INFLUENCE OF POLYMER ADMIXTURES ON THE TURBULENCE STRUCTURE OF FLOW BEHIND A GRATING

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Experimental investigations of the action of small (20-80 ppm) polymer admixtures on the turbulence structure in the wake behind a grating are performed in a water channel of closed type. The velocity fluctuations are measured by using a single-component Doppler laser velocimeter (DLV). A signal from the DLV was recorded on magnetic disc from three channel sections and the one-dimensional energy and dissipation spectra were computed therefrom. It is shown that polymer insertion resulted in reduction of the turbulence level at short ranges from the grating and its increase far from the grating. Influence of the polymer in the spectral distribution appeared in an energy increase in the low-frequency domain and its fast degeneration in the high-frequency band, accompanied by contraction of the spectrum width.

The effect of reducing the drag in the turbulent flow of weak polymer solutions (20-100 ppm) is known and used for a long time. A considerable number of researches, including experimental, is devoted to the study of this phenomenon, however, there is no complete comprehension of the mechanism of the change in the turbulence structure. The complicated situation is explained to a definite degree by the ambiguity of the experimental results as well. Thus, visualization of flows of the mentioned polymer solutions showed suppression of fine-scale turbulence [1, 2] but this was not reflected in the energy spectrum that practically agreed with that for water [1-4]. At the same time, a noticeable diminution in the energy was observed in the high-frequency spectrum range for (500-1000 ppm) concentrations [2]. Addition of a polymer to water resulted in a change in the level of turbulence but if a reduction in velocity fluctuations was mentioned in [1, 2], their increase was reported in [3, 5, 6]. In connection with the above elucidation, it is of interest to perform further experimental investigations of the turbulent characteristics of weak polymer solutions. Because of the build-up of isotropy and homogeneity of water properties at a certain distance from a grating, the flow behind it permits studying the features of polymer action on the turbulence structure with the greatest completeness.

The experiment was performed in a closed type water channel [7] (Fig. 1). The measurements were conducted in a section 1 of length L = 1.2 m with a constant cross-sectional area 0.25 × 0.25 m. The side walls of this section were fabricated from organic glass which permitted application of optical methods to measure the turbulent flow characteristics. The translations stream motion was produced by the impeller 2 connected to the electrical motor 3.

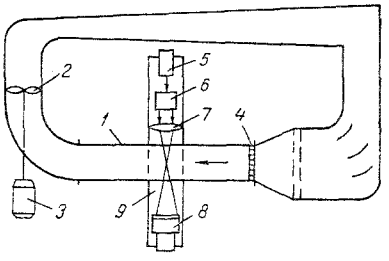

Fig. 1. Diagram of the experimental set-up.

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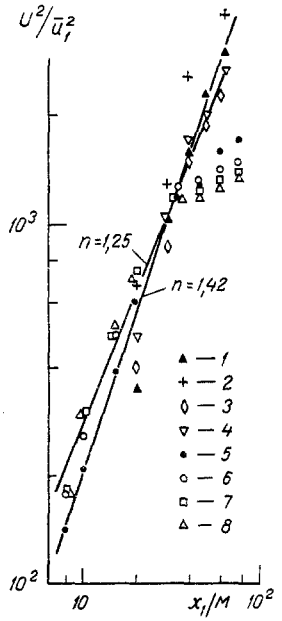

Fig. 2. Degeneration of longitudinal velocity fluctuations along the channel axis for water and polymer solutions: 1) water; 2) 100 ppm; 3) 500; 4) 1000 ppm [2]; 5) water; 6) 20 ppm; 7) 40; 8) 80 ppm results of present studies.

The number of rotations of this latter were maintained by a tachogenerator included in the feedback. The grating 4 behind which the measurements were performed was installed at the entrance to the working section. It is fabricated from circular metallic rods of d = 0.003 m diameter that form a square cell M = 0.01 m in the light.

The polymer, the powder "Polyox 300", was dissolved in tap water in a tank (located above the water channel) from which the prepared solution overflowed into the channel by gravity flow. The polymer solution was held in the tank for three days at room temperature. The concentrations required for the investigations (20, 40, 80 ppm) were obtained after pouring the solution from the tank into the channel and filling the latter with water to a known level.

