AVERAGE AND PULSATION COMPONENTS OF VELOCITY IN SUBMERGED JETS OF POLYMER SOLUTIONS

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Results are presented of measurements with a laser anemometer of the average velocities, root-mean-square pulsations, and probability distributions of the pulsations in submerged jets of polyoxyethylene solutions.

The study of turbulent submerged jets of polymer solutions, which reduce the turbulent frictional resistance, makes it possible to establish the nature of the effect of polymer additions on free turbulence.

The measurements were made with a laser anemometer. The principle of the operation of this instrument is based on the Doppler effect. If a monochromatic beam is directed at the experimental point of the stream the light scattered by moving optical heterogeneities takes on a frequency shift proportional to the velocity. In the system which we use two focussed laser beams intersect at the experimental point. The light scattered from the volume formed by the intersection of the laser beams is collected by the objective on the photocathode of an FÉU-38 photoelectric amplifier and gives rise to the component of the photocurrent at the Doppler frequency $f_d = (k_1 - k_2)u$. The possibility of calculating the characteristics of a turbulent stream through a spectral analysis of the Doppler signal was first indicated in [1] and substantiated in [2]. In our system the analysis of the Doppler signal was accomplished using a V6-1 selective voltmeter operating on the principle of a narrow-band filter (band transmission 10 kHz). The output signal was squared and time averaged (averaging time ~3 sec) by a low-frequency filter, after which it was measured with an automatic potentiometer. The scanning of the selective voltmeter was synchronized with the tape winder of the potentiometer. With a sufficiently long averaging time and a small transmission width of the filter the spectrum of the Doppler signal traced on the tape of the automatic potentiometer can be identified with the distribution of probability densities of the velocities.

One peculiarity of the system used is that low-frequency noise is picked up along with the recoring of the Doppler signal spectrum. When the descending branch of the noise and the signal were in the same frequency region the noise component was subtracted out. For this the photocurrent spectrum was recorded with one of the probing beams covered, in this case representing the noise without the Doppler signal. The gain in the recording was increased to the point where the amplitude of the noise in the region of frequencies far from the Doppler signal was the same as in the recording of the photocurrent spectrum with the Doppler signal.

After such subtraction the standard procedure for finding the average velocity and root-mean-square value of the pulsations can be applied to the useful signals obtained which represent the distribution of the probability density of the velocities:

$$\bar{u} = \int uP(u)\,du \Big/ \int P(u)\,du,$$

$$\overline{u'^2} = \int (u - \bar{u})^2 P(u)\,du \Big/ \int P(u)\,du.$$

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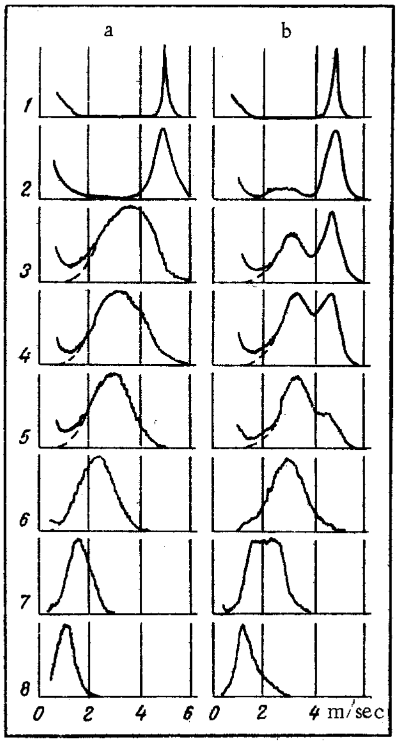

Fig. 1. Probability density distribution of velocities at jet axis for water (a) and a freshly prepared solution of Polyox WSR-301 polyoxyethylene with a concentration of 10^{-4} (b) at the following distances from the nozzle cut: 1) 0; 2) 10; 3) 15; 4) 22.5; 5) 27.5; 6) 35; 7) 55; 8) 80 mm.

Usually when the normal velocity distribution is realized and the Doppler signal spectrum has a Gaussian form the average velocity can be found from the maximum on the distribution curve P(u), and the root-mean-square value of the pulsation velocity from the width of the distribution at the level corresponding to half the maximum amplitude.

The pulsation velocity can be represented in the form $u' = u'_x \cos\alpha + u'_y \sin\alpha$. It is obvious that $\sqrt{\overline{u'^2}} = \sqrt{\overline{u_x'^2}\cos^2\alpha + \overline{u_y'^2}\sin^2\alpha + \overline{u'_x u'_y}\sin 2\alpha}$. Thus, to obtain the principal characteristics of the turbulent stream it is sufficient to make three measurements at each point, rotating the plane of the probing beams through three fixed values of the angle α.

