TURBULENT STRUCTURE OF FLOWS WITH FRICTION-REDUCING ADDITIVES

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The mean-velocity and turbulence intensity profiles are measured in water flows containing additives of polymers and surface-active agents.

The most important area of investigation in relation to the structure of the velocity field of turbulent fluid flows in channels and boundary layers is the wall region, including the viscous sublayer and the transition zone. The maximum generation and dissipation of turbulent energy take place in this region. It is reasonable to expect that the effect of injecting turbulent fluid flow with high polymers or other additives tending to reduce turbulent friction will be felt primarily in the flow structure in the wall region.

The relative dimensions of the viscous sublayer and the transition zone are very small, making it virtually impossible to obtain reliable experimental data by means of total-head tubes or hot-wire anemometers. For this reason, the current practice in the study of turbulent structure in the wall region is to use contactless methods for measuring hydrodynamical quantities: the optical Doppler velocimeter (laser Doppler anemometry) method [1] and the stroboscopic method [2].

Khabakhpasheva and Perepelitsa [3, 4] have measured the profiles of the mean velocity and intensity of turbulence in dilute high-polymer solutions by stroboscopic visualization. They found that high-polymer additives increase the transition flow zone. The rms values of the longitudinal fluctuations, referred to the mean local velocity, remain practically unchanged in this case, and their normalization to the dynamic velocity even yields a certain increase in their relative values in comparison with pure water. On the other hand, the relative values of the transverse velocity fluctuations decrease significantly.

The results of laser anemometer measurements of the profiles of the mean velocity and longitudinal component of the eddy velocity in turbulent water flows with Metaupon additives are described in [5-7]. The additive is an industrial paste, the principal surfactant of which is β-[N-methyl N-olenoyl] ethylsulfonic acid sodium salt. It was found that Metaupon additives, in contrast with polymers, induce greater thickening of the transition flow zone and substantially reduce the relative values of the longitudinal velocity fluctuations in the wall region.

To determine the fundamental laws governing the reduction of turbulent friction by additives it is necessary to obtain more complete information about flows of micellar surfactant solutions and, most important, data on the turbulent characteristics of flows containing additives of pure surfactants. We have therefore carried out comprehensive studies of turbulent flows of aqueous solutions of chemically pure micellar surfactants, measuring the profiles of the mean velocity and intensities of the longitudinal and transverse components of the eddy velocity and then using the experimental data to calculate the rates of generation of turbulent energy and dissipation of average-flow energy. For comparison we have performed similar measurements in water flows containing high-polymer additives.

For the investigations we used a Disa Elektronik (Denmark) type 55L optical Doppler velocimeter (laser anemometer). The hydrodynamic characteristics were determined in a rectangular channel with dimensions $(2 \times 5) \cdot 10^{-2}$ m at a distance of 150 widths from the nozzle. In the measurements of the mean velocity and intensity of the longitudinal fluctuations the probe beams were situated in a horizontal plane. For the determination of the intensity of the transverse velocity fluctuations the plane of the probe beams was rotated 90° about the optic axis of the velocimeter. As a result of this orientation of the probe beams the minimum attainable distance from the wall was $y^+ \approx 18$.

The additives used to reduce the turbulent friction of the water were a polymer (polyacrylamide with a molecular mass $M \approx 2 \cdot 10^6$) and chemically pure micellar surfactants (potassium oleate and a mixture of cetylpyridinium chloride with α-naphthol). It is well known [6] that the majority of micellar surfactants diminish the turbulent friction of water only in the presence of electrolytes. Also, the concentration of the surfactant

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in the solution must be greater than the second critical concentration for micelle formation, viz. for the formation of anisometric micelles [7, 8]. The appropriate concentrations of surfactants and electrolytes were chosen on the basis of these requirements. In the experiments we used aqueous solutions of potassium oleate with a concentration $C = 0.08\%$ in the presence of 5.2% potassium chloride, as well as a mixture of cetylpyridinium chloride $C = 0.08\%$ with α-naphthol $C = 0.04\%$, which reduces the turbulent friction of water without electrolyte additives; the concentration of polyacrylamide was $C = 0.01\%$.

In the coordinate system used for processing and analysis of the experimental data the axis OX was directed along the axis of the channel, the axis OY was perpendicular to the flow direction, and the origin was situated in the lower plane of the channel.

The dimensioned mean-velocity profiles in water and in aqueous solutions of polyacrylamide and potassium oleate, measured for a constant nozzle velocity $U_n = 1.57$ m/sec, are shown in Fig. 1. It is seen that in the additive flows (as compared with pure water) a decrease of the mean-velocity gradients is observed in the wall flow region ($y < 3.5 \cdot 10^{-3}$ m). In the region $y > 3.5 \cdot 10^{-3}$ m the mean-velocity gradients in the solutions are greater than in pure water. The deformation of the velocity profile is stronger in the potassium oleate solution, its distribution in the flow cross section approaching a parabolic function.

