

EFFECT OF FRICTION-REDUCING POLYMER ADDITIVES ON TAYLOR VORTICES

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The article presents experimental results on the stability of circular Couette flow in the gap between an inner rotating and an outer stationary cylinder. Aqueous solutions of polyoxyethylene and of guarana resin were used in the study.

The effect of polymer additives on the stability of circular Couette flow has been studied before. Small quantities of polymer additives which reduce turbulence friction were noted to have a considerable effect on the stability of such a flow. According to the data in [1], polymer additives raise the critical Taylor number whilst, in [2], not only an increase but in some cases also a decrease of the Taylor number was observed. These and similar experimental results were used as the basis for far-reaching hypotheses concerning the mechanism of the Toms effect (decrease of the turbulence friction in polymer solutions flowing along smooth walls) [3, 4]. The latter discovery, together with the contradictory experimental evidence, has provided the stimulus for a renewed study of the stability of circular Couette flow.

The operating unit of the test apparatus (Fig. 1) was a set of two coaxial cylinders. The inner cylinder was 90.8 mm in diameter and 105 mm long. Its shaft was coupled hydraulically to a RĖV-1 rotary viscometer which permitted smooth variation of the speed over a wide range. The outer cylinder made of translucent Plexiglas was mounted rigidly on the test stand. Several such translucent cylinders with different inside diameters were available and could be readily installed, making it possible to perform tests with two different radial gaps, 1.05 and 3.1 mm, between the stationary and the rotating cylinder.

A loss of stability in the flow was observed visually. The test liquid, dyed with methylene blue, was fed from a separating funnel, via a collector with rubber seals, onto the shaft of the inner cylinder and into the gap already filled with colorless liquid, through millimeter holes arranged in two rows of three — one row 42 mm above the other. Any possible extraneous sources of flow perturbation due to the holes were thus prevented from affecting the center portion of the gap space.

The dyed liquid was fed into the gap, while the inner cylinder rotated at a speed much lower than that at which Taylor vortices would appear. At such a slow rotation the dyed liquid could spread uniformly over the surface of the inner cylinder. After that, the rotational speed was gradually increased until characteristic color streaks appeared, indicating the existence of Taylor vortices. This speed was measured to an accuracy of within 0.25%. Its constancy was checked by means of a photoelectric transducer the signals of which, marking every revolution of the cylinder, were recorded on a loop oscillograph and compared with the time-base signal. The speed fluctuations also did not exceed 0.25%.

The temperature of the test liquid was measured during the tests to within an accuracy of 0.1°C. The temperature of the liquid differed only slightly from the room temperature and varied within the range 19.0–22.5°C.

We studied the effect of adding polyoxyethylene (Polyox WSR-301) and guarana resin (J2-FP) on the stability of circular Couette flow, with the additive concentration varying up to 1000 ppm. The presence of the dye (methylene blue) in these solutions did not affect their viscosity nor their friction-reducing ability.

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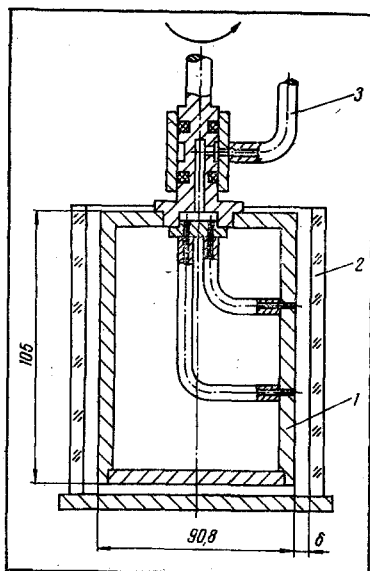


Fig. 1. Operating unit of the test apparatus, shown schematically: 1) rotating inner cylinder; 2) stationary outer cylinder; 3) tube for feeding dyed liquid. $\delta = 1.05$ or 3.1 mm.

The latter was checked by comparison tests; the decrease in friction was measured in low-concentration polyoxyethylene solutions (10^{-5} and $2.5 \cdot 10^{-5}$) both without dye and heavily dyed with methylene blue.

Solutions of these polymers are nonhomogeneous liquids containing coarse (approximately 1 mm in size) agglomerates of the macromolecules with molecules of the solvent and these agglomerates behave like elastoviscous droplets [5].

