EFFECT OF HIGH-MOLECULAR FORMATIONS ON TURBULENCE IN DILUTE POLYMER SOLUTIONS

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The marked reduction of hydrodynamic resistance with addition of certain soluble high polymers to a liquid, discovered by Toms in 1948 [1], later attracted considerable attention by researchers. The Toms effect is observed both under conditions of the internal problem (flow in pipes) and the external problem (flow past bodies). The Toms phenomenon was discovered using a solution of polymethyl methacrylate in monochlorobenzene. Later many experiments were made in aqueous solutions of the sodium salt of carboxymethylcellulose with a molecular weight of about 70,000, where a marked effect was obtained with concentrations of order $10^{-4}$. Attention to this effect increased sharply after it was found (apparently first published by Hoyt and Fabula [2]) that there are far more effective polymers, such as polyoxyethylene; the addition of a few dozen parts per million permits reduction of hydrodynamic frictional resistance in pipe flow by about a factor of three.

To date no explanation or description of the phenomenon exist which give an exhaustive qualitative and quantitative physical picture. Various authors have proposed several hypotheses to explain the phenomenon. In particular, in [3, 4] the hypothesis was suggested that the Toms effect may be associated with formation in the solution of comparatively rigid clumps of matter (fibers, globules) as a result of immobilization of a portion of the solvent by the polymer molecules. The dimension of such "associations" of polymer macromolecules and solvent molecules must be, at the least, no less than the Kolmogorov turbulence scale, since only in this case can we assume that an effect of the associations on the turbulent flow develops. It should be noted that the rigidity of the associations resulting from their viscoelasticity apparently increases with increase of the pulsation frequency, i.e., with the deformation rate.

This hypothesis is supported by experiments with suspensions of fibers and sawdust in a liquid, in which it was established that the addition of nylon fibers or sawdust with a concentration of about one percent by volume leads to a marked reduction of the frictional resistance.

In concentrated solutions of polymers which reduce the friction, such as the solution of the sodium salt of carboxymethylcellulose (CMC) in water, particles were detected both visually and indirectly, by the slowing down of filtration. The present paper presents data obtained in experiments with very dilute solutions of polymers such as polyoxyethylene and guar gum. These data also support the hypothesis of the effect of high molecular formations on turbulence and resistance reduction.

§1. In the experiments we used aqueous solutions of polyoxyethylene with a molecular weight of three to four million and guar gum. It is known that these polymer solutions show a reduction of the hydrodynamic frictional resistance in flow past solid walls. This is indicated, in particular, by the data obtained in measurements of the torque developed during rotation of a disk in a housing filled with the test liquid.

In the test setup the disk had a diameter of 14 cm and thickness 3 mm. The gap between the housing and disk was 1.4 mm. In the experiment the test liquid was temperature controlled by water supplied from a thermostat and flowing around the housing. This eliminated variation of the torque resulting from viscosity change with temperature variation. A variable speed electric motor was used for the drive. The rotational speed was held constant in the course of the tests.

![Fig. 1](image)

The reduction of the hydrodynamic resistance with addition of various amounts of the polymer to water is shown by the data presented in Figs. 1 and 2. In Fig. 1, the quantity $M^* = (M_0 - M)/M_0$ is plotted along the ordinate axis; here $M_0$ is the torque for pure water, and $M$ is the torque using the polyoxyethylene solution. The weight concentration $c$ of the polymer in the solution is plotted along the abscissa axis. The data were obtained at a rotational speed of 3000 rpm. The magnitude of the torque obtained using the polyoxyethylene solution is not constant; it increases during the process of disk rotation (solution degradation). The values in Fig. 1 relate to the initial torque. Figure 2 shows similar data for guar gum. The magnitude of the torque obtained using the guar gum solution also increases with disk rotation time; however, the rate of rise is considerably less than that observed in the polyoxyethylene solutions. (Degradation of the CMC solutions was not noted.)

The nature of the curves of Figs. 1 and 2 is similar to the nature of the variation of the hydrodynamic frictional resistance in pipes as a function of dilute polymer concentration in the study of Hoyt [6]. The only difference is in the magnitude of the effect, which in small tubes of millimeter diameter reaches 80 percent. The magnitude of the drag reduction increases with increase of the disk rotational speed.

§2. As mentioned previously, a plausible explanation for the effect of diluted polymers on turbulence is given by the idea of the formation in the solutions of large associations of polymer macromolecules and solvent macromolecules, which behave like solid particles with respect to high frequency pulsations. Such particles have been noted previously [3, 4] in aqueous solutions of the sodium salt of the carboxymethylcellulose (CMC) polymer, which shows the resistance reduction effect for comparatively large concentrations. These are elongated fibrillar structures, which are to some degree saturated with water. The structures which are weakly saturated with water can be...
seen under a microscope in polarized light. In strongly diluted solutions they are so saturated with the solvent that they cannot be detected visually. However, the presence of the particles in the solution may be established from the retarded filtration of the solution.

