FLOW OF DILUTE POLYMER SOLUTIONS ALONG TUBING AND AROUND AN ENCLOSED DISC

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Measured results are presented for the hydrodynamic drag arising in the flow of water containing small amounts of polyoxyethylene or guar gum.

The hydrodynamic drag of aqueous solutions of the polyoxyethylene Polyox WSR-301 and of the guar gum J2-FP was investigated. The experiments were performed with two devices. One of them was built for the measurement of the hydrodynamic drag created in the flow around a smooth disc which rotated in a case, and the other, for the measurement of drag in a thin, smooth tube.

To rotate the case, a constant-current motor was used with an electromagnetic amplifier in a feedback circuit which made it possible to maintain a fixed rate of rotation even when there was a varying load moment on the rotor shaft. The rotations of the motor were measured by a photoelectric sensor connected to a digital frequency meter. The drive made it possible to maintain a given rate of rotation over the range 40 to 2600 rpm with 1% accuracy. The error in the measurement of rotations was no more than 0.5%. The moment of the hydrodynamic drag force was calculated from a measured force on a known arm. The magnitude of the force was measured by a capacity sensor with auxiliary equipment from the DISA company and recorded with a self-recording potentiometer. The construction of the sensor made it possible to

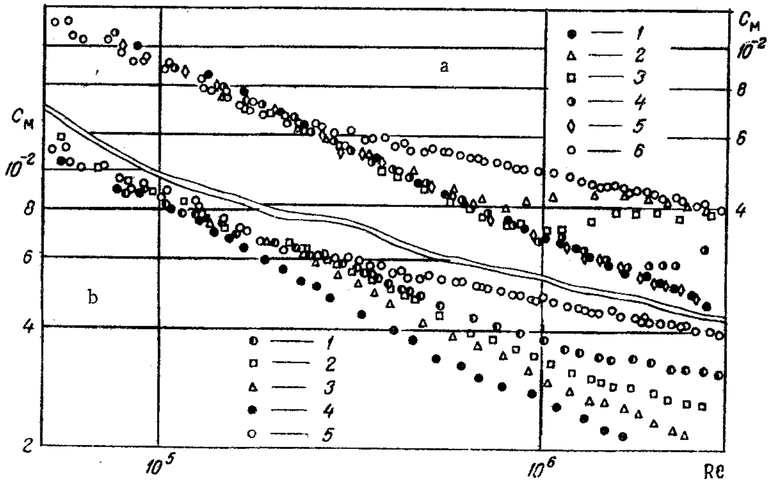

Fig. 1. Dependence of torque drag coefficient for a disc in a case on Reynolds number for (a) polyoxyethylene solutions of varying concentrations [1) $c = 2.5 \cdot 10^{-5}$; 2) $0.5 \cdot 10^{-6}$; 3) 10^{-6}; 4) $3 \cdot 10^{-6}$; 5) 10^{-5}; 6) water] and (b) guar gum solutions of varying concentrations [1) $c = 5 \cdot 10^{-5}$; 2) 10^{-4}; 3) $2 \cdot 10^{-4}$; 4) $5 \cdot 10^{-4}$; 5) water].

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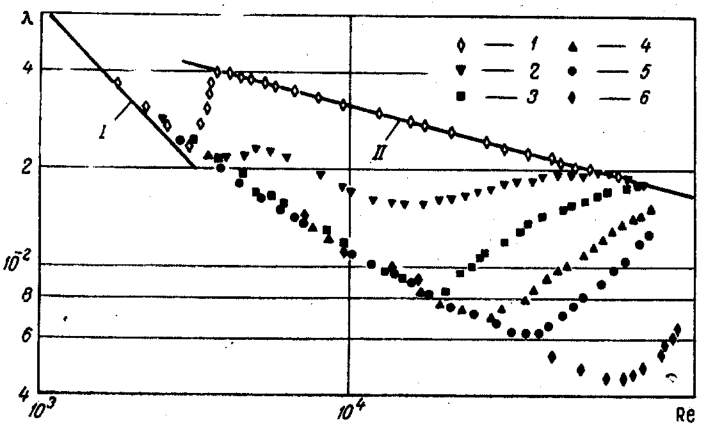