The observed signal spectrum has a finite width even in the case of the absence of a pulsation velocity. This width is determined by the transmission band of the narrow-band filter, the averaging time, the finite thickness of the probing beams, and the statistical nature of the Doppler signal which consists of individual sinusoidal components with random phase. This instrument width can be measured experimentally by determining the spectral width in a practically laminar stream such as in the potential core of a water jet. Since the level of turbulence at the nozzle cut is low, independent measurements of the turbulence at this point were made with a thermoanemometer and it was possible to introduce the appropriate corrections allowing for the instrument width of the Doppler signal spectrum.

The measurements were carried out in jets of polyoxyethylene solutions (Polyox WSR-301). Since polyoxyethylene solutions undergo degradation to a much greater extent than solutions of guar gum, used in the experiments reported on in [3], the liquid was injected from a supply vessel with a capacity of 120 liters. The pump was eliminated from the circuit. The discharge took place through a nozzle with an opening diameter of 3.1 mm. The discharge velocity was 5 m/sec in all the experiments.

The solutions were prepared in the supply vessel 2 h before the start of the tests. Immediately before the experiment the solution was mixed for 4-5 min with the immersible pump of a thermostat. If after the solution had been held for 2 h the flow rate through the nozzle was less than would be expected from the readings of a piezometer mounted on the supply tube, after 4-5 min of mixing the flow rate corresponded to the piezometric pressure with an accuracy of 5%.

Tests were conducted with fresh solutions and solutions which had undergone partial degradation. A state of partial degradation was attained after 8 h of mixing the solution with the submersible pump of a thermostat. The degree of degradation of the solution was controlled in an assembly containing rough coaxial cylinders [4]. Such control was possible thanks to the fact that on the degradation curves (the variation in the moment of frictional forces on the shaft of the inner cylinder during rotation of the outer cylinder with a constant velocity) there is a characteristic point corresponding to certain structural changes in the solution. In the testing of freshly prepared polyoxyethylene solutions in the gap between rough cylinders a decrease in resistance is first observed, an increase occurs in the moment of frictional forces in proportion to the degradation, the coefficient of resistance reaches the value obtained in a test of water, and then exceeds it. With further degradation the moment of frictional forces decreases to the value obtained in a test of pure water. It is found that the degree of degradation of the solution at the moment of transition from reduction to increase in resistance is the same as that for a solution after 8 h of mixing with a thermostat pump. A submerged jet of such a solution has the smallest range in discharge through a nozzle 3.1 mm in diameter.

Recordings of the probability density distribution of the velocity at the jet axis at different distances from the nozzle cut for the flow of water and a freshly prepared solution of Polyox WSR-301 polyoxyethylene with a concentration of 10^{-4} are presented in Fig. 1. The dashed curves correspond to the useful signal. They are found by subtracting the low-frequency noise. The probability distribution of pulsations for the flow of water everywhere has the form of a Gaussian distribution, whereas for the fresh solution the curves have two maxima at a certain distance from the nozzle. From the form of such a bimodal distribution one can reconstruct the nature of the realization of the velocity at the point. The presence of two maxima in the distribution indicates the increased probability of the velocities corresponding to these maxima and a decreased probability for the velocities between the peaks. In the realization this means that the duration of the intervals with values close to the values of these velocities will be greater. This effect could be connected with some vibrational process (for example, in [5] it is shown that a distribution with two maxima develops when a jet impinges on a wedge and is connected with the formation of auto-oscillations). However, it should be noted that the region of the jet where the bimodal distribution is observed consists of a long volume localized near the jet axis, stretching from 10 to 35 mm from the nozzle cut, and having a diameter of about 2 mm. This was established by measurements in radial directions at distances of 15 and 22.5 mm. If fluctuations with a high amplitude occur in this volume then despite the limitation in the use of a thermoanemometer in work with polymer solutions a pickup mounted in the stream ought to record these changes if their frequency does not exceed 400 Hz (which is the transmission band of the thermoanemometer channel). A thermoanemometer pickup was mounted at the axis of the jet at a distance of 22.5 mm from the nozzle cut and no auto-oscillations were noted in this frequency range. It is difficult to assume the possibility of the existence of a vibrational process with large amplitude occurring with a frequency exceeding 400 Hz, especially in such a spatially restricted region of the jet.

The difficulties in explaining the reasons for the formation of bimodal distributions can be overcome if one recalls the properties of the structure of polymer solutions which reduce the frictional resistance. As was shown earlier [6], fresh solutions of polyoxyethylene consist of suspensions of viscoelastic associations whose size reaches 2 mm. At the nozzle exit the associations obviously have the same velocity as the liquid surrounding them. At the end of the potential core the turbulized liquid penetrates from the mixing zone to the axis of the jet, although because of the viscoelastic nature of the associations the penetration of turbulence into their volume is hindered. For this reason and because of inertial effects connected with size the associations have a different velocity from the surrounding liquid in the region of high accelerations.

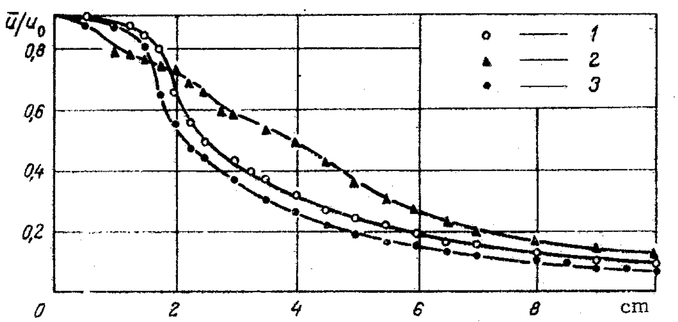

Fig. 2. Variation in average velocity at jet axis for water (1), a freshly prepared solution of Polyox WSR-301 polyoxyethylene with a concentration of 10^{-4} (2), and the same solution subject to partial degradation (3).

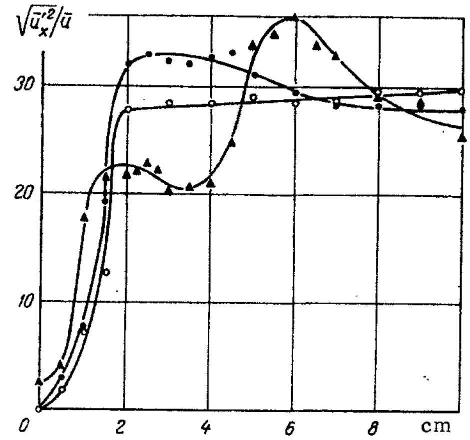

Fig. 3. Relative level of longitudinal component of turbulence (%) at jet axis for water and polyoxyethylene solutions (notation same as in Fig. 2).

They move with higher velocity and outrun the surrounding liquid in the section of abrupt decrease in velocity in the jet. For this reason distributions with two maxima are observed in a narrow axial region within the jet.

If this scheme is correct the intensity of the peak corresponding to high velocities and connected with the motion of the associations must be decreased during dilution of the solution because of the decrease in the volumetric concentration of the associations. In fact, a fourfold dilution of the original solution led to a decrease in the amplitude of the maximum in the probability distribution connected with high velocity.

Fluctuations connected with the motion of individual associations could not be recorded by the thermoanemometer since under our conditions this would have required transmission bands of at least 2.5 kHz (the size of an association is ~2 mm and its velocity is ~5 m/sec).

The associations become smaller in the process of degradation of the solution. When the size of the associations becomes less than the size of large vortices in the jet the effect on the average characteristics of the flow is apparently accomplished through action on the pulsation components of the velocity. Observation of the evolution in the form of the probability distributions in the process of degradation of the solution showed that at the time when the greatest decrease is observed in the range of the jet the distributions acquire a Gaussian form, i.e., the same as in the flow of pure water.

The results of measurements of the average velocity are presented in Fig. 2. The variation along the jet axis of the root-mean-square value of the longitudinal component of the pulsation velocity normalized to the value of the local velocity is presented in Fig. 3. The measurements were conducted with the plane of the probing beams aligned with the average velocity vector.

Since the Reynolds stresses are equal to zero at the axis of an axially symmetrical jet, to determine the root-mean-square value of the transverse component of the pulsation velocity at the jet axis it was sufficient to conduct measurements with rotation of the plane of the probing beams by the angle $\alpha = \pi/4$, and in this case $\sqrt{u'^2} = \sqrt{2(\sqrt{\overline{u'^2}})^2 - (\sqrt{\overline{u_x'^2}})^2}$.

The relative level of the transverse component of the turbulence at the axis of the water jet reached 22-23%. In the entire range of distances from the nozzle cut studied this value was 20-30% higher for the flow of a solution which had undergone partial degradation. In freshly prepared solutions the transverse pulsations were markedly suppressed and the level of the transverse component of the turbulence was at least 2-2.5 times lower than in the flow of pure water.

Thus, the increase in the range of freshly prepared polyoxyethylene solutions is connected with a decrease in the transverse velocity pulsations on the one hand and with the greater velocity of the associations in the section beyond the potential core of the jet on the other. The decrease in the range of solutions which have undergone partial degradation is connected with the destabilizing effect of the small associations on the turbulent pulsations in the jet.

NOTATION

u	is the velocity vector;
k_1, k_2	are the wave vectors of incident light beams;

f_d	is the Doppler frequency;
$P(u)$	is the distribution function;
$\bar{u}$	is the average velocity;
$\overline{u'^2}$	is the root-mean-square value of velocity pulsations;
u'_x, u'_y	are the velocity pulsations;
α	is the angle between average velocity vector and plane of probing beams;
u_0	is the velocity at nozzle cut.

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