EFFECT OF POLYMER ADDITIVES ON WALL TURBULENCE

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The average and fluctuation velocities associated with turbulent flow of a weak polyox solution in smooth and rough ducts have been investigated experimentally. The suppression of wall pressure fluctuations is discussed on the basis of the data obtained on the influence of polymer additives on the shear and transverse velocity fluctuations.

The influence of high-molecular polymer additives on the structure of a turbulent flow is important not only with regard to discerning the factors responsible for the reduction of the drag and heat-transfer coefficients, but also for explaining the diminution of wall pressure fluctuations and of the acoustical and hydrodynamical phenomena associated with them. It has been shown [1, 2] that polymer additives of the polyethylene oxide (polyox) type, which lower the frictional drag by 50 to 70%, also effectively suppress wall pressure fluctuations; remarkably, at high frequencies for a solution concentration of about $5 \cdot 10^{-5}$ to 10^{-4} the pressure fluctuations are diminished by 1/40 for motion along rough boundaries, by contrast with low frequencies, for which the pressure fluctuation reduction is inconsequential. It would be interesting to determine the possible nature of the action of polymer additives on wall pressure fluctuations on the basis of data pertaining to the influence of polymers on the kinematic characteristics of the flow.

The published data on the kinematic characteristics of flows of high-molecular solutions are somewhat conflicting. It is difficult to compare the results of these studies because of the dissimilar experimental conditions and the different polymers used. In fact, even for the same polymer under similar flow conditions the authors' conclusions regarding the transformation of the average-velocity profile are in

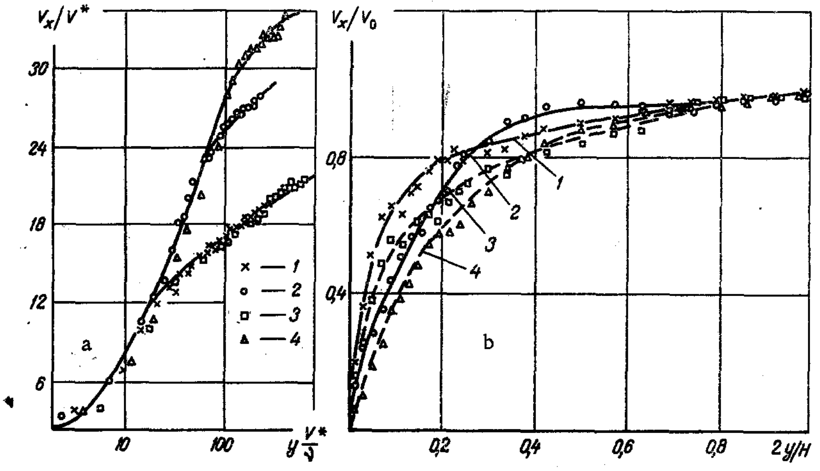

Fig. 1. Average-velocity profiles. a) In a smooth duct, dimensionless coordinates: 1) water, Re = 10^4; 2) polyox solution, Re = 10^4; 3) water, Re = $2.2 \cdot 10^4$; 4) polymer solution, Re = $2.2 \cdot 10^4$: b) In smooth and rough ducts, dimensionless coordinates, Re = 10^4: 1) smooth duct, water, V_0 = 122 cm/sec; 2) smooth duct, polyox solution, V_0 = 129 cm/sec; 3) rough-wall duct, water, V_0 = 124 cm/sec; 4) rough-wall duct, polymer solution, V_0 = 138 cm/sec.

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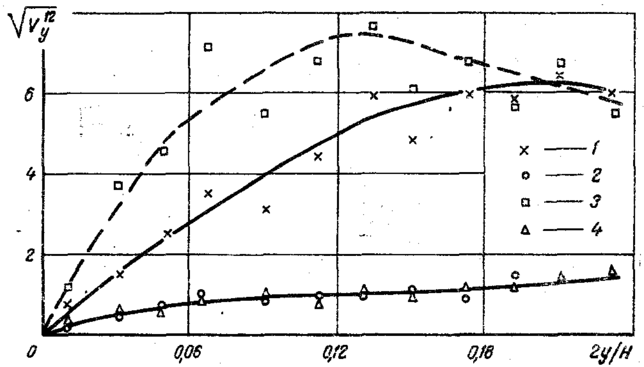

Fig. 2. Rms transverse velocity fluctuation (cm/sec) versus dimensionless coordinate for $\mathrm{Re} = 10^4$. 1) Smooth duct, water; 2) smooth duct, polyox solution; 3) rough duct, water, $kV^*/\nu = 21$; 4) rough duct, polymer solution, $kV^*/\nu = 12$.

diametric contradiction [3-6]. Inasmuch as the measurement of flow fluctuation characteristics poses a more difficult experimental problem than the measurement of the average variables, only extremely limited data are available on the influence of polymers on the fluctuation components of the velocity with allowance for wall roughness.