Fig. 2. Dependence of drag coefficient on Reynolds number for flow of polyoxyethylene solutions along tubing with d = 3 mm, unshaped entrance, and an initial section 60d long. 1) water; 2) $c = 10^{-6}$; 3) $2.5 \cdot 10^{-6}$; 4) $5 \cdot 10^{-6}$; 5) 10^{-5}; 6) $3 \cdot 10^{-5}$; I) $\lambda = 64/\mathrm{Re}$; II) $\lambda = 0.3164/\mathrm{Re}^{0.25}$.

change its sensitivity by replacement of an elastic plate. The minimum force increment recorded by such a system was 2-3 g. The basic dimensions of the device are: disc radius r = 10.5 cm; internal radius of the case, 11.5 cm; disc thickness, 0.4 cm; gap between disc and case, 0.6 cm.

The flow in tubing was crated by means of an expulsion device. Air pressure supplied from compressors could reach 18 atm. The internal diameter of the tubing was d = 3 mm. The portion in which the pressure drop was measured had a length of 30d. The tubing length from the measuring portion to the end of the tubing was 20d. Depending on the experiment, the tubing either ahd sharp edges at the entrance or was shaped for ~1.5d from the entrance. In both cases the initial section of the tubing was in the plane of the internal wall of the pressure tank. A regulating valve was located at the end of the tubing. The average velocity could reach $\bar{u} = 30$ m/sec. Flow was measured by the volume method with automatic measurement of flow time into a tared container. The accuracy of the time measurement was 0.01 sec. The pressure drop in the measuring section was recorded by means of two liquid differential manometers with a scale length of 200 cm. Mercury and carbon tetrachloride were used as working fluids in the manometers. Either manometer could be connected to the measuring section during an experiment. This provided a measurement of pressure loss from 2 cm to 25 m of water. Measurement error was no more than 1%.

Polyoxyethylene solutions were prepared by mixing the dry powder with water or by dilution of a concentrated solution no more than two hours before an experiment. The guar gum solutions were held for

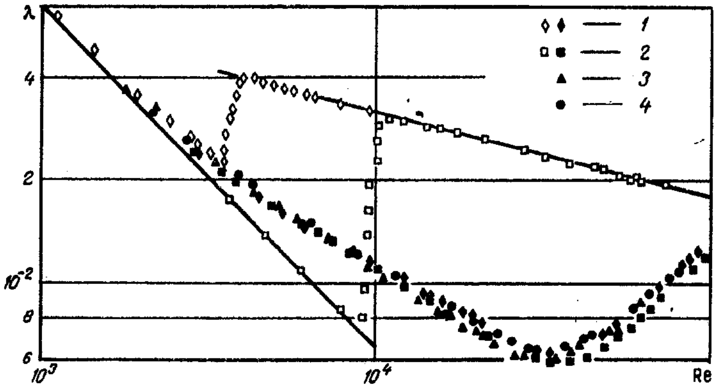

Fig. 3. Dependence of drag coefficient on Reynolds number for a polyoxyethylene solution at a concentration $c = 10^{-5}$ in tubing with d = 3 mm and various entrance conditions: 1) unshaped entrance, initial portion 60d; 2, 3, 4) shaped entrance, initial portions 185d, 275d, and 335d respectively. Solid symbols refer to polymer solution, open symbols to water.