The reduction of turbulent friction in the additive flows is accompanied by broadening of the transition flow region and a decrease in the relative dimensions of the turbulent core. This effect is particularly conspicuous in Fig. 2, which shows the mean-velocity profiles in universal coordinates (the dimensionless coordinate $y^+ = yU_*/\nu$ is referred to the viscosity of the solutions). In micellar surfactant solutions, unlike polymers, the turbulent core region of the flow is practically nonexistent, and the velocity profiles in the transition region vary much more abruptly, approaching the curve for laminar flow of a Newtonian fluid. We note that a similar distribution of the velocity profiles can also be realized for polymer solutions in a channel of small cross section and for a sufficient reduction of the hydrodynamic friction [4].

It is inferred from a comparison of curves 2 and 5 for flows of aqueous solutions of potassium oleate that for lower flow velocities additives of a micellar surfactant exert a stronger laminarizing effect on the overall flow.

Figure 3 shows the rms values of the velocity fluctuations, normalized to the dynamic velocity. It is seen that in the micellar surfactant solutions both the longitudinal and the transverse velocity fluctuations exhibit a reduction in their intensity, more so in the case of the transverse component. The greatest reduction of the velocity fluctuation intensities occurs in the solution of the cetylpyridinium chloride + α-naphthol mixture. In this case the intensity distribution of the velocity fluctuations for the micellar surfactant solutions does not have the distinct maxima typical of Newtonian fluid flows.

In the polyacrylamide solution we observe a somewhat different pattern. The relative values of the longitudinal velocity fluctuations are higher on the average than in water, consistent with the results of [3, 4]. Clearly, the difference in the behavior of the intensity of the velocity fluctuations in the polymer and micellar surfactant solutions is attributable to the characteristics of the molecular and supermolecular structures of the solute. In particular, micellar surfactants are capable of forming in solution not only kinetically independent molecular aggregates, i.e., micelles, but also spatial micellar structures. The specific characteristics of the viscosity variation of the polymer and micellar surfactant solutions can also have a definite influence. For the polyacrylamide solution with $C = 0.01\%$ the viscosity scarcely differs from the viscosity of pure water and is practically independent of the shear stress. The viscosity of micellar surfactant solutions, in turn, is much greater and decreases as the shear stress is increased. These problems will certainly require further study.

It is inferred on the basis of the measurements of the turbulence velocity and intensity profiles that additives of micellar surfactants exert a much stronger laminarizing effect than polymer additives on the overall flow under equal hydrodynamic conditions.

It is generally known that the structure of any turbulent flow is characterized by local equilibrium of the processes of generation, transport, and dissipation of turbulent kinetic energy. If, as in the case of a Newtonian fluid, the friction in turbulent flow with additives is written in the form

$$\tau = \tau_w(1 - y/H) = \rho\nu \frac{dU}{dy} - \rho\,\overline{uv}$$

and the expressions for the rates of direct dissipation of average-flow energy D and generation of turbulent energy P are written in the form

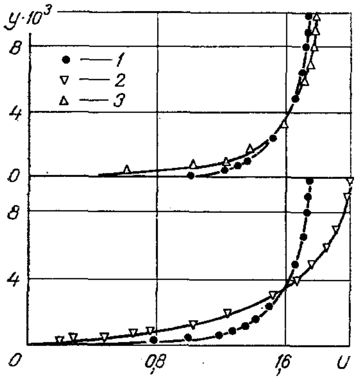

Fig. 1. Mean-velocity profiles: U (m/sec) vs. y (m), for $U_n = 1.57$ m/sec in water (1) and in aqueous solutions of potassium oleate (2) and polyacrylamide (3). 1) $U_* = 0.08$ m/sec; 2) $U_* = 0.04$ m/sec; $\lambda_s/\lambda_0 = 0.192$; 3) $U_* = 0.064$ m/sec, $\lambda_s/\lambda_0 = 0.628$.

