VELOCITY AND TURBULENT FLUCTUATION FIELDS IN WATER CONTAINING LOW CONCENTRATIONS OF HIGH-MOLECULAR SUBSTANCES

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The stroboscopic visualization method has been used to measure velocity profiles and RMS values of the longitudinal and transverse components of the velocity fluctuations in weak solutions of DNA.

Numerous investigations have shown that when small quantities (hundredths or thousandths of a percent) of certain high-molecular substances are dissolved in water the friction drag in a turbulent flow is considerably reduced. The reasons for this are not yet clear and various hypotheses, based on the assumption that the solutions possess elastic properties, have been proposed. In 1965–1966 the velocity fields were investigated in weak solutions of polyvinyl oxide, carboxymethyl cellulose (CMC), and guar gum. Wells [1] concluded that as the concentration of guar gum rises the slope of the logarithmic velocity profile increases considerably and the viscous sublayer grows thicker. In their experiments Ernst [2] and Elata [3] established that in the case of weak solutions the turbulence constant remains the same as for ordinary liquids. According to [3], the thickness of the viscous sublayer in guar gum solutions increases as the concentration rises to 0.3%. A further increase in concentration led to a diminution of this effect. In all cases Pitot tubes were used to measure the velocities. However, with Pitot tubes it is not possible to measure the velocities in the immediate vicinity of the walls. Accordingly, in the experiments the dimensions of the regions of viscous flow were found by extrapolating the velocity profile measured in the turbulent core to intersect the linear velocity profile in the viscous sublayer.

In the case of non-Newtonian liquids Pitot tubes have an additional serious disadvantage: if motion (shear) of the liquid is accompanied by the development of normal stresses, a Pitot tube in the flow measures the difference between the total pressure and the sum of the static pressure and the normal stress. The results of such measurements are difficult to analyze.

To investigate the velocity fields in DNA (desoxyribonucleic acid) and CMC solutions at low concentrations, we used an electronic stroboscope developed in the Hydrodynamic Research Laboratory [4]. Using this instrument we obtained average velocity profiles in all regions of the flow, including the viscous sublayer, together with RMS values of the longitudinal and transverse components of the velocity fluctuations as a function of the distance from the wall.

The velocity field measurements were made in rectangular channels with cross sections measuring 5×10 mm and 10×10 mm, the length of the channels being 750 mm. The solution was circulated with a centrifugal pump. A tube-in-tube type cooler was used to keep the temperature of the solution constant during the experiment.

The quality of the DNA was determined from the hyperchromic effect—the increase in ultraviolet absorption of denatured DNA solutions. The hyperchromic effect and viscosity of both fresh and used DNA solutions were measured. In the first series of experiments (upper points in Fig. 1) the viscosities of the initial and used solutions were practically the same, while in the second series of experiments the difference was 4–5%. In these series the hyperchromic effect differed by 6–8%. In all the experiments the concentration of the DNA solutions was from 100 to 200 parts per million. The viscosity of these solutions measured with a capillary viscometer, exceeds that of water by 20–30%.

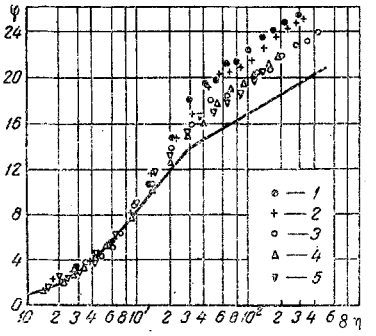

Fig. 1. Velocity profiles in dimensionless coordinates: 1) Re = 17 000; 2) 16 000; 3) 25 000; 4) 11 000 (channel cross section 5×10 mm); 5) Re = 11 000 (channel 10×10 mm). Solid curve—universal velocity profile.

Since the DNA molecules may be mechanically destroyed by the shear stresses, the experiments lasted 10–12 min.

For flow visualization purposes, reflecting aluminum particles 2–10 μ in diameter were introduced into the solutions.

A series of three stroboscope flashes produced tracks on each frame in the form of three successive images of the particles within the light beam. At the same time, an image of the luminous bottom of the channel was obtained, which was required to determine the transverse coordinate of the particle entering the frame.

The films were analyzed on a PUOS-1 apparatus; the mean values of the longitudinal and transverse velocity components and the RMS values of the fluctua-

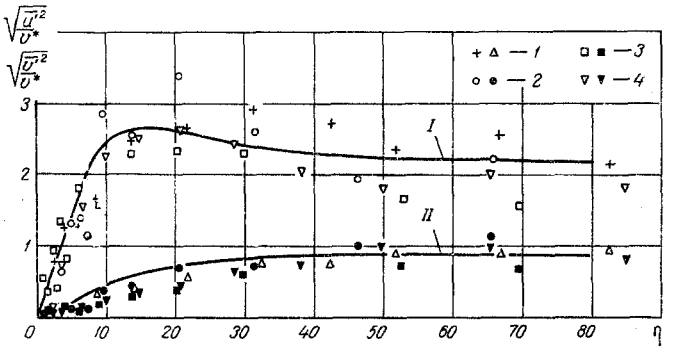

Fig. 2. Relative RMS values of the longitudinal (I) and transverse (II) fluctuations of the velocity vector: 1) Re = 17 000; 2) 25 000; 3) 11 000 (channel cross section 5 × 10 mm); 4) 11 000 (channel 10 × 10 mm). Solid curve—Laufer's data [5].

tions were calculated on an M-20 electronic computer. Up to 1500 tracks were measured and analyzed for each flow regime in a strip about 2.5 mm deep. This strip was divided into 20 vertical intervals, so that 6–8 intervals corresponded to the viscous sublayer. From the velocity profiles obtained we determined the velocity gradient in the viscous sublayer and calculated the shear stress at the wall.

The agreement between the mean velocity profiles obtained for a flow of water and a 30% solution of glycerin in water and the universal velocity profile served as a check on the method employed.

In Fig. 1 the mean velocity profiles measured for the DNA solutions are presented in dimensionless coordinates. The measurements embrace the entire region of turbulent flow from the viscous sublayer to the center of the channel. It is clear from the figure that for all the DNA solutions the points lie above the universal velocity profile characteristic of ordinary liquids (continuous curve), while the slope of the logarithmic profile remains practically unchanged. This indicates that a drag reduction is observed for all the solutions investigated.

A calculation of the resistance coefficient from the measured velocity profiles showed that for the points located furthest from the universal profile the drag reduction in a circular tube is 40%. For solutions of DNA of the lowest quality the drag reduction is somewhat less. These data are consistent with measurements of the pressure drop and pump power.

In the intermediate region the velocity profiles are steeper than for ordinary liquids. This indicates that adding a high-molecular polymer impedes the development of turbulence and displaces the region of developed turbulent flow somewhat further from the walls.

In Fig. 2 the RMS values of the longitudinal and transverse components of the velocity fluctuations are shown as a function of the distance from the wall. The solid curves represent the analogous data obtained by Laufer in air [5] and by the authors in water. It is clear from the graph that the magnitude and distribution of the longitudinal component do not differ from the corresponding characteristics of ordinary liquids. At the same time, the transverse component is significantly reduced near the wall. Similar, but weaker effects were obtained with CMC solutions at concentrations up to 0.13% by weight.

NOTATION

$\varphi = v_x/v^*$ is the dimensionless velocity; $\eta = yv^*/\nu$ is the dimensionless coordinate; u' and v' are the longitudinal and transverse fluctuation components of the velocity vector; v^* is the shear rate at wall; Re is the Reynolds number.

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