Turbulence Suppression by Polymer Solutions in Opposed Jets Flow

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It is well known that small amounts of polymers can affect the structure of turbulent flows. One of the most dramatic effects in this respect is the phenomenon referred to as drag reduction in which dilute polymer solutions exhibit friction factors that are appreciably smaller than those of the solvent (Bird et al., 1987). Another example of this effect is the change that the presence of the polymer induces on turbulent velocity fluctuations in elongational flows, such as in jets impinging on a flat surface and free jets (Koziol and Glowacki, 1989).

Frank et al. (1971) suggested that two impinging jets would produce localized areas of longitudinal velocity gradients. These investigators devised a system consisting of two cylindrical capillaries immersed in a fluid, facing each other. The fluid is forced out of both capillaries simultaneously, thus creating a uniaxial compression flow in the region of jet impingement. This technique evolved to a more stable and experimentally simpler approach, with the objective of attaining a closely ideal elongational flow: the direction of the fluid was reversed, that is, the fluid was sucked simultaneously into both capillaries (see, for instance, the review by Keller and Odell, 1985). A stagnation point is located at the center of the flow field (see Figure 1). Along the center line, a fluid element experiences an acceleration from the stagnation point to the capillary entrance, eventually reaching Poiseuille flow inside it. Ever since its creation, the opposed-jets flow has been extensively used in the literature. In fact, this system can be used as an extensional flow rheometer (Macosko, 1994) either by measuring the torque exerted by the fluid on the capillaries (Fuller et al., 1987), or by measuring the pressure drop through the flow field (Keller et al., 1987). Another application is the study of the stretching of polymer molecules in solution, where the changes in molecular conformation are usually monitored by measuring the birefringence in the central region of the jets (Keller and Odell, 1985; Odell et al., 1988; Müller et al., 1988). All such works have avoided turbulent flow by working at Reynolds numbers below the critical value for the onset of turbulence.

In this article we study turbulent flow in opposed jets for Newtonian fluids and high-molecular-weight polymer solutions in the dilute concentration regime. Our main emphasis is to analyze the effect of the addition of polymers on the pressure drop in the turbulent flow regime and on the transition to turbulence, as compared to the behavior of Newtonian fluids.

Experimental Studies

The experimental apparatus consisted of an opposed-jet flow system, in which pressure drops across the jets could be measured as a function of flow rates. The apparatus also allowed flow visualization. Details of the experimental setup can be found elsewhere (Müller et al., 1988). The capillaries

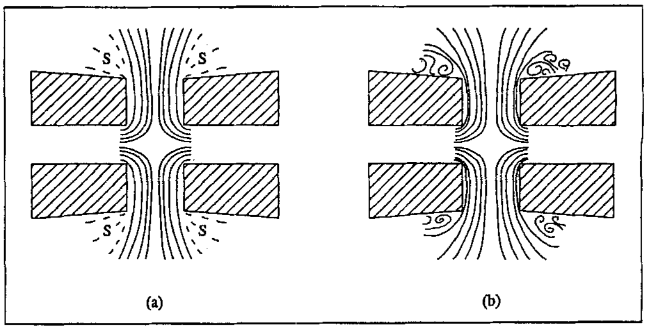

Figure 1. Flow patterns in the opposed-jets system.
(a) Laminar regime. (b) Turbulent regime.

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used had an internal diameter of 0.85 mm and a separation between them of 1.21 mm.

The nominal strain rate was calculated in terms of the flow rate as follows:

$$\dot{\epsilon} = \frac{Q}{Ad} \tag{1}$$

where Q is the volumetric flow rate through both capillaries, A is the cross-sectional area of the capillary entrance, and d is the capillary separation.

We have used as Newtonian fluids distilled water and aqueous solutions of isopropanol. The polymer used was a BDH hydrolyzed polyacrylamide (HPAA) with a degree of hydrolysis of 16%, and a broad molecular weight distribution with a mean weight average molecular weight of 5×10^6. The HPAA was dissolved either in distilled water or in a 0.5-M NaCl–water solution. Solutions containing 0.5-M NaCl were in the high ionic strength limit, that is, further addition of NaCl caused no additional conformational changes in the molecules (Odell et al., 1988). All the experiments were performed at 25°C.