The guar gum dissolves like the CMC; individual bits of the dry polymer soak up water, swell, and propagate throughout the entire liquid volume. Some particles can be observed visually in the solution. However, we must consider that, just as in the CMC solutions, we can see only those particles which are weakly saturated with water, and not all the particles. On the average, the dimension of the visible formations is 60 microns.

The dissolution of polyoxyethylene in water differs from that of guar gum and CMC. First the dry particles of polyoxyethylene are also impregnated with water; then they disperse and occupy the entire volume. The solution, if its concentration is not too low, acquires elastic properties: it is possible to draw out quite long fibers from the solution. In the elongation process droplets of solvent separate from the fibers. This indicates that a dense network occupying the entire volume develops in polyoxyethylene solutions.

Elasticity is also observed in highly diluted polyoxyethylene solutions with weight concentration of the order $10^{-5}$, if these solutions are prepared by dilution of sufficiently highly concentrated solutions. But this state rapidly disappears in the diluted solutions. After some storage time the network breaks down, and the solution loses the elastic properties. The network breakdown occurs particularly rapidly in shear flow. After loss of the elastic properties the solution becomes such that it cannot be differentiated superficially from ordinary water. However, it is precisely in this state that quite rigid particles appear in the polyoxyethylene solutions, which can be detected when calibrating total pressure tubes (Pitot tubes).

As noted previously by several investigators [7], the indications of total head tubes placed in the polyoxyethylene solution flow are considerably lower than they should be. This anomalous behavior of total pressure tubes was observed during measurements of the velocity profile in a pipe and was related with the appearance of additional normal stresses in the shear flow. But experiments showed that these same anomalies are also observed in a flow with uniform velocity profile.

The total head tubes were mounted in the potential core of the jet issuing from a calibrated nozzle. The tube tests were conducted with a constant discharge velocity of 5 m/sec. The discharge velocity was controlled by the pressure ahead of the nozzle. This pressure was measured by a piezometric tube, whose indications were verified by the values of the flow rate measured by the volumetric method. Total head tubes with internal diameters of 2.0, 1.4, 0.6, 0.5, 0.4, 0.3, 0.2 were used. All the total head tubes tested gave low indications during the initial period of solution motion. For example, the tube with 0.2-mm diameter indicated 90 cm H$_2$O for polyoxyethylene solution flow with concentration $10^{-4}$ rather than the velocity head of 127.5 cm H$_2$O.

In the course of time the difference between the real existing velocity head and the Pitot tube indications decreases, and, finally, the difference disappears. The time from flow initiation to the appearance of normal indications is shorter the larger the tube diameter. Figure 3 shows the curve of the variation of this time $t$ (min) as a function of the Pitot tube internal diameter d (mm), recorded for a polyoxyethylene solution with weight concentration $5 \cdot 10^{-4}$.

The discrepancy between the indications of the Pitot tube and the actual existing head may arise for several reasons. This discrepancy can be observed in homogeneous liquids: in a Bingham liquid as a result of the initial shear stress, in a viscoelastic liquid because of the additional normal stresses. However, these explanations are not valid in the case being considered here. There is no initial shear stress in the polyoxyethylene solutions, which can be seen from the fact that the liquid column in the piezometer returns to the initial position of the total head tube is removed from the flow. The explanation associated with the viscoelastic properties of the liquid is not applicable, since a dependence of the indications on the Pitot tube diameter is observed in the experiment. For the same reason we must reject the explanation for the low indications of the tubes which is based on expansion of the polyoxyethylene solution jet as it leaves the nozzle because of its viscoelastic properties.

It appears to us that the explanation for the observed phenomenon is that the polyoxyethylene solution ceases to be a homogeneous liquid after the motion is initiated, and particles which are quite strong mechanically develop in the solution; then these particles in some way (i.e., individually or possibly in groups) shield the tube entrance from the approaching flow. This leads to a reduction of the tube readings in comparison with the total head magnitude. Shielding of the Pitot tube opening can be observed only in the case when the particle dimension is comparable with the tube diameter. The gradual approach of the Pitot tube indications to the value of the total head (Fig. 3) also indicates fractionation of the associations in the flow process.

The continuous network which forms in polyoxyethylene solutions cannot exist for long. It breaks down and transitions into thicker and more stable networks of individual "associates." This process is accelerated considerably in a shear flow under the