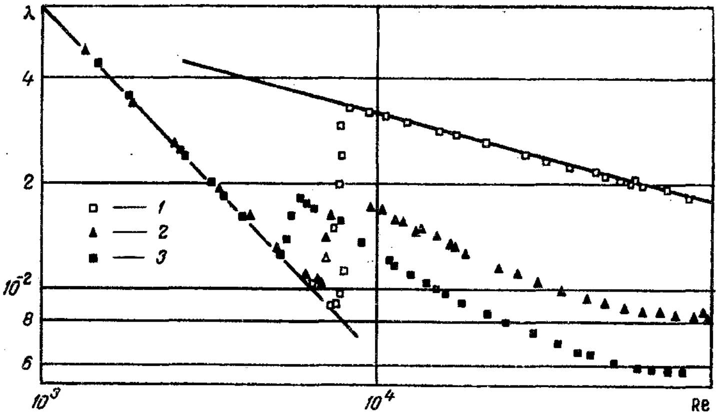

Fig. 4. Dependence of drag coefficient on Reynolds number for flow of guar gum solutions along tubing with d = 3 mm, a shaped entrance, and an initial section 185d long: 1) water; 2) $c = 2 \cdot 10^{-4}$; 3) $c = 4 \cdot 10^{-4}$.

1-2 days after mixing. Solutions used in the disc experiments were prepared with distilled water. Tap water was used in the tubing experiments; before preparing polyoxyethylene solutions at a concentration of 10^{-6} by weight, the tap water was filtered to remove particulates, which promote rapid aging of dilute solutions.

In analyzing the data from disc experiments, values for solution viscosity measured in 8-mm tubing was used [1] while the viscosity was determined in a viscosimeter with an internal diameter of 3 mm for the tubing experiments. The latter differed little from the values measured earlier.

Experimentally determined values of the drag coefficient for the disc in a case are given in Fig. 1. The experimental points correspond to the drag measured immediately after arrival at established rotation of a case containing a fresh portion of solution. The data for the drag coefficient obtained for a pure solvent agrees with that in the literature [2]. As follows from Fig. 1a, the drag coefficient curves obtained with polyoxyethylene solutions have a limiting asymptote. Similar asymptotic behavior of the drag coefficient was also observed for a disc rotating in an unbounded fluid [3].

Departure from the limiting asymptote and arrival at a curve corresponding to a Newtonian fluid is observed for low-concentration solutions as the Reynolds number increases. Such a rise in the curves is associated with irreversible changes in the solution which occur in the brief time it takes for the device to arrive at a constant rate of rotation. This was revealed in the following manner.

The device was set in rotation at a rate corresponding to complete return of the drag to the Newtonian curve. Then the rate of the rotor was reduced to a rate for which a considerable reduction in drag was ordinarily observed. However, in this case there was no such reduction in drag. It was also completely unobserved in the case where the initial startup was made at a rate corresponding to the rising branch of the drag curve.

The drag curves obtained with guar gum solutions (Fig. 1b) do not have a limiting asymptote. A greater reduction is observed for the drag coefficient as compared with the values for water than for polyoxyethylene solutions.

Values of the drag coefficient λ are shown in Fig. 2 for the flow of water and aqueous solutions of polyoxyethylene in tubing with an initial section of 60d and sharp edges at the entrance. The somewhat slower rise in the values of λ to the Blasius curve for water results from the fact that turbulence is not completely developed in the short length of the initial portion. In the flow of water, on the other hand, a slightly earlier departure from the Poiseuille curve is observed which obviously results from the downstream flow of perturbations produced at the sharp edges of the entrance section. The data obtained for the flow of polyoxyethylene solutions has a limiting asymptote which agrees with the asymptote given in [4]. Only the values of the drag for a polyoxyethylene concentration of 10^{-6}, the smallest concentration studied for flow in tubing, do not reach this asymptote.

A question arises as to how stable the results are with respect to the conditions at the entrance and the length of the initial section. The answer is given in Fig. 3 where data is given for a polyoxyethylene solution at a concentration of 10^{-5}. It is clear that the results obtained for the polymer solution depend neither on the length of the initial section over the range from 60d to 335d nor on the smoothness of the entrance while λ for water depends significantly on these conditions.

