion it was shown that the longitudinal component of the pulsation velocity is connected with the pulsations in total pressure by the equation

$$\frac{[\overline{(u')^2}]^{1/2}}{\bar{u}} = \frac{[\overline{(p_t')^2}]^{1/2}}{\rho \bar{u}^2}, \qquad (1)$$

obtained with disregard for the effect of normal stresses. The estimates made and experimental measurements have showed [9] that in viscoelastic liquids the readings of a piezoceramic pickup give somewhat understated results as the shear velocity in the stream increases.

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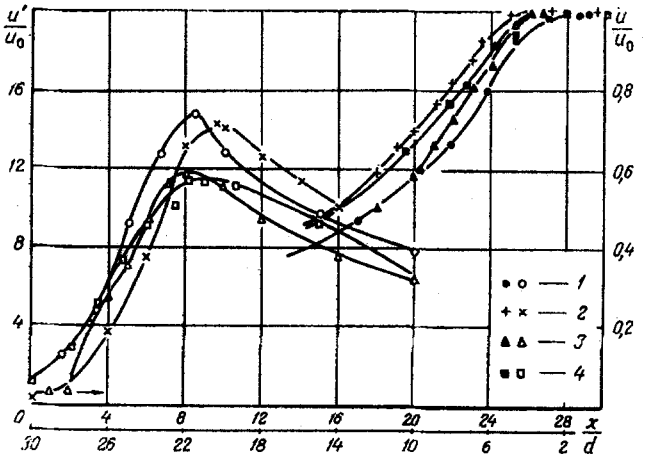

Fig. 1. Variation in average velocity (symbols on left) and turbulent intensity (symbols on right) along axis of water jet: 1) from [5]; 2) [11]; 3) authors' data; 4) [12]. u'/u_0 in %.

In the present work a TsTS-19 piezoceramic made in the form of a cylinder 1.4 mm in diameter and 15 mm long was used as the sensing element in the measurements. The piezopickup was placed in the region of the intake opening of the Pitot tube head. Depending on the conditions of application and the properties of the polymer, heads of different outer diameters could be used, with the help of which the average total pressures were also measured. The sensitivity of the piezopickup was 50 μV/mm of water column. The measuring system, incorporating a cathode repeater with amplifier, an F-563 effective value voltmeter, and an FSP-80 spectrum analyzer, assured a sensitivity threshold no worse than 0.2 mm of water column and the possibility of frequency analysis in the range of 2-20,000 Hz. Moreover, the signal from the pickup could be recorded on the tape of an N-700 oscillograph with subsequent conversion into a digital code in a semiautomatic instrument and insertion into a Minsk-22 electronic computer for calculation of the autocorrelation and spectral functions. The pulsation spectrum of the longitudinal velocity component calculated in this way could be limited below only by the frequency characteristics of the pickup (0.1 Hz). The measurements were conducted in a submerged round jet escaping from a nozzle 5 mm in diameter into a vessel 250 × 250 × 1000 mm^3 in size. An unpumped instrument assured the maintenance of a constant velocity which could be regulated in the range of 1-5 m/sec.

The results of the measurement of the average velocity and the turbulent intensity of the longitudinal component of the pulsation velocity compared with the data of other authors [5, 11, 12] are presented in Fig. 1. Observing the good agreement of the data, it should be noted that it is hard to expect absolute coincidence of the measured results of different authors. This is determined not so much by the use of different means of measurement as by the relatively strong dependence of the variation in average velocity and turbulent intensity on the past history of the flow of the liquid: the shape of the exit opening, the initial level of turbulence, the irregularity of the velocity profile at the exit from the nozzle, etc.