Results and Discussion

The onset of turbulence and the flow patterns in the laminar and turbulent regimes were analyzed by means of flow visualization of scattered light at 90° from tracer particles in the fluid. For the case in which the fluid is sucked through the capillaries (inflow mode), the laminar regime at high strain rates exhibited streamlines such as those depicted in Figure 1a. In this regime, the region close to the plane of symmetry is characterized by high velocities, and there is a relatively wide region close to the wall of the capillaries (S) in which the flow is practically stagnant. In the turbulent flow regime (Figure 1b), the fluid is better distributed through the whole volume around the capillaries, and recirculating unsteady vortices are formed close to the walls. The streamlines depicted in Figure 1b correspond to the time-averaged velocity distribution, since unsteady velocity fluctuations are observed throughout the flow field. These observations have relevance in explaining the behavior of the pressure drop in the system, as discussed below.

The pressure drop for water in the opposed jets is shown in Figure 2 as a function of flow rate for the impinging jets (outflow mode) and the inflow mode. Both curves are well-behaved below a critical strain rate at which a sudden change in the derivative is observed. This strain rate signals the onset of turbulence, a fact that was confirmed by flow visualization. The Reynolds number within each capillary at which turbulence sets in is 1600 for the inflow mode, and 850 for the outflow mode.

Below the critical strain rate, both curves are perfectly fitted by an equation of the form

$$\Delta P = a\dot{\epsilon} + b\dot{\epsilon}^2. \tag{2}$$

The linear term in Eq. 2 is mainly due to viscous effects, whereas the quadratic term is a consequence of inertial effects due to the curvature of the streamlines and variations in the magnitude of the velocity.

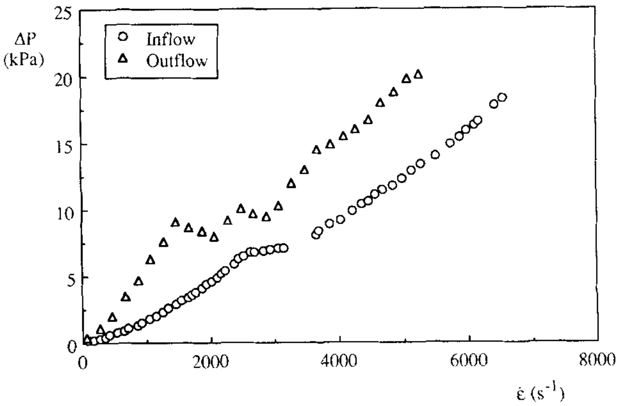

Figure 2. Pressure drops for water.

In the outflow mode the quadratic component of the pressure drop—strain rate relationship is larger than in the inflow mode. This is due to the fact that the outflow mode is a diverging flow and therefore it has a greater inertial contribution to the pressure drop. Flow visualization indicates that the outflow mode does not behave as depicted in Figure 1a. In this case, as the strain rate is increased in the laminar regime, large recirculating but steady vortices are formed around the capillaries. The diverging nature of the outflow mode makes it more unstable and, therefore, it reaches the transition to turbulence at a lower Reynolds number than the inflow mode.

An interesting observation of the results presented in Figure 2 is the fact that the slope of the pressure drop curves decreases at the onset of turbulence so that this flow field has the peculiarity that the increase in drag with strain rate in the turbulent regime is lower than in the laminar regime. This behavior is possibly due to the better flow distribution in the turbulent regime, confirmed by the visualization of the streamlines. The improvement of the flow distribution is a consequence of the high levels of mixing induced by turbulent velocity fluctuations.

We explored the effect of the physical properties of Newtonian fluids on the onset of turbulence in the inflow mode. Figure 3 shows how the pressure drop varies with isopropanol concentration in aqueous solutions. Notice that the onset strain rate increases with isopropanol concentration. In fact, the onset strain rate cannot be achieved in the setup used in this work for the 18.4% solution. From the results in Figure 3, it can be shown that the onset strain rate scales with the inverse of the kinematic viscosity of the solution within 10%. This means, as expected, that the critical Reynolds number at which turbulence starts is independent of the Newtonian fluid used.