Note the departure of the drag coefficient curve for the polyoxyethylene solution upward from the Poiseuille curve even for $Re < 2300$. The departure is also observed for tubing with a smooth entrance, which significantly delays the transition from laminar mode to the turbulent mode in the case of water. This indicates the early creation of turbulent flow, previously noted [5], which is associated with properties of the polymer solution and not with tubing geometry. The production of turbulence was also recorded with an induction pressure sensor installed at 90d from the beginning of tubing with a sharp entrance. The appearance of pulsations was noted for a polyoxyethylene solution at a concentration of 10^{-5} when $Re \approx 1350$. An intermittent flow mode was not observed, in contrast to a Newtonian fluid. Turbulent pulsations uniformly occupied the entire setup and increased in amplitude as the Reynolds number increased. Such a pattern of the turbulence phenomenon was noted [6] in the flow around a free disc.

The invariability of the drag curves for the polyoxyethylene solution in Fig. 3 indicates the absence of degradation over tubing lengths from 60d to 335d. However, this does not mean that degradation did not occur in an initial length less than 60d. Just as in the case of the drag curves for a disc in a case, the values depart from the asymptote as Re increases (the lower the concentration, the lower the Re value at which this occurs) and rise to the drag curve for a Newtonian fluid. Thus, as in the case of a disc, arrival at the Blasius curve is associated with degradation. Consequently, a polyoxyethylene solution at a concentration of $2.5 \cdot 10^{-6}$ which has once passed through tubing at $Re = 9 \cdot 10^4$, i.e., at a point of total return of to the Blasius curve, does not yield a reduction in drag on second passage for the entire range of Reynolds numbers studied.

Experiments involving peripheral sampling of the fluids were performed to determine irreversible changes in the solutions. In these measurements, tubing consisting of two identical sections was used. The initial portion of each section was 60d, the measuring section was 30d, and the length beyond the measuring section was 20d. The first half of the tubing ended in a diverging portion in which the second section, having at its beginning an internal converging portion, was arranged coaxially with a certain gap present. Thus there was a possibility for circumferential sampling of the fluid at the point where the two sections of the tubing joined. Sampling was accomplished at a fixed rate and therefore one could have a flow in the second section with a lower Reynolds number than in the first section. Loss of pressure at the sampling point was negligibly small. The sampling experiments confirmed that the rising branch of the drag curves for flow of polyoxyethylene solutions arose because of degradation of the solution. The nature of this degradation is remarkable in that the irreversible changes in the solution occur in a very short length of tubing, less than 60d.

The specific features of the degradation require special care in the discussion and interpretation of data obtained in experiments with polyoxyethylene solutions. In particular, one should expect degradation to have a strong effect on results for the flow of polyoxyethylene solutions in rough tubing.

Data for guar gum solutions obtained with tubing with a smooth entrance and an initial section 185d long is shown in Fig. 4. Some difference in the position of the transition from laminar flow to turbulent flow for flow of water in the tubing (open symbol 2 in Fig. 3 and symbol 1 in Fig. 4) is related to the fact the experiments were performed with different tubing in which it was difficult to accomplish absolutely identical entrance shaping. As in the case of a disc in a case, the data for the guar gum solutions differ significantly from the data for polyoxyethylene solutions. Asymptotic behavior is not observed, at least not up to concentrations of $4 \cdot 10^{-4}$. There is a sharp transition from laminar flow to turbulent flow. There is no production of turbulence for $Re < 2300$. At the same time, a lesser persistence is observed for the laminar mode, which is quite long for the flow of water in the case of tubing with a smooth entrance.

NOTATION

r	is the disk radius;
d	is the tube diameter;
$\overline{u}$	is the mean velocity of liquid in tube;
λ	is the drag coefficient of the tube;
$c_M = 2M/\rho\omega^2 r^5$	is the torque drag coefficient of the disk in the casing;
m	is the torque;
ρ	is the liquid density;

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ω	is the angular velocity of the disk;
Re	is the Reynolds number (for a disk, $\mathrm{Re} = r\omega^2/\nu$; for a tube, $\mathrm{Re} = \bar{u}d/\nu$);
ν	is the liquid viscosity;
c	is the dimensionless weight concentration of polymer in solution.

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