Normalized energy spectra of the longitudinal component of the pulsation velocity at different points on the axis of the jet (x/D = 2, 10, 20, 30, 54) are plotted in Fig. 2. The data of [13] at x/D = 30 and of [14] at x/D = 50 are presented in the same figure for comparison. The form of the spectra presented corresponds to the presence of three regions of the mixing zone of the jet (according to the system of G. N. Abramovich [19]): a laminar-wave region; a region of regular vortex formation with vortex dimensions comparable with the thickness of the mixing zone and increasing in the direction of flow; a region with an established turbulent mode of flow. The form of the spectra for cross sections close to the nozzle has a clearly expressed "resonance" nature and indicates the presence of regular vortex formation with a frequency which depends on the velocity and nozzle diameter: $f = Sh(u_d/D)$, where $Sh \approx 0.6$. This is well seen in Fig. 4b. At a large enough distance from the nozzle the spectrum takes on a form corresponding to the nature of developed turbulent flow; in particular, one can isolate a considerable band of frequencies (the "inertial range") where the $-5/3$ rule is satisfied. The difference in Re numbers compared with the data of [13, 14] results in only partially overlapping ranges of wave numbers, and the shift in the spectra is a natural result of satisfying the normalization condition

$$\int_{(k)} F_{1,n}(k)\, dk = 1. \qquad (2)$$

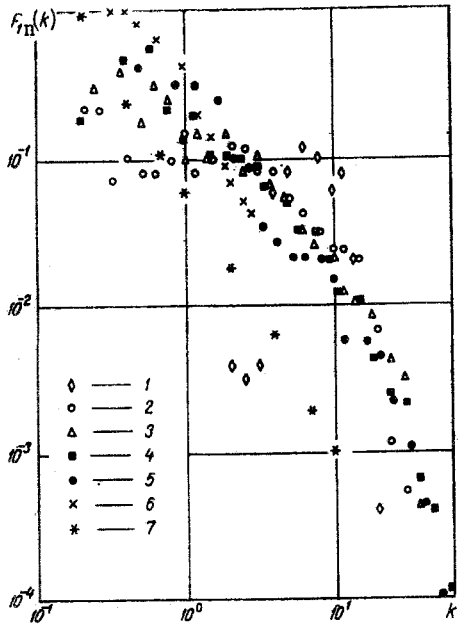

Fig. 2

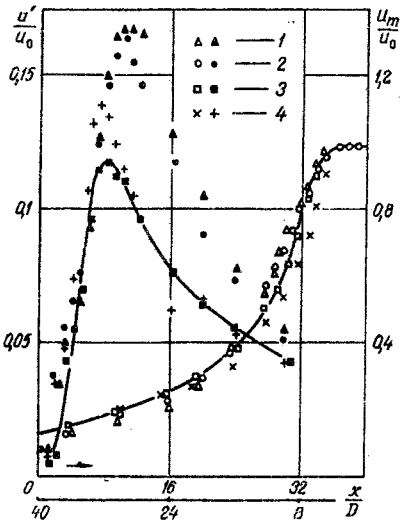

Fig. 3

Fig. 2. One-dimensional normalized energy spectra of longitudinal component of pulsation velocity at axis of water (air) jet: 1) $x_0 = 2$; 2) 10; 3) 20; 4) 30; 5) 54; 6) from [13]; 7) [14]. k, cm^{-1}.

Fig. 3. Variation in average velocity (symbols on left) and turbulent intensity (symbols on right) at axis of jet ($Re = 1.5 \cdot 10^4$). Water and solution of polyethylene oxide: 1) PEO, C = 0.007%; 2) PEO, C = 0.003%; 3) water; 4) PEO, C = 0.003% (degraded solution).

Moreover, in the transition from the frequency f to the wave number k the Taylor hypothesis was used in the classical form $k = 2\pi f/\bar{u}$. However, it must be considered that in the presence of large vortex structures, as was shown in [15], the transport velocity $\bar{u}_l$ of the large vortices is related to the external velocity $\bar{u}_0$ by the equation

$$\bar{u}_l = 0.8\bar{u}_0. \tag{3}$$

The longitudinal scales were also determined using the Taylor hypothesis of frozen-in turbulence

$$L_x = T_l \bar{u}_m, \tag{4}$$

$$\lambda_x = \tau_l \bar{u}_m, \tag{5}$$

where the Eulerian time scales can be found from the autocorrelation function calculated from the realization of the process:

$$T_l = \int_0^\infty R(\tau)\, d\tau, \tag{6}$$

$$\frac{1}{\tau_l^2} = \lim_{\tau \to 0} \frac{1 - R(\tau)}{\tau^2} \tag{7}$$

or determined from the measured energy spectrum of the pulsation of the longitudinal velocity component

$$L_x = \frac{\pi}{2} \lim_{k \to 0} F(k), \tag{8}$$

$$\lambda_x = \left(\frac{2}{\int_0^\infty F(k)\, k^2 dk} \right)^{1/2}. \tag{9}$$

The results of the measurement of the longitudinal microscales in the axial cross sections x/D = 36, 42,

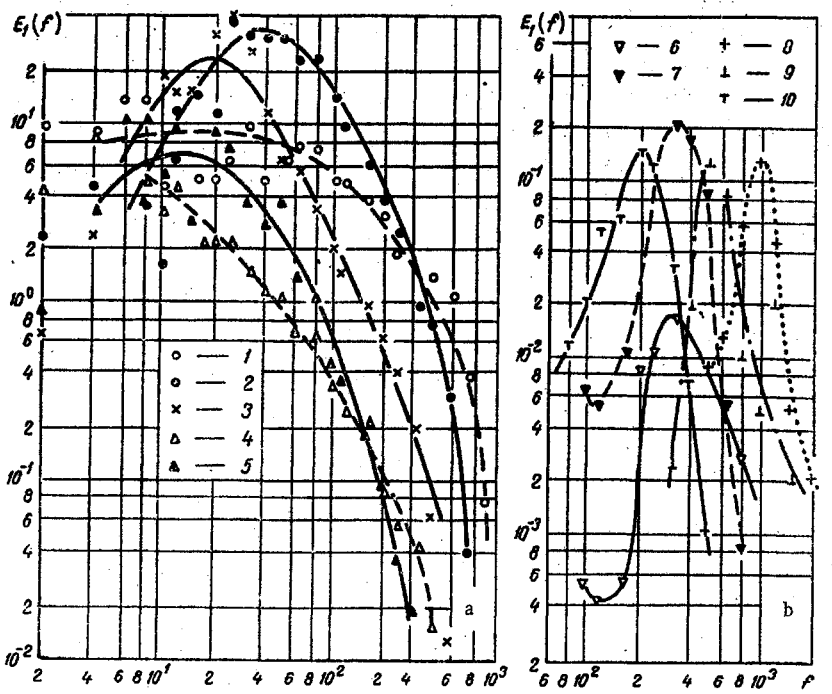

Fig. 4. Energy spectra of longitudinal component of pulsation velocity at axis of jet. For a: 1) water, $x_0 = 10$; 2) PEO, C = 0.007%, $x_0 = 10$; 3) PEO, C = 0.007%, $x_0 = 20$; 4) water, $x_0 = 30$; 5) PEO, C = 0.007%, $x_0 = 30$; for b: 6) water, d = 5 mm, $\bar{u}_0 = 3.15$ m/sec; 7) 5 and 3.15; 8) 3 and 4.43; 9) 3 and 3.13; 10) 8 and 2.85 m/sec. $E_1(f)$, $cm^2 \cdot sec^{-1}$; f, Hz.

and 48 showed that they are almost constant ($\lambda_g \approx 0.11$ cm, $\lambda_g/D \approx 0.22$). This agrees well with Goldschmidt's measurements [13] ($\lambda_g/D \approx 0.22$) made under similar conditions and also confirms that the scale of dissipation remains constant into the fully developed region of the jet. The measured macroscales at the axis in the sections x/D = 36 and 48 were 1.79 and 1.9 cm, respectively.