Figure 4 shows the effect of adding a small amount of HPAA to a 0.5-M NaCl solution (curve labeled as 5 ppm, original). In this solution, the polymer molecule tends to adopt a coiled conformation as a result of the complete screening of its anionic groups by the sodium cations. It behaves as a flexible macromolecule that undergoes a coil-stretch transition in elongational flows beyond a particular strain rate. For this polymer, this strain rate is of the order of 500 s^{-1} (Odell et al., 1988). At this low level of polymer concentration, the

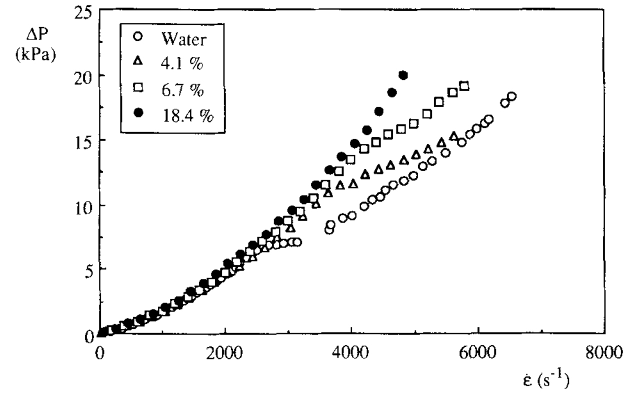

Figure 3. Pressure drops for water and aqueous solutions for isopropanol (isopropanol concentrations in weight percent).

extensional viscosity increase induced by molecular stretching is negligible, since chain extension is confined to a small region close to the stagnation point (Odell et al., 1988). This is why the pressure drops for this solution are virtually equal to those of water (Figure 4) until the transition to turbulence occurs. The presence of HPAA suppresses turbulence, causing a shift to higher strain rates for the onset of turbulence. This shift cannot be attributed to a viscosity increase since, in this case, the viscosity of the solution is equal to that of water, a fact that is confirmed by the similar pressure drops observed at low strain rates between the polymer solution and pure water. Koziol and Glowacki (1989) have observed a similar delay for the onset of turbulence in the flow of a jet impinging on a wall by using a flexible polymer, poly(ethylene oxide). In that case, however, drag reduction was observed in the turbulent regime, whereas in this work we have observed a drag increase. This fact is a consequence of the high rate of change of pressure drop with flow rate in the laminar regime, which persists at higher flow rates when the onset of turbulence is delayed.

When the polymer solution is repeatedly passed through the flow cell, the onset strain rate gradually diminishes (results after ten runs are shown as an example in Figure 4). In fact, the behavior eventually goes back to that of pure water. Previous works (Müller et al., 1989; Odell et al., 1992) in the opposed-jets device have shown that flow-induced chain scission occurs only after the polymer molecules have been fully stretched. Since the longest molecules degrade first (at lower strain rates), a progressive reduction in molecular weight is taking place with each pass of the solution through the jets. The observed turbulence suppression is therefore related to the presence of high molecular weight macromolecules in the solution.

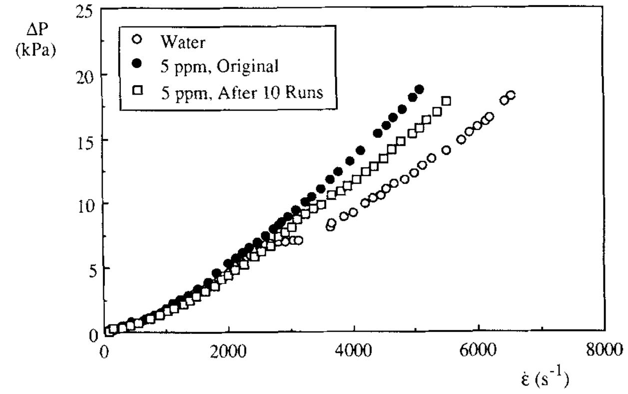

Figure 4. Pressure drops for water and HPAA in 0.5 M NaCl aqueous solution.