In order to eliminate anomalies in the viscosity characteristics of such liquids which are observed when using capillary viscometers and are most probably related to the comparable dimensions of those agglomerates and of the capillary, the viscosity was measured with special viscometers having large-diameter tubes. These tubes had been made of polyethylene with inside diameters 8.0 and 4.2 mm. Now the agglomerates could be assumed to have very little effect on the Poiseuille velocity profile and the viscosity could thus be measured without errors. The pressure was measured at points far removed (by a distance of approximately 250 diameters) from the tube entrance so as to eliminate the effect of the initial flow pattern, which, in elastoviscous liquids such as freshly prepared polyoxyethylene water solutions, may extend quite far into the stream.

The 8.0 mm tube 45 m long was wound into a helix 1 m in diameter and, together with the supply tank, immersed into a thermostatic (within 0.1°C) bath. The pressure drop was measured with a U-tube differential manometer. The latter had been charged with monochlorobenzene (density 1.107 g/cm^3 and immiscible with water). In order to maintain a constant density difference between the solution (or water) and the monochlorobenzene, the manometer was placed into a Plexiglas jar thermostatically controlled with the entire system. Such a manometer could serve for measuring pressure drops to an accuracy of within 0.1 mm Hg. The flow rate was determined by the volumetric method.

As is well known [6], at Dean numbers $D = \text{Re} \sqrt{r/R} > 20$ there appear intensive secondary currents which considerably increase the drag in a curved tube. For this reason, the viscosity measurements could be made at a rather slow flow with the Reynolds number not exceeding 200 and a shear rate $\gamma = 2\text{Re}v/r^2$ not higher than 25 sec^{-1} .

In order to obtain information about the viscosity of the solutions at higher rates of shear, we used the 4.2 mm tube for measurements. This tube was straight and placed inside another polyethylene tube with an inside diameter 20 mm. A thermostatically controlled liquid was pumped through the larger tube while the pressure drop across a 15.5 m segment of the 4.2 mm tube was measured with piezometers.

The critical Taylor number was calculated by the formula

$$T = \frac{4(r_2 - r_1)^3 r_1^2}{r_2 + r_1} \left(\frac{\omega}{v} \right)^2.$$

The theoretical value of this number for a Newtonian liquid [7], as has been verified by many tests, is 3430. In our experiment with water we obtained 3510 and 3420 for a radial gap width between cylinders

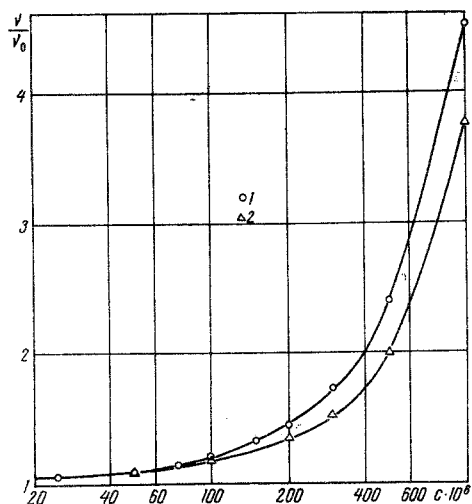


Fig. 2

Fig. 2. Relative viscosity of polymer solutions, as a function of the polymer concentration at 20°C. Measurements with the 8.0 mm tube: polyoxyethylene (1) and guarana resin (2).

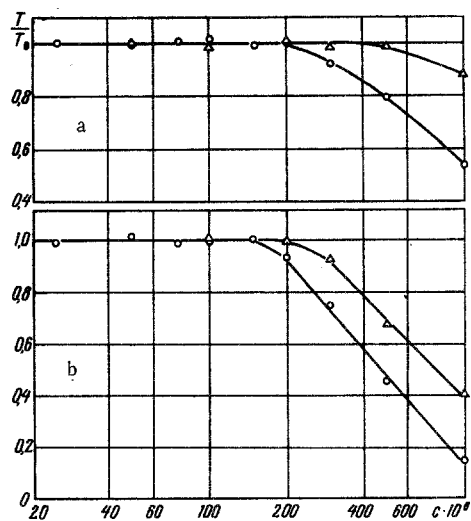


Fig. 3

Fig. 3. Critical Taylor number for polymer solutions and for water, as a function of the mass concentration of the polymer: gap between cylinders 3.1 mm (a) and 1.05 mm (b). Symbols are as in Fig. 2.