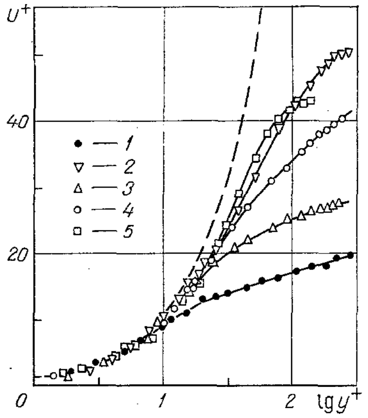

Fig. 2

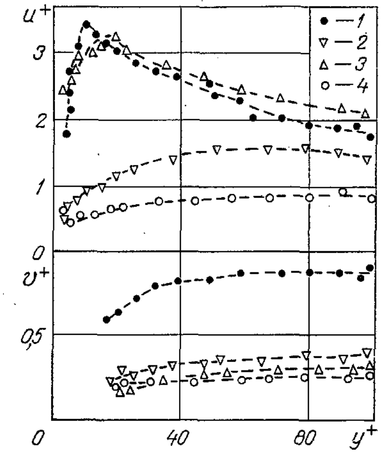

Fig. 3

Fig. 2. Universal flow-velocity profiles in water (1) and in aqueous solutions of potassium oleate (2, 5), polyacrylamide (3), and a mixture of cetylpyridinium chloride with α-naphthol (4). 1-3) Same parameters as in Fig. 1; 4) $U_n = 1.5$ m/sec, $U_* = 0.046$ m/sec, $\lambda_s/\lambda_0 = 0.34$; 5) $U_n = 0.59$ m/sec, $U_* = 0.0187$ m/sec, $\lambda_s/\lambda_0 = 0.29$.

Fig. 3. Relative rms values of the longitudinal and transverse velocity fluctuations (same nomenclature as in Fig. 2).

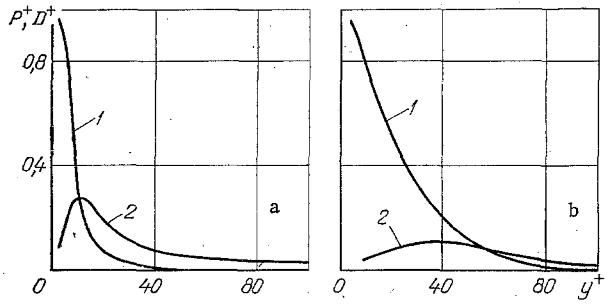

Fig. 4. Rates of dissipation of average-flow energy P^+ (1) and generation of turbulent energy D^+ (2) versus dimensionless coordinate y^+ for $U_* = 0.0187$ m/sec, $U_n = 0.59$ m/sec. a) Water; b) potassium oleate solution.

$$D = \rho\nu\left(\frac{dU}{dy}\right)^2, \quad P = \rho\,\overline{uv}\,\frac{dU}{dy},$$

then from the measured velocity profiles we can calculate the values of D and P. The results of the calculations are best analyzed on the basis of the dimensionless rates of dissipation of average-flow energy $D^+ = \nu D/\rho U^4_*$ and generation of turbulent energy $P^+ = \nu P/\rho U^4_*$.

Figure 4a shows the variation of the quantities D^+ and P^+ along the normal to the wall in a water flow. It is seen that near the wall ($y^+ < 10$) the bulk of the flow energy is used up in viscous dissipation directly from the average flow. The relative generation of turbulent energy in this region is small. It attains a maximum and equalizes with the direct viscous dissipation at a coordinate $y^+ \simeq 11$. In this case the direct dissipation of average-flow energy occurs mainly in a very thin wall region $0 < y^+ < 30$.

Figure 4b shows the values of D^+ and P^+ for an aqueous solution of potassium oleate. It follows from a comparison of the data in Figs. 4a and 4b that the micellar surfactant additives have a stronger influence on the ratio between the generation of turbulent energy P^+ and the dissipation of average-flow energy D^+ as well as on the distribution of these quantities in the flow cross section. Above all, the rate of direct dissipation increases, apparently due to an increase in the molecular viscosity. Here the viscous dissipation effect propagates to large distances, attaining $y^+ \simeq 90$ (in comparison with $y^+ = 30$-40 for pure water). Moreover, the maximum in the distribution of the rate of generation of turbulent energy becomes more diffuse and shifts toward larger values of y^+, and equilibrium between the viscous dissipation and generation of turbulent energy is observed already at $y^+ = 60$ (in comparison with $y^+ \simeq 11$ for pure water).

The results presented in this article indicate that additives capable of reducing turbulent friction (high-molecular-weight polymers and surface-active agents) exert a significant influence on the flow structure in the wall region.

NOTATION

U, local average velocity, m/sec; u, v, longitudinal and transverse components of the eddy velocity, m/sec; U_*, dynamic velocity, m/sec; τ_w, tangential stress at the wall, N/m^2; τ, local tangential stress, N/m^2; $\rho\overline{uv}$, turbulent tangential stress, N/m^2; y, distance along the normal from the wall, m; ρ, fluid density, kg/m^3; ν, kinematic viscosity, m^2/sec; D, rate of dissipation of average-flow energy, J/m^3 · sec; P, rate of generation of turbulent energy, J/m^3 · sec; C, concentration, %; U_n, nozzle velocity, m/sec; λ_s, λ_0, coefficients of hydrodynamic friction in flow of the solution and the solvent (water), respectively; H, half-height of the channel, m.

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