We have investigated the special characteristics of a turbulent flow of a polyox solution in a duct. For the investigation we used the method of stroboscopic flow visualization. Aluminum particles were used for visualization. The experiment was carried out in an open-loop system, whose test section was a rectangular duct with a cross section of 1×1 cm^2 and a length of 50 cm. A knife-edge light beam was used to illuminate the thin layer of water in the middle of the duct at a distance of 40 diameters from its entrance. The light beam was interrupted by a mechanical shutter, whose frequency was measured with an electronic strobe light.

A large number of motion picture frames were processed to obtain a set of values of the instantaneous velocities, which was then used to calculate the average velocities for the 26 strips into which the half-height of the duct was partitioned. The rms values of the fluctuations of the longitudinal and transverse velocity components were also calculated. These characteristics of the flow were determined for flows of water and the polymer solution with velocities of 100 and 220 cm/sec in ducts with smooth and rough walls. The concentration of the polymer solution was 10^{-4}, and the most probable grid size of the rough wall was $2.5 \cdot 10^{-2}$ cm. Our investigations of the kinematic flow characteristics in the rough duct were referred to the transient roughness regime for the pure water flow, whereas the flow conditions for the polymer solution were close to the regime of a hydraulically smooth wall.

Decomposition of the solutions did not take place in the course of the tests. In the case of motion along smooth walls the polymer additives lowered the frictional drag by 50%, and with roughness present they lowered it by 60%; similar results have been obtained in [7, 8].

Figure 1a shows how the average-velocity profile in a smooth duct is transformed with the introduction of polymer additives. The experimental profile for pure water is highly consistent with the universal profile represented by the solid curve. The profile for the polymer solution differs significantly; the wall zone is greatly expanded, the velocity at the boundary of the turbulent core is greater, and the points of the logarithmic profile are higher than for water. The upper boundary of the buffer zone is shifted from $yV^*/\nu = 30$ to 100 and 150, respectively, for flow velocities of 100 and 220 cm/sec.

For the further analysis of the influence of polymer additives on the pressure fluctuation spectrum it is practical to partition the height of the duct conditionally into three regions, in which it is required to estimate the variation of the shear with the addition of polymer to the solution. It is apparent in Fig. 1b that in the first region extending from the duct wall to $2y/H = 0.1$ the velocity gradient decreases by about 50% with the addition of polymer. In the region $0.1 < 2y/H < 0.4$ the velocity gradient is greater in the polymer solution flow than in the water flow. In the third region, which adjoins the duct axis, the flow profile for the polymer solution is flatter than for the water flow. Even though the magnitude of the velocity gradient in this region is difficult to determine because of its smallness, the tendency toward a reduction of shear with the addition of polymer is obvious. Figure 1b also gives the distribution of the average velocity over the duct cross section for a rough wall. The presence of roughness in the case of water causes the profile to become shallower and the velocity gradient near the wall to decrease [9]. The addition of polymer induces the same changes in the velocity distribution near a rough wall as in the smooth-wall case; the velocity gradient decreases at the wall and in the flow core, but increases in the intermediate region.

Our experimental procedure enabled us to measure the fluctuation components of the velocity. We found that the longitudinal fluctuations are only slightly reduced in a smooth duct by polymer additives, while the maximum in the distribution of the fluctuations over the duct cross section shifts at the same time away from the wall toward the core. On a rough wall the polymer elicits a sizable reduction of the longitudinal-component fluctuations, so that the rms longitudinal fluctuations in the smooth and rough ducts turn out to be the same for a polyox flow. The polymer additives have the strongest influence on the transverse velocity fluctuations. Figure 2 gives the distribution of the rms fluctuations of the transverse velocity component over the duct cross section. It is seen that the velocity fluctuations in the flow interior at $2y/H = 0.05$ to 0.2 decrease by 1/5 to 1/6 in the smooth duct and by 1/6 to 1/7 in the rough duct. The velocity fluctuations V_y' on the duct axis (flow core) in this case decrease by one half.

We now discuss the expected spectral suppression effects in application to the wall pressure fluctuations, using the data on the influence of polymer additives on the kinematic flow characteristics.