$r_2 - r_1 = 3.10$ and 1.05 mm, respectively. The maximum deviation from theory was thus 2.3%, entirely permissible considering that the gap width was not measured with a precision greater than ± 0.025 mm.

The viscosities of the polymer solutions are given in Fig. 2 relative to water. The values which had been obtained on the viscometer with the 8.0 mm tube at a temperature of 20°C and a shearing rate below 10 sec^{-1} , were then used for calculating the critical Taylor number for the flow of polymer solutions between two cylinders. The relative viscosity of a polymer solution was measured also at 25°C. The relative viscosities of the test solutions varied only slightly with the temperature within the 20–25°C range. The viscosity of a solution at the temperature at which the flow stability was tested could be found by linear interpolation from the viscosity test data.

Measurement with the 4.2 mm viscometer revealed no dependence of the viscosity on the shear rate in aqueous low-concentration polyoxyethylene and guarana resin solutions up to 400 sec^{-1} . A decrease in the viscosity with an increase in the shear rate is observed in guarana resin solutions beginning at concentrations above $2 \cdot 10^{-4}$.

The viscosity values obtained with the 8.0 mm tube (Fig. 2) may be regarded as values of the first Newtonian viscosity, since up to shear rates of 10 sec^{-1} the viscosity of the tube liquids is known not to change with a changing shear rate [8].

The critical Taylor number for the flow of polymer solutions has been referred to its value for water flow in the 3.1 mm gap in Fig. 3a and in the 1.05 mm gap in Fig. 3b. The viscosity values used in the formula for the critical Taylor number for the solutions were obtained by decanting through the 8.0 mm viscometer the same solutions which were also tested for stability. The stability tests and the viscosity measurements were performed simultaneously. Within the range of low concentrations, where the friction-reducing effect is most pronounced, the critical Taylor number for polymer solutions is the same, within 1%, as that for Newtonian liquids. Deviations toward lower values begin at concentrations $1.5 \cdot 10^{-4}$ for polyoxyethylene solutions and $2 \cdot 10^{-4}$ for guarana resin solutions. A sharper decrease was observed in the smaller 1.05 mm gap, due to the higher shear rate realized here. (During the appearance of Taylor vortices the shear rates varied from 15 to 60 sec^{-1} in the 3.1 mm gap and from 250 to 650 sec^{-1} in the 1.05 mm gap).

The observed lowering of the critical Taylor number could be related not only to the decrease in viscosity or increase in the shear rate but possibly also to an increase in the elastoviscosity of the

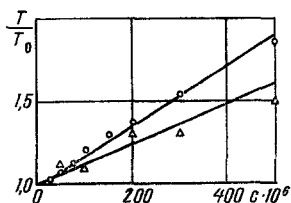


Fig. 4. Apparent increase in the relative critical Taylor number, following an increase in the concentration, if calculations are based on viscosity values measured using a viscometer with a 1.12 mm capillary. Symbols as in Fig. 2.

solutions as the polymer concentration increases. According to calculations [9], the critical Taylor number should drop considerably as a liquid becomes elastic. A definitive explanation would require further analysis.

Our results concerning the invariability of the critical Taylor number at low concentrations are in disagreement with the earlier results obtained by other authors. These discrepancies are evidently caused by incorrect viscosity measurements in the case of polymer solutions. If the critical Taylor number is calculated on the basis of our data and with viscosity values obtained using, for example, an Ostwald viscometer with a 1.12 mm capillary (which is known to be an incorrect procedure for such complex liquids as our polymer solutions), then the critical Taylor number will seem to increase even at very low concentrations, as is shown in Fig. 4. The curves on this diagram have, qualitatively, the same trend as those in [1].

NOTATION

- r_1, r_2 are the radii of the inner and of the outer cylinder, respectively;
 ω is the angular velocity of the inner cylinder during the appearance of Taylor vortices;
 r is the inside radius of the viscometer tube;
 R is the radius of the viscometer helix;
 ν is the kinematic viscosity of the liquid;
 c is the mass concentration of polymer in the solution;
 $\dot{\gamma}$ is the shear rate;
 D is the Dean number;
 Re is the Reynolds number;
 T is the critical Taylor number.

Subscript

- 0 denotes a pure solvent.

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