Measurements of the turbulent flow characteristics were performed by using a single-component Doppler laser velocimeter (DLV) from the firm DISA-55L in a direct scattering scheme (Fig. 1). The laser 5, the optical component 6, the lens 7, and the photomultiplier 8 are mounted rigidly on the surface of the traversing probe 9, which permitted realization of three-coordinate scanning of the working section. The photomultiplier output signal was converted by the electronic module 55L32 into a voltage proportional to the instantaneous velocity. The mean value of the voltage proportional to the mean velocity was measured by a 55D31 voltmeter. The low-frequency part of the signal was eliminated by using a 55D26 filter module. The high-frequency part, corresponding to velocity fluctuations, was measured by a 55D35 r.m.s. voltmeter. To compute the higher order moments, the turbulence energy spectrum distribution, and the probability density function, the filtered signal was inscribed on a SM-3 magnetic disc of the electronic computer by using an automated system. This latter permitted execution of a record of the realizations (4096 byte arrays) continuously if the upper limit of the sampling frequency is $f_x \leq 10$ kHz. A signal corresponding to velocity fluctuations was recorded for two frequency bands 1-400 Hz and 1-5 kHz with the sampling frequency f_{s1} = 1000 Hz and f_{s2} = 10 kHz, respectively. Selection of the frequency bands is due to the tendency to obtain more detailed information about polymer influence on the long- and high-frequency parts of the turbulent spectrum. The time of signalinscription was t_1 = 82 sec for the cutoff frequency f_{c1} = 400 Hz and t_2 = 65 sec for the cutoff frequency f_{c2} = 5 kHz.

The experiment was realized at a U = 1.7 m/sec constant stream velocity which was maintained with ±2% accuracy. The Reynolds number computed by means of the characteristic dimension equal to the grating parameter M was $Re = UM/\nu = 17 \cdot 10^3$. Measurements of the longitudinal velocity component fluctuations (u_1) were performed by an analogous method in nine sections (x_1/M = 8, 10, 15, 20, 25, 35, 45, 60, 75). Measurements in pure water preceded the investigations in the polymer solution every time. Taking into account that the properties of the polymer solutions vary with time for each concentration, the determination of the quantity u_1 was realized at least twice and the measurements were started with sections both near to and far from the grating.

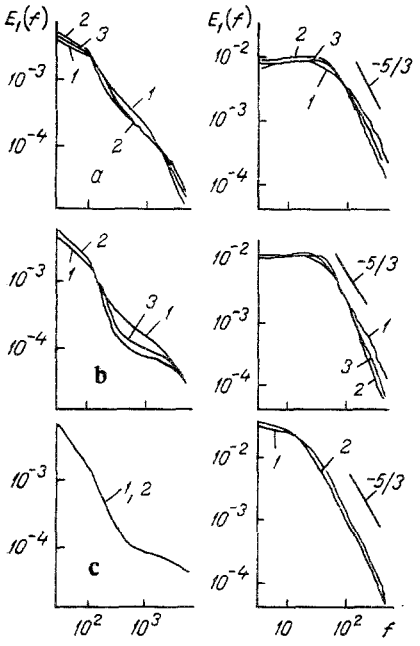

Fig. 3. One-dimensional energy spectrum in a double logarithmic scale in the sections x_1/M: a) 10, b) 20; c) 75 (1 is water; 2 is 80 ppm; 3 is 40 ppm).

The experimental values of u_1 obtained for water and the polymer solutions are represented in Fig. 2 and they were compared with data from [2] in which a broad spectrum of concentrations (50-1000 ppm) was investigated. In contrast to [2], the flow isotropy for water held from the distance $x_1/M \geq 8$. It is known ([8], p. 254) that isotropic flow behind a grating is formed the more rapidly, the smaller the parameter M/d. In the present investigations this parameter is M/d = 3.3, while M/d = 5 in [2], i.e., the observable discrepancy in the values of u_1 in the works being compared correlates with the features of the grating geometry. Degeneration of the velocity fluctuations in the initial section is described by the power law

$$\frac{U^2}{\overline{u_1^2}} = \left(\frac{x_1}{M} + \frac{x_0}{M}\right)^n$$

with the virtual origin $x_0 = 0$ and the power exponent n = 1.42. This value agrees with those obtained in [3] for the numbers $Re = (9.5\text{-}23.7)\cdot 10^3$ and n = 1.37-1.47. A detailed investigation of the influence of grating geometry on turbulence degeneration [9] showed that for $Re = 24\cdot 10^3$ the values of the exponent varied between n = 1.22 and n = 1.48. In [2] for water n = 1.9 ($Re = 9.6\cdot 10^3$). However, for $x_1/M \geq 30$ the changes in the velocity fluctuations are described well by a power law with exponent n = 1.42 (see Fig. 2). This fact permits assuming that the value of u_1 obtained for $x_1/M + 20$ [2] and which principally determines the quantity n = 1.9 refers to the flow domain where isotropy has not been established completely. Higher values of the fluctuations in these investigations for $x_1/M > 30$ as compared with those presented in [2] are related to the influence of the boundary layer whose rapid growth on the walls of the channel working section from $x_1/M > 35$ is due to construction features. At the same time it is impossible not to note the satisfactory agreement of the magnitudes of u_1 of these researches for weak polymer solutions in the distance range $x_1/M < 35$. The experiments carried out did not permit estimation of the influence of the concentration on the exponent of the power-law dependence. Changes in the velocity fluctuations along the channel axis axis for three solutions (20, 40 and 80 ppm) were approximated satisfactorily by a dependence with the exponent n = 1.25. Diminution of the power-law dependence exponent for fluctuation degeneration in polymer solutions held even in [2], where only for a substantial change in the concentration was a difference observed in the exponents: n = 1.7 (50-250 ppm) and n = 1.5 (1000 ppm). The investigations performed therefore confirm the known tendency to a reduction in the fluctuation degeneration rate in polymer solutions [2, 3]. Meanwhile,

it is established in this paper that the turbulent fluctuation intensity in less at a distance $x_1/M < 35$ from the grating and greater with respect to the values of u_1 in water for $x_1/M > 45$. The fluctuation level dropped in the whole range $x_1/M \leq 60$ investigated in [2] for analogous concentrations. Since flow isotropy was established in this paper considerably later as compared with that represented, the it is logical to associate the difference observed in the nature of the degeneration of the quantities u_1 to the inadequate range of distances x_1/M. In this case it is natural to expect that as the polymer solution concentration increases because of the diminution in the rate of fluctuation degeneration, a tendency towards an increase in the turbulence level should appear. Indeed, the values of u_1 for 500 ppm and 1000 ppm concentration solutions (Fig. 2) exceeded analogous values for water for $x_1/M \geq 30$. The exposed regularity in the change in turbulent fluctuation along the flow axis in the wake behind the grating is similar to that detected in studying the action of a polymer on fluctuations u_1 in a circular pipe [10]. The fluctuation level was reduced at a distance $x_1/D \leq 8$ (D is the pipe diameter) along the pipe axis from the site of polymer insertion, and increases for $x_1/D > 40$. Therefore, the present investigations in combination with the results in [2, 10] and the fact, acknowledged by all researchers, of a diminution in the rate of velocity fluctuation degeneration in these solutions permit making the deduction that under the influence of a polymer the turbulence level initial is lowered and then grows relative to the beginning in water. Hence, depending on the initial conditions (M/d, Re, concentration), each of these stages has a different extent in space.

In substance, the measured values $\bar{u}_1^2$ are averaged from the velocity fluctuation distributions over all the frequencies

$$\overline{u_1^2} = \int E_1(f)\, df. \tag{1}$$

Since the addition of a polymer results in a noticeable change in the quantity u_1 it is interesting to examine in what manner this is perceived by the fluctuation frequency distribution.

The turbulent fluctuation spectrum of the longitudinal velocity component on the channel axis was computed by using the fast Fourier transform algorithm. The computation was carried out for the sections $x_1/M = 10, 20, 75$ for both water and for two polymer solution concentrations: 40 and 80 ppm. The mentioned concentrations are of interest in that a reduction and increase in the turbulence level was observed, respectively, in polymer solutions here. The reliability of the spectrum distributions was estimated by the criterion of their convergence during reduction of the volume of information being utilized that is inscribed on the magnetic disc by two and four times. Analysis showed the sufficiency of half the available information. Energy values are normalized to the variance characteristic for this section so that the dimensionality of the spectrum being obtained will be in seconds while the area under the spectrum distribution equals unity. The turbulent fluctuation spectra represented in Fig. 3 demonstrate the energy increase in the low-frequency domain and the reduction of the spectrum width because of high frequencies with distance from the grating, which agrees with known results ([8], p. 239). The observable tendency in polymer solutions was manifested more clearly and is thus different from [2], where deviations from the spectrum of u_1 in water is not detected for analogous concentrations. Only for solution concentrations of 250, 500, and 1000 ppm did the nature of the energy spectrum distributions [12] correspond to those presented in Fig. 3. The dependences $E_1(f)$ obtained permitted comprehension of the reason for the reduction in the turbulence level for $x_1/M \leq 35$ and its increase for $x_1/M > 45$. The rapid fluctuation degeneration in the high frequency domain, accompanied by a diminution in the spectrum width, results in a general reduction in the spectrum energy (Figs. 3a and b) and in conformity with (1) results in diminution of the average fluctuations $\bar{u}_1^2$. At a distance of $x_1/M > 45$ from the grating the spectrum of the polymer solution does not differ, in practice, from the spectrum of water, with the exception of a narrow band in the low-frequency domain (Fig. 3c) where an increase in the values of the fluctuations occurred that was reflected in the growth of the measured values of $\bar{u}_1^2$.

In conformity with the known representations, the low-frequency domain is determined by the contribution of large-scale vortices that occur during stream passage through the grating. The interaction of these vortices result in the formation of finer vortices and energy transport over the whole spectrum of scales is thereby realized. A domain of scales and their corresponding frequencies exists (the universal equilibrium domain) in which energy transport due to intertial forces is governing, i.e., is independent of the viscosity. The fluctuation energy distribution in this domain is characterized by the law $E(f) \sim f^{-5/3}$. It

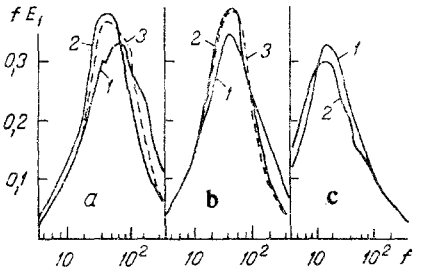

Fig. 4

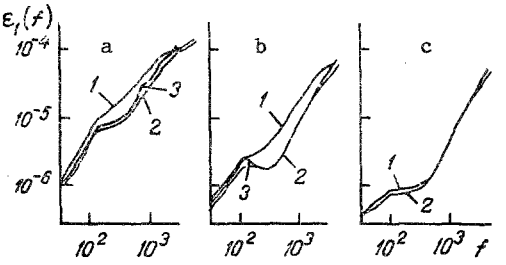

Fig. 5

Fig. 4. One-dimensional energy spectrum in a semi-logarithmic scale. Notation the same as in Fig. 3.

Fig. 5. One-dimensional dissipation spectrum in a double logarithmic scale. Notation the same as in Fig. 3.

is seen well from Fig. 3 for the f = 1-400 Hz frequency band that the universal equilibrium domain shifts towards lower frequencies with distance from the grating, i.e., the vortex scale grows in the inertial subdomain. Enlargement of the vortices and a simultaneous rise in their stability, and as a result, the reduction in the production of finer vortices that result in making energy pumping difficult from the large-scale energy-containing vortices to the fines vortices on which the energy dissipates. Energy conservation in large vortices is manifest in the increase in fluctuation energy at low frequencies and the reduction in energy transfer to the dissipative vortices is expressed in reduction of the energy spectrum width. The spectrum domain in which the "−5/3" law is satisfied in polymer solutions is shifted towards lower frequencies as compared with water (Fig. 3), i.e., the polymer results in stabilization of the large-scale flow structure in each of the sections considered. The polymer influence on energy redistribution over the frequencies appears more graphically in the construction of the dependence [fE_1, f], that reflects the contribution of each value of the frequency in the total energy of the velocity fluctuation spectrum (Fig. 4). As is seen, a significant increase in the energy of the energy-containing vortices and the rapid decrease in the energy at frequencies exceeding those where the "−5/3" law is satisfied (Figs. 4a and b). Energy growth of the largest of the vortices is accompanied by diminution of its content even in the energy containing vortices.

Let us examine the fluctuation energy dissipation spectrum

$$\varepsilon_1 = 2\nu \int k^2 E_1(k)\, dk. \tag{2}$$

The relation between the computed energetic spectra $E_1(f)$ and dissipation is set up by using the relationships

$$k = \frac{2\pi f}{U}, \quad E_1(f) = \frac{U}{2\pi} E_1(f),$$

i.e.,

$$\varepsilon_1 = 8\pi^2 \nu \left(\frac{u_1}{U}\right)^2 \int f^2 E_1(f)\, df.$$

The obtained distributions of ε_1 (Fig. 5) showed that a substantial reduction in the dissipation occurred at higher frequencies than those where the "−5/3" law is satisfied. The drop in dissipation as the energy frequency transmitted in this domain diminishes (Figs. 3 and 4) is a result of the reduction in the number of vortices being formed in this scale interval. Therefore, the action of the polymer on the turbulence structure appears in deceleration of the process of destroying the energy-containing vortices, which is adequate to "freezing" energy transfer from these vortices to the dissipative vortices. The stabilizing influence of the polymer with distance from the grating is felt only for all the larger scale vortices. As a result of diminution in the energy of the small vortices they degenerate rapidly, as is indeed confirmed by visual observations [1-3].

NOTATION

U is the longitudinal component of the mean velocity; u_1 is the longitudinal component of the velocity fluctuations; M is the size of the grating cell; d is the diameter of the grating rods, Re_λ is the turbulent Reynolds number; $E_1(f)$ is the energy of the longitudinal velocity fluctuations; ε_1 is dissipation of the longitudinal velocity fluctuations; ν is the kinematic viscosity; x_1 is the longitudinal coordinate; f_s is the sampling frequency, and f_c is the cutoff frequency.

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INFLUENCE OF PARTICLES ON THE INITIAL STAGE OF HOMOGENEOUS TURBULENCE DEGENERATION

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The influence of particles on the degeneration of homogeneous turbulence at high Reynolds numbers is analyzed.

On the basis of the solution of a system of equations for two-point moments of gas and particle velocity fluctuations without taking account of the triple correlations, the influence of the disperse phase on the final stage of homogeneous isotropic turbulence degeneration is investigated in [1] for moderate Reynolds numbers; it is obtained here that the presence of particles magnifies the damping of the turbulent fluctuations. It is noted in [2] that particles in a jet result in two oppositely directed effects: on one hand, a reduction in the fluctuation intensity of the lifting stream velocity occurs because of additional turbulent energy dissipation, and on the other, growth of turbulent energy generation occurs because of the increase in the average gas velocity gradient. Attenuation of the turbulent fluctuation intensity is established for near-wall flows in [3, 4] because of the additional dissipation in the presence of coarse particles in the stream, and conversely, a rise in the fluctuation intensity because of additional turbulence generation due to the average flow in the case of fine particles present in the stream. Therefore, depending on the inertia characterized by the ratio between the relaxation time to the time scale of the turbulence, the particles can contribute to both laminarization and turbulization of the stream. Such a regularity of the particle influence on turbulence is inherent to different kinds of flows. The nature of the particle influence on the turbulent fluctuation intensity is illustrated in this paper in an example of the problem of homogeneous turbulence degeneration for high Reynolds numbers.

The flow of a gas stream with solid particles ($\rho_2 \gg 1$) for a moderate volume concentration of the disperse phase ($\varphi \ll 1$) is considered. The equations of motion for the gas and particles are written in a Stokes approximation in the form

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