According to Kraichnan [10], pressure fluctuations determined by intersection of the turbulence-shear type are of the order $\rho(\partial V_x/\partial y)V_y' l$, whereas pressure fluctuations determined by interaction of the turbulence-turbulence type are of the order $\rho V_y'^2$. These approximate estimates are basically deduced from a dimensional analysis of the solution of the Poisson equation, which is well-known in the theory of incompressible Newtonian fluids and relates the velocity and pressure fluctuations:

$$\frac{\partial^2 P}{\partial x_i^2} = -2\rho\frac{\partial V_i}{\partial x_j}\cdot\frac{\partial V_j'}{\partial x_i} - \rho\frac{\partial^2}{\partial x_i \partial x_j}(V_i' V_j' - \overline{V_i' V_j'}).$$

It is assumed [11] that this equation is also valid for flows of low-concentration polymer solutions. Approximate estimates indicate that the variations of the pressure fluctuations under the influence of polymer additives are determined by the variations of V_y', $\partial V_x/\partial y$, and l. Our measurements did not enable us to ascertain the character of the influence of polymer additives on the value of l (longitudinal scale of V_y'). We know from the literature [5, 12], however, that polymer additives increase the longitudinal correlation of V_x' and $\partial V_x'/\partial x$, so that it is reasonable to expect polymer additives to induce a certain increase in the scale l.

In the boundary layer interior, which determines the high-frequency pressure fluctuations, the transport of vortices situated at a distance y from the wall gives rise to wall pressure fluctuations with a certain characteristic frequency of order V_x/y. Of all the kinematic flow parameters the one most conspicuously affected by polymer additives is V_y', and their influence is a maximum at the vortex in a layer situated at a distance $2y/H = 0.05$ to 0.2, where $V_x \simeq 0.5V_{av}$. We infer from this statement that polymer additives exert their greatest influence on the pressure fluctuations in the interval of dimensionless frequencies $\omega H/V_{av} \simeq 30$ to 120. At these frequencies the maximum net reduction of pressure fluctuations determined by turbulence-turbulence interaction is of the order $(V_{yp}'/V_{yw}') \approx 1/30$ to $1/50$. In the boundary layer interior the product $l\,\partial V_x/\partial y$ changes only slightly under the influence of polymer additives, so that the pressure fluctuations determined by a linear turbulent-shear mechanism cannot be reduced in this case more than in the ratio $V_{yp}'/V_{yw}' \approx 1/5$ to $1/7$. We note that in an experiment [1] using a similar polymer solution a reduction of the high-frequency pressure fluctuations by 1/20 to 1/40 was obtained for $\omega H/V_{av} = 70$. At high frequencies, therefore, the pressure fluctuations are determined by a nonlinear interaction of the turbulence–turbulence type.

Low-frequency pressure fluctuations ($\omega H/V_{av} \sim 2\pi$) are caused by turbulent flow in the central core of the flow. In the experiments of [1] the pressure fluctuations at these frequencies were not decreased by more than 2/3. It may be inferred from the present investigations that the low-frequency pressure fluctuations are determined by interaction of the turbulence-shear type. The level of these low-frequency pressure fluctuations depends on the magnitude of the shear. The curious fact is that polymer additives increase the shear in the interval $0.1 < 2y/H < 0.4$ and decrease it for $2y/H > 0.4$. A certain increase in the net reduction of fluctuations in the frequency interval $\omega H/V_{av} < 2\pi$ should be possible in this connection.

We note in conclusion that contradictory points of view have been advanced in studies of the Poisson equation [10, 13-15] with reference to the possibility of its linearization.

The results obtained here show that the predominance of a linear mechanism of the generation of pressure fluctuations in the flow core justifies the linearization of the indicated equation in the theoretical analysis of the properties of low-frequency pressure fluctuations.

NOTATION

V_x	is the average longitudinal velocity component;
V^*	is the dynamic velocity;
ν	is the kinematic viscosity of the medium;
y	is the distance from the duct wall;
H	is the duct height;
V_{av}	is the volumetric-average flow velocity;
V_0	is the flow velocity at the duct axis;
$Re = HV_{av}/\nu$	is the Reynolds number;
V'_y	is the fluctuation value of the transverse velocity component;
ρ	is the density of the medium;
l	is the longitudinal scale of V'_y;
ω	is the pressure fluctuation frequency;
k	is the most probable roughness grit diameter;
P	is the pressure fluctuation value.

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