

CONNECTION BETWEEN AVERAGE AND PULSATION  
 CHARACTERISTICS IN TURBULENT FLOW OF  
 POLYMER SOLUTIONS IN A ROUND TUBE

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UDC 532.517.4

Results are given for measurements of the average and pulsation characteristics of dynamically stable turbulent flows of polymer solutions in a round tube. Experimental dependences are presented which indicate the presence of a close and unique connection between the turbulent pressures and shear stresses at the wall of the tube.

We have attempted to obtain additional information on the mechanism of action of polymer solutions on boundary turbulent flow. Controlled changes in the concentration and degree of degradation of the solutions and a change in the type of dissolved polymer served as the means of investigation. In this connection all the other experimental conditions were kept constant. For example, the experiments were conducted in a closed circulating instrument filled with a homogeneous polymer solution. The measurement section was located at a distance of more than 100 diameters from the start of the working section of the instrument, a round tube of constant diameter. This eliminated the effect of longitudinal gradients in the average flow characteristics and transverse gradients in the polymer concentration. Since the experiments were conducted on a continuously moving solution, statistically stationary dynamically steady flow was achieved, at least in the absence of degradation of the solution.

Finally, the average stream velocity was chosen within limits such that the shear stress did not affect the magnitude of the Toms effect [1], thanks to which the most stable limiting modes were achieved.

The effect of extraneous instrument noises which interfere with measurements of the pulsation characteristics of the flow was also eliminated by the choice of the modes of operation. This choice was made

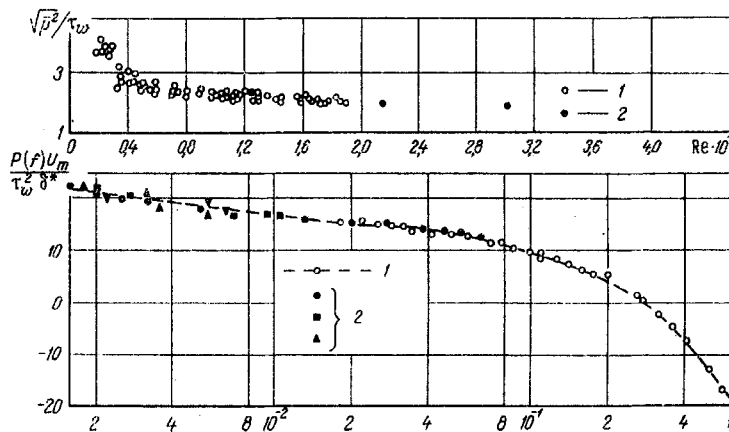


Fig. 1. Comparison of results obtained with data of experiment of [2] in an air stream. For a: 1) data of Corcos; 2) our experiment; for b: 1) our experiment; 2) data of Corcos.

Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 25, No. 6, pp. 1016-1022, December, 1973. Original article submitted July 27, 1973.

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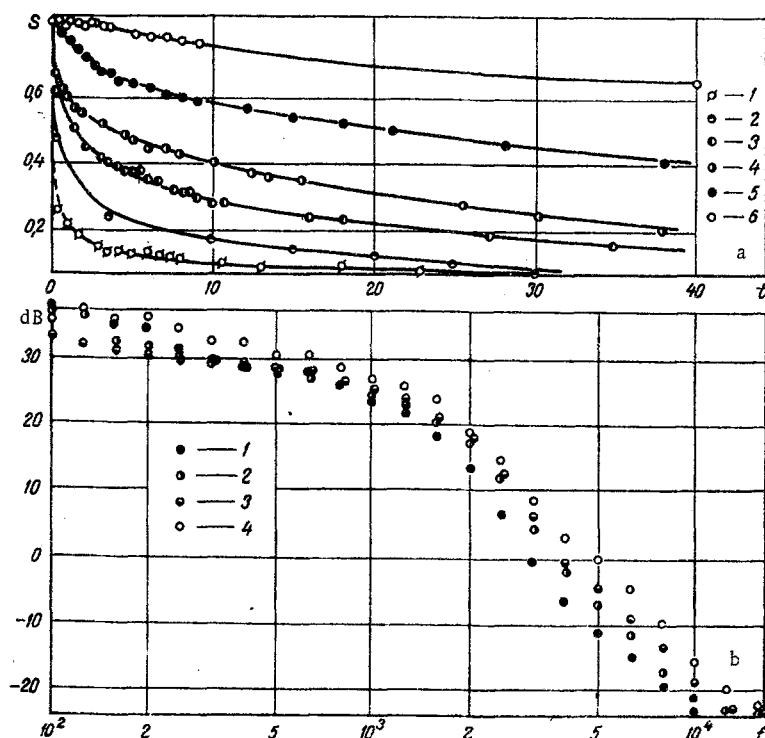


Fig. 2. Degeneration of effects of polymer solutions on shear stress  $S$  at wall and on spectral power densities  $P(f)$  of pressure pulsations.  $\text{dB} = 10 \log [P(f)/\text{rel}[1 \mu\text{bar}]^2 \cdot \text{Hz}]$ . For a: 1)  $C_{\text{init}} = 10^{-6} \text{ g/cm}^3$ ; 2)  $5 \cdot 10^{-5}$ ; 3)  $10^{-5}$ ; 4)  $2.5 \cdot 10^{-5}$ ; 5)  $10^{-4}$ ; 6)  $5 \cdot 10^{-4}$ ; for b: polyox  $C_{\text{init}} = 10^{-4} \text{ g/cm}^3$ ;  $U_{\text{av}} = 7.05 \text{ m/sec}$ ; 1)  $t = 0.5 \text{ min}$ ;  $S = 0.765$ ; 2) 7.0 and 0.6, respectively; 3) 38.0 and 0.4; 4) water.

on the basis of a special spectral and mutual spectral analysis of the instrument noises. The average and pulsation characteristics of the flow were recorded during the experiment and their relationship was studied. The average characteristics measured included the average flow velocity and the shear stress at the wall. In addition, profiles of the transverse distributions of the average velocity, and consequently any scale of the average flow, were known.\* The intensity of the pressure pulsations at the wall of the tube and their power spectra and mutual spectra were chosen as the pulsation characteristics studied. It is known that polymer additions introduced into the stream distort the readings of a thermoanemometer used to measure the velocity pulsations. In this regard a pickup for the pressure pulsations at the wall which is mounted flush with the inner surface of the tube is more acceptable. And this, of course, had its own difficulties: the measured levels of the high-frequency pressure pulsations were distorted by the finite dimensions of the pickups. The magnitude of these distortions can be calculated, however, if the dimensionless mutual spectral functions of the pulsations are known. The spectral characteristics of flows of solutions obtained are very useful as a whole since these characteristics contain much more information than the overall pulsation intensity. In order to exclude the possibility of measuring random individual results, the characteristics of the average [1] and pulsation flows of streams of the solvent, water, were studied before the start of the experiments. Pressure pulsations in tubes have been measured much more rarely than in boundary layers. Of the published results one can mention only the results of the spectral analysis of Corcos [2] in an air stream for its velocities from 30 to 150 m/sec, and the data which have appeared recently in [3], [4]. In the latter case the measurements were conducted in a tube with a rectangular cross section. A comparison with the results of Corcos is presented in Fig. 1. The agreement of the intensity levels and the low-frequency pulsation spectra is fully satisfactory despite the great difference in experimental conditions. The disagreement of the spectral levels at high frequencies is explained by the difference in pickup sizes. The frequency range in the measurements was 0.2-20 kHz. The range of variation in average stream velocities was from 4 to 10 m/sec. All the characteristics enumerated

\*From previous measurements of Yu. F. Ivanyuta and L. A. Chekalova.

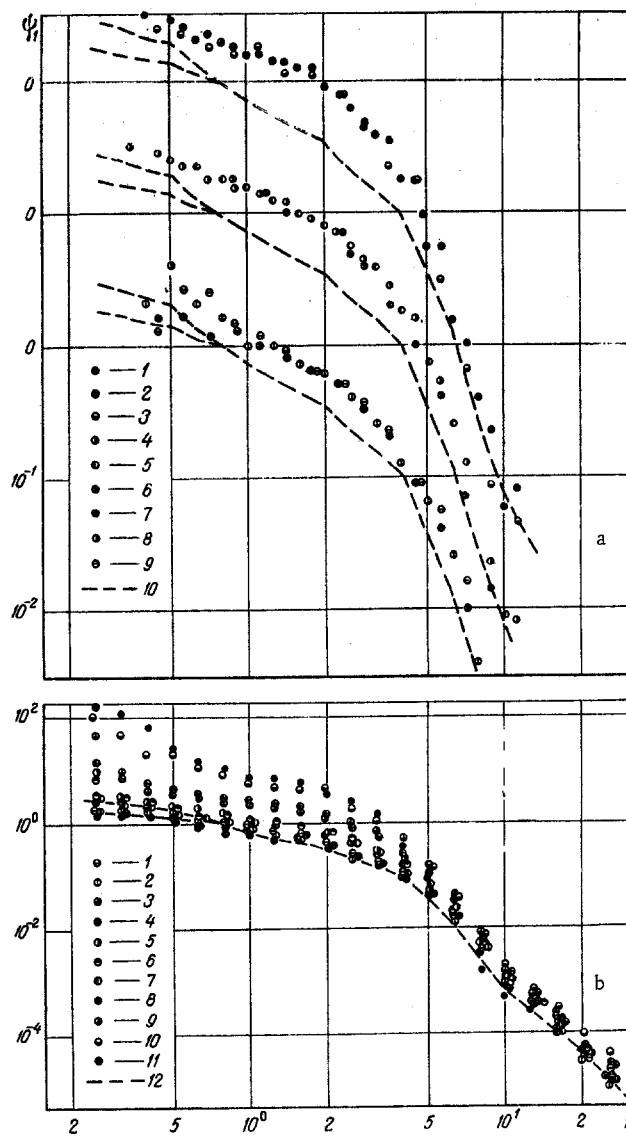


Fig. 3. Dependence of  $\psi_i$  on dimensionless frequency  $\tilde{f} = fr/U_{av}$ : a) guar gum: 1)  $U_{av} = 10$  m/sec,  $C = 4 \cdot 10^{-4}$ ; 2) 7 and  $4 \cdot 10^{-4}$ , respectively; 3) 4 and  $4 \cdot 10^{-4}$ ; 4) 10 and  $2 \cdot 10^{-4}$ ; 5) 7 and  $2 \cdot 10^{-4}$ ; 6) 4 and  $2 \cdot 10^{-4}$ ; 7) 10 and  $1 \cdot 10^{-4}$ ; 8) 7 and  $1 \cdot 10^{-4}$ ; 9) 4 and  $1 \cdot 10^{-4}$ ; 10) water; b) polyox;  $U_{av} = 7.05$  m/sec; 1)  $C = 1 \cdot 10^{-6}$  g/cm<sup>3</sup>,  $S = 22$ ; 2)  $5 \cdot 10^{-6}$  and 0.22, respectively; 3)  $1 \cdot 10^{-5}$  and 0.22; 4)  $2.5 \cdot 10^{-5}$  and 0.22; 5)  $1 \cdot 10^{-5}$  and 0.4; 6)  $2.5 \cdot 10^{-5}$  and 0.4; 7)  $1 \cdot 10^{-4}$  and 0.4; 8)  $1 \cdot 10^{-4}$  and 0.6; 9)  $10^{-5}$  and 0.6; 10)  $1 \cdot 10^{-4}$  and 0.765; 11)  $5 \cdot 10^{-4}$  and 0.81; 12) water.

above were measured in parallel in the work. The elapsed time from the start of the experiment was measured simultaneously. The average stream velocity (from the flow rate) and the shear stresses were measured with a bellows pulse pickup and a two-component pulse recorder, and the pressure pulsations were measured with piezoceramic pickups 1.3 mm in diameter. The latter were mounted in pairs along the generatrix of the tube flush with its surface. The spectral analysis and calibration of the pickups were conducted with a specially built instrument\* and an instrument of the Bruell and Kjar Company.

Solutions of polyoxyethylene (POE) and guar gum (GG) were tested. The latter were hardly degraded at all in the course of one experiment but were relatively ineffective. The POE solutions degraded

\*The instrument was designed and built by G. P. Morozov-Rostovskii and the piezopickups by A. L. Chernyshev.

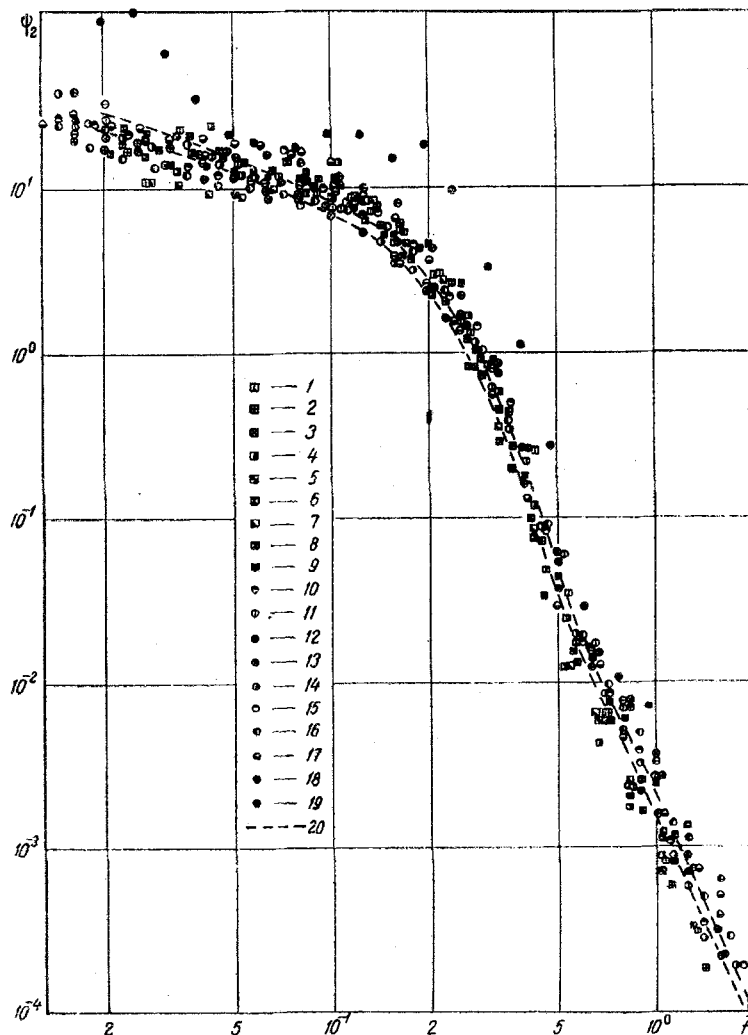


Fig. 4. Universal dependence of  $\psi_2 = P(f) / \tau^2 \delta * U_m^{-1}$  on dimensionless frequency  $\bar{f} = f \delta * / U_m$  for different effective polymer solution concentrations  $C_{ef}$ , g/cm<sup>3</sup>, starting with the following initial concentrations  $C_0$ , g/cm<sup>3</sup>, average stream velocities  $U_{av}$ , m/sec, and types of polymers: 1-9) guar gum; 1)  $C_0 = 1 \cdot 10^{-4}$ ,  $C_{ef} = 1 \cdot 10^{-4}$ ,  $U_{av} = 4$ ;  $S = 0.297$ ; 2)  $1 \cdot 10^{-4}$ ,  $1 \cdot 10^{-4}$ , 7, and 0.382, respectively; 3)  $1 \cdot 10^{-4}$ ,  $1 \cdot 10^{-4}$ , 10, and 0.403; 4)  $2 \cdot 10^{-4}$ ,  $2 \cdot 10^{-4}$ , 4, and 0.384; 5)  $2 \cdot 10^{-4}$ ,  $2 \cdot 10^{-4}$ , 7, and 0.486; 6)  $2 \cdot 10^{-4}$ ,  $2 \cdot 10^{-4}$ , 10, and 0.51; 7)  $4 \cdot 10^{-4}$ ,  $4 \cdot 10^{-4}$ , 4, and 0.404; 8)  $4 \cdot 10^{-4}$ ,  $4 \cdot 10^{-4}$ , 7, and 0.545; 9)  $4 \cdot 10^{-4}$ ,  $4 \cdot 10^{-4}$ , 10, and 0.582; 10-19) polyox; 10)  $C_0 = 1 \cdot 10^{-6}$ ;  $C_{ef} = 0.2 \cdot 10^{-6}$ ;  $U_{av} = 7.05$ ;  $S = 0.22$ ; 11)  $5 \cdot 10^{-6}$ ,  $0.2 \cdot 10^{-6}$ , 7.05, and 0.22, respectively; 12)  $1 \cdot 10^{-5}$ ,  $0.2 \cdot 10^{-6}$ , 7.05, and 0.22; 13)  $2.5 \cdot 10^{-5}$ ,  $0.2 \cdot 10^{-6}$ , 7.05, and 0.22; 14)  $1 \cdot 10^{-5}$ ,  $0.65 \cdot 10^{-6}$ , 7.05, and 0.4; 15)  $2.5 \cdot 10^{-5}$ ,  $0.65 \cdot 10^{-6}$ , 7.05, and 0.4; 16)  $1 \cdot 10^{-4}$ ,  $0.65 \cdot 10^{-6}$ , 7.05, and 0.4; 17)  $2.5 \cdot 10^{-5}$ ,  $2.5 \cdot 10^{-6}$ , 7.05, and 0.6; 18)  $1 \cdot 10^{-4}$ ,  $2.5 \cdot 10^{-6}$ , 7.05, and 0.6; 19)  $5 \cdot 10^{-4}$ ,  $10.6 \cdot 10^{-6}$ , 7.05, and 0.81; 20) water,  $U_{av} = 4, 7, 10$ .

rapidly but even a low concentration (on the order of  $10^{-5}$  g/cm<sup>3</sup>) was sufficient to obtain a fivefold reduction in the shear stress. The POE concentration in the experiments was varied from  $10^{-6}$  to  $5 \cdot 10^{-4}$  g/cm<sup>3</sup> and the GG concentration in the range from  $10^{-4}$  to  $4 \cdot 10^{-4}$  g/cm<sup>3</sup>. At the start of each measurement the tube was filled only with fresh solutions prepared no more than 0.5 h earlier. The reliability of the results obtained was tested by multiple repetitions of the measurements in the course of two months of work.

Control experiments were also conducted two years after the completion of the main series of measurements. The effect of degradation was studied using solutions of WSR-301 polyoxyethylene of different initial concentrations. The streams of these solutions moved in the instrument continually for several hours. The spectral analysis of the pulsations was conducted permanently and the variations in the shear stress and the time from the start of the experiment were recorded. Typical results of the experiment are presented in Fig. 2. The time for a single passage of the entire volume of the solution through the instrument at an average velocity of 7 m/sec was 70 sec. The nature of the variations in spectral pulsation levels during degradation is seen in Fig. 2b. It is seen first of all that the high-frequency pulsations are increased during degradation. Since the shear stresses also increase simultaneously it can be asserted that they are connected with the high-frequency pulsations, i. e., the fine boundary pulsations, in the stream. As for the low-frequency pulsations, as follows from Fig. 2, at first they are even reduced somewhat and only later, in the last stage of degradation, do they also increase. This result indicates the dominant role of boundary processes in all the phenomena in the shear flow of the solutions, particularly in the generation of turbulence. The changes in the low-frequency pulsations, the large-scale pulsations, are connected with a change in the entire flow. The magnitude of the changes is determined by the longitudinal gradient of the pulsation velocity and by the transverse gradient in the average velocity. The latter increases and does not decrease upon the introduction of polymer additions, hence the changes in the low-frequency pulsations are relatively small. The maximum changes in the high-frequency pulsations somewhat exceeded (by 2-3 dB) the maximum Toms effects in the experiment (81%). The maximum changes in the low-frequency pulsations corresponded to only a 30% decrease in the shear stresses. Total degradation of the polymer in the experiment could be achieved only at low polyoxyethylene concentrations. The time of total POE degradation from an initial concentration in the solution of  $2.5 \cdot 10^{-6}$  g/cm<sup>3</sup> was 130 min. In all cases the Toms effect also disappeared along with the disappearance of changes in the pulsations. When the Toms effect was saturated the changes in pulsations also ceased. To bring out more detailed connections between the average and pulsation parameters their dimensionless ratios were constructed. For this purpose complexes with the dimensionality of the spectral power density were constructed from the average characteristics, for example  $\tau^2 U_{av}^{-1} r$  or  $\tau^2 U_m^{-1} \delta^*$ . Two families of such ratios  $\psi_1 = P(f)/\tau^2 r R_{av}^{-1}$  as functions of the dimensionless frequency are presented in Fig. 3. One ratio is constructed from the data of measurements in POE solutions, the other in solutions of guar gum. The latter were used only to study the effect of the polymer concentration on the flow. It is curious that both these families are monoparametric. Only in the case of POE the parameter is  $S = \tau_w - \tau_p/\tau_w$ , the Toms effect, while in the case of GG it is the concentration. There were no other possibilities for putting the results in order. This state of affairs naturally made the study of the effect of the type of polymer on the flow more difficult. A way out of the difficulty was found through the introduction of the concept of the effective concentration in the degrading solution. This value was understood as the concentration of a fresh solution giving the same Toms effect as the given solution. If one considers another ratio  $\psi_2 = P(f)/\tau^2 U_m^{-1} \delta^*$ , one can propose a simple and unique equation for the value  $\psi_{2\text{polym}}/\psi_{2\text{water}}$  for the two polymers to take into account the effective concentrations ( $C_e$ ) of polymers in the solutions and the optimum concentration ( $C_{opt}$ ) providing for saturation of the Toms effect:

$$\lg \frac{\psi_{2p}}{\psi_{2w}} = \left( \frac{C_e}{C_{opt}} \right)^2 \lg \left( \frac{\bar{f}}{f_0} \frac{v_w}{v_p} \right).$$

With its help all the results can be approximately represented in the form of a single dependence (Fig. 4). This circumstance and the fact that  $\bar{f}_0 = f_0 \delta^*/U_m = 0.4$  is a constant which does not depend on the type of polymer indicate a mechanism unique in hydromechanics for the action of these two polymers on turbulent flow.

#### NOTATION

d	is the tube diameter of working channel, cm;
r	is the radius, cm;
$U_{av}$	is the average flow velocity, cm/sec;
$U_m$	is the maximum flow velocity;
$\nu_w$	is the viscosity of water;
$\nu_p$	is the viscosity of polymer solution;
$Re = U_{av}d/\nu_w$	is the Reynolds number;
$\delta^*$	is the thickness of displacement flow, cm;
$\tau_w, \tau_W$	are the shear stress at wall for water flow, dyn/cm <sup>2</sup> ;
$\tau_p, \tau_p^0$	are the shear stress at wall for flow of polymer solution, dyn/cm <sup>2</sup> ;

$S = \tau_w - \tau_p / \tau_w$	is the gain in resistance;
$C$	is the concentration of solution by weight;
$C_0, C_{init}$	are the initial concentration of solution, g/cm <sup>3</sup> ;
$C_e, C_{ef}$	are the effective concentration of solution, g/cm <sup>3</sup> ;
$C_{opt}$	is the optimum concentration of solution corresponding to maximum S;
$\overline{p^2}$	is the mean square pressure pulsation at wall;
$P(f)$	is the spectral power density of pressure pulsations, dyn <sup>2</sup> ·sec/cm <sup>4</sup> ;
$f$	is the frequency, 1/sec;
$t$	is the time from start of experiment, min;
$\psi_1 = P(\tilde{f}) / \tau^2 r U_{av}^{-1}$ ,	are the dimensionless ratios;
$\psi_2 = P(\tilde{f}) / \tau^2 \delta * U_m^{-1}$	
$\tilde{f} = fr / U_{av}, \bar{f} = f\delta * / U_m$	are the dimensionless frequencies.

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