In moving on to an analysis of the flow structure of a submerged jet of polymer solutions we must dwell on some peculiarities of the preparation of these solutions. It is known that water solutions of polyethylene oxide of low concentration have the capacity to change their properties especially rapidly under the effect of shear flow and with age. In order to exclude as much as possible the effect of structural change in the solution the time from the moment of dissolving to the moment of testing was kept constant at 110 h. The solution was prepared as follows: a concentration of polyethylene oxide 15 times higher than that at which the experiments were conducted was first prepared and aged for 4.5 days; the solution was reduced to the final concentration immediately before the test. The inelastic solutions of guar gum and the sodium salt of carboxylmethyl cellulose underwent aging to a much lower degree. The concentrated solutions of these polymers were aged for about 2.5 days. In the measurements the outer diameter of the Pitot tube head was selected in such a way that no anomalies appeared in the readings of the Pitot tube in the potential core of the submerged jet. The head diameter selected in this way was 1.6 mm in all the experiments including those in pure water. Because of the low content by weight of the polymers the viscosity of the solutions studied is practically independent of the shear velocity [16] and does not exceed 1.2 cS at 20°C. The temperature of the solution in the experiments lay in the range of 19 ± 1°C.

The results of the measurement of average velocity and turbulent intensity for two concentrations of polyethylene oxide (WRS-301) in comparison with the analogous data for water are presented in Fig. 3. The curve of variation in average velocity along the axis of the submerged jet confirms the fact established earlier concerning an increase in the range of a jet of a polyethylene oxide polymer solution which is in the elastic stage. The measurements also made of the average velocity in cross sections of the jet confirm the decrease in the transverse dimension and the increase in range. Such a tendency is retained up to x/D = 16. In farther cross sections some decrease is observed in the average velocity compared with the flow of a pure water jet. The curves of variation in the intensity of the pulsations in the longitudinal velocity component along the axis of the jet which are presented in Fig. 3 do not correspond, as appears at first

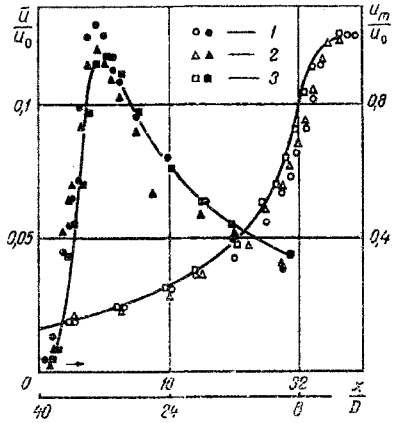

Fig. 5. Variation in average velocity (symbols on left) and turbulent intensity (symbols on right) at axis of jet (Re = 1.5 $\cdot 10^4$). Water and solutions of guar gum and Na—CMC: 1) GG, C = 0.03%; 2) Na—CMC, C = 0.04%; 3) water.

glance, to a marked increase in the range. Actually, the increase in average velocity can be explained by a decrease in turbulent diffusion, i.e., by a decrease in the level of the velocity pulsations. However, a considerable increase in the intensity of the longitudinal component of the pulsation velocity in a polyethylene oxide jet which is in the elastic state was established in numerous series of tests.

What more or less likely reasons could explain such an increase in the readings of a Pitot tube with a piezoceramic transducer?

1. Pulsations of the normal stresses in a shear stream of viscoelastic liquid. However, theoretical estimates and experimental measurements for the turbulent flow of a solution of viscoelastic liquid (polyisobutylene) in a tube showed that in this case a piezopickup gives somewhat understated pulsation intensities [9]. Moreover, measurements which we conducted in a submerged jet of polyethylene oxide using an electrodiffusion pickup not sensitive to pressure also showed an increase in the intensity of the longitudinal component of the pulsation velocity.

2. The effect of associations recorded by the sensing element of the Pitot tube. But, first, the outer diameter of the Pitot tube head was chosen from conditions of the absence of blockage of the intake opening. Second, such an effect of individual associations, as was shown in thermoanemometric measurements [4], should be accompanied by broadening of the spectrum, which did not occur in the present case. An experiment was also conducted on the measurement of the intensity of temperature pulsations during discharge from a nozzle of a preliminarily heated weak solution of polyoxyethylene which was in an elastic stage. The experiments showed that with the same temperature drops in the discharging jet and the chamber the temperature pulsations in water were considerably lower than in the polymer solution. The increase manifested in the intensity of the pulsations in the longitudinal velocity component is apparently explained by the instability of the viscoelastic solution [6]. It can be assumed that the velocity pulsations take on an essentially anisotropic structure. The intensity of the longitudinal component of the

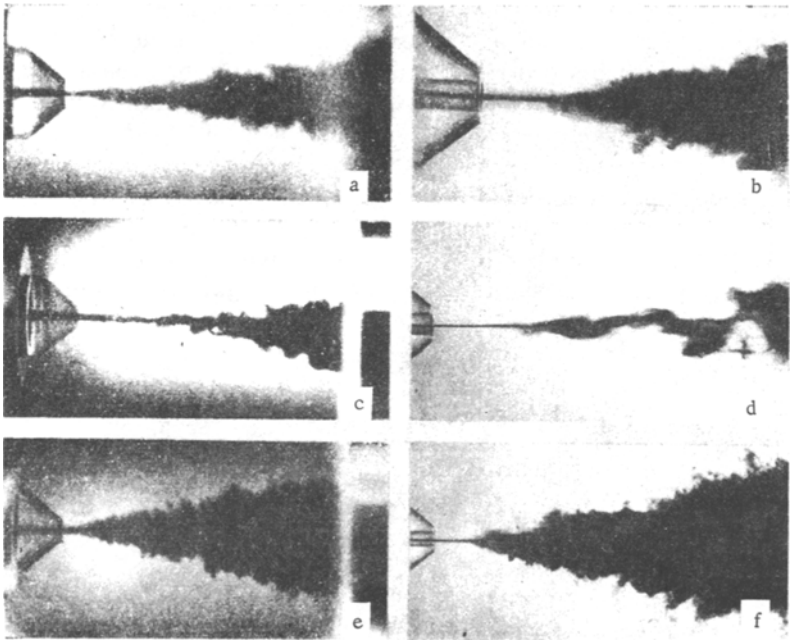

Fig. 6. Visualization of flow: a, b) jet of pure water; c, d) jet of polyethylene oxide solution, C = 0.007%; e, f) jet of Na—CMC solution, C = 0.04%.

TABLE 1

Liquid	l_0	ε	D_t, cm²/sec
Na-CMC(1%)	$\sim 3,1x_0$	$\sim 6,3\%$ $(x_0=4)$	$\sim 1,03$
PEO (0.2%)	$\sim 4,2x_0$	$\sim 2,6\%$ $(x_0=5)$	$\sim 0,17$
Water	$\sim 3,6x_0$	$\sim 3,5\%$ $(x_0=4)$	$\sim 0,77$

pulsation velocity increases while the intensity of the transverse component probably decreases, which is accompanied by a general reduction in turbulent diffusion and an increase in the range of the jet.

It must be observed that such "longitudinal" instability, not accompanied by an increase in resistance, was probably the reason for the appearance of considerable pulsations in the shearing stress of friction at the wall of a disk rotating in an elastic solution of polyethylene oxide [17].

The energy spectra of the pulsations in the longitudinal velocity component presented in Fig. 4a show that the increase in the pulsation energy in a solution of polyethylene oxide is connected with the considerable redistribution of the pulsation energy by frequency: an increase in the contribution of the low-frequency components and a decrease in that of the high-frequency components of the spectrum. The shape of the spectrum with clearly expressed maxima indicates that along with the suppression of the energy-containing fine-scale motion the presence of the polymer promotes processes of regularization and strengthening of the longitudinal components of large-scale vortex structures, processes which are accompanied by intermittence, reduction in the intensity of transverse pulsations, and an increase in the range as a result. In measurements of the pulsation and average velocities in a jet of polyethylene oxide solution which was not in the elastic phase (the solution was passed through a centrifugal pump for 15 min) a decrease in the range and an increase in the turbulent intensity compared with water were noted, as in [18]. These data are presented in Fig. 3. With further degradation of the solution the average velocity and turbulent intensity approach the analogous characteristics of water.

Inelastic solutions of guar gum (GG) and the sodium salt of carboxylmethyl cellulose are interesting by analogy with the degraded solution of polyethylene oxide. In the present work experiments were conducted on GG and Na—CMC solutions with concentrations of 0.015 and 0.03 and of 0.02, 0.04, and 0.05%, respectively. The results of measurements of the average velocity and turbulent intensity of these polymer solutions are presented in Fig. 5. The effects of the two polymers on the turbulence characteristics coincide qualitatively and, as mentioned above, are analogous to the behavior of a solution of polyethylene oxide degraded by passage through a centrifugal pump for 15 min; the behavior of the solution of the sodium salt of carboxylmethyl cellulose agrees well with the results of [5] obtained with a laser measuring instrument. The difference in the characteristics of the development of jets of water, an 0.007% solution of polyethylene oxide, and an 0,04% solution of Na—CMC are seen from Fig. 6a, c, e. Frames of films made with an SKS-1M high-speed motion picture camera are presented there. The visualization was accomplished through the supply of India ink to the input tube. It is easy to note the essential properties of the polyethylene oxide jet: the wave-like form up to $x/D \approx 16$ and the slight increase in the thickness of the jet. Since the intensity of the increase in thickness of the jet along its length $d\delta/dx$ is proportional to the transverse pulsation velocity [20]

$$\frac{d\delta}{dx} \sim \frac{[\overline{(v')^2}]^{1/2}}{\bar{u}}, \tag{10}$$

one can make a comparative estimate of the intensity of the transverse pulsation velocity. This estimate, made from the results of an analysis of film frames, gives a decrease in the intensity of the transverse pulsation velocity in the initial sections of a jet of polyethylene oxide of about two times compared with water. For a jet of Na—CMC the opposite tendency is observed, the same increase in the intensity. An attempt was also made to determine some characteristics of the turbulent transport by the method of diffusion of a transportable substance [15, 22]. For this purpose a thin tube, from which dye was supplied, was mounted in front of the nozzle. A fine stream of dye (India ink) flowed out along the axis of the jet and its thickness remained practically constant over the entire length l_0 of the initial section of the submerged jet (see Fig. 6b, d, f). The filming made it possible to follow the increase in thickness in the section $x > l_0$.

The value of the dispersion was determined on the assumption of a Gaussian distribution of the dye concentration, and then the intensity of the transverse component of the pulsation velocity and the coefficient of turbulent diffusion [15] were determined. In these experiments the discharging water jet was without polymer additions. The polymer solution could be supplied together with the stream of dye, i.e., a system of injection of the polymer into the water jet was achieved. The ratio of flow rates of the polymer solution and the main jet was 0.045. As seen from Fig. 6d, from the nature of the spreading of the colored stream of polyethylene oxide (up to $x_0 \simeq 16$) one can judge that there is considerable suppression of the turbulent diffusion of the dye and that intermittence develops. The injection of a solution of Na—CMC leads to more intense mixing compared with water. The results of the measurements, which additionally confirm the marked differences in the characteristics of transport in the flow of submerged jets of water and polymer solutions, are presented in Table 1.

NOTATION

D	is the diameter of exit nozzle;
$x_0 = x/D$;	
$\bar{u}$	is the average velocity;
u_d	is the velocity of discharge from nozzle;
u_m	is the average velocity at axis of jet;
$u' = [\overline{(u')^2}]^{1/2}$	is the root-mean-square value of longitudinal component of pulsation velocity;
$[\overline{(P_t')^2}]^{1/2}$	is the root-mean-square value of pulsation in total pressure;
$Re = u_0 d/\nu$	is the Reynolds number;
f	is the frequency, Hz;
k	is the wave number, cm^{-1};
$E_1(f)$, $F_1(k) = (\bar{u}/2\pi)E_1(f)$	are the one-dimensional energy spectrum of longitudinal component of pulsation velocity, $cm^2 \cdot sec^{-1}$; $cm^3 \cdot sec^{-2}$;
$F_{1,n}(k) = F_1(k)/\bar{u}'^2$	is the one-dimensional normalized spectrum;
l_0	is the length of undisturbed zone of flow;
σ	is the dispersion;
δ	is the thickness of jet;
D_t	is the coefficient of turbulent diffusion.

LITERATURE CITED

1. V. N. Kalashnikov and A. M. Kudin, "Anomalous readings of Pitot tube in heterogeneous liquids," Preprint, In-ta Prikl. Mekhan. Akad. Nauk SSSR, No. 6 (1971).
2. R. W. Serth and K. M. Kiser, Am. Inst. Chem. Eng. J., 16, No. 2, 163-168 (1970).
3. E. M. Khabakhpasheva, Author's abstract of doctoral dissertation [in Russian], Novosibirsk (1972).
4. G. I. Barenblatt, V. N. Kalashnikov, and A. M. Kudin, Zh. Prikl. Mekhan. i Tekh. Fiz., No. 5, 118-122 (1968).
5. S. A. Vlasov, V. N. Kalashnikov, B. F. Mul'chenko, B. S. Rinkevichyus, and V. I. Smirnov, in: Transactions of Fourth All-Union Conference on Heat and Mass Exchange [in Russian], Vol. 3, Minsk (1972).
6. V. A. Gorodtsov and A. I. Leonov, Prikl. Matem. i Mekhan., 31, No. 2 (1967).
7. I. L. Chung and W. P. Graebel, Phys. Fluids, 15, No. 4 (1972).
8. C. S. Wells, J. Harkness, and W. A. Meyer, AIAAJ., No. 2 (1968).
9. J. M. Rodriguez, G. K. Patterson, and J. L. Zakin, J. Hydronaut., 5, No. 3 (1971).
10. N. A. Pokryvailo, É. F. Saenko, A. P. Yakimakho, A. S. Sobolevskii, and G. N. Pashik, In ; Transactions of Fourth All-Union Conference on Heat and Mass Exchange [in Russian], Vol. 1, Minsk (1972).
11. S. C. Grow and F. H. Champagne, J. Fluid Mech., 48, No. 3, 547-591 (1971).
12. S. Corrsin and M. S. Uberoi, NASA Tech. Rept. 1040 (1952).
13. V. W. Goldschmidt and S. C. Chuang, Teor. Osnovy Inzh. Raschetov, No. 1 (1972).
14. M. M. Gibson, J. Fluid Mech., 15, No. 2 (1963).
15. I. O. Khintse, Turbulence [in Russian], Fizmatgiz, Moscow (1963).
16. V. S. Belokon', S. A. Vlasov, and V. N. Kalashnikov, Inzh.-Fiz. Zh., No. 5 (1972).

17. N. A. Pokryvailo, V. I. Kordonskii, E. B. Kaberdina, and V. D. Lyashkevich, "Properties of boundary turbulence in polymer solutions," in: Transactions of Fourth All-Union Conference on Heat and Mass Exchange [in Russian], Vol. 3 (1972).
18. G. I. Barenblatt, V. A. Gorodtsov, and V. N. Kalashnikov, in: Transactions of Third All-Union Conference on Heat and Mass Exchange [in Russian], Vol. 3, Minsk (1968).
19. G. N. Abramovich, In: Transactions of All-Union Symposium on Problems of Turbulent Flows. Turbulent Flows [in Russian], Nauka, Moscow (1970).
20. G. N. Abramovich, Dokl. Akad. Nauk SSSR, 190, No. 5 (1970).
21. A. S. Ginevskii, Theory of Turbulent Jets and Wakes [in Russian], Moscow (1969).
22. Yu. A. Ivanov and S. Yu. Krasheninnikov, "Determination of characteristics of turbulence using diffusion measurements," Izv. Akad. Nauk SSSR, Mekhan. Zhidk. i Gaza, No. 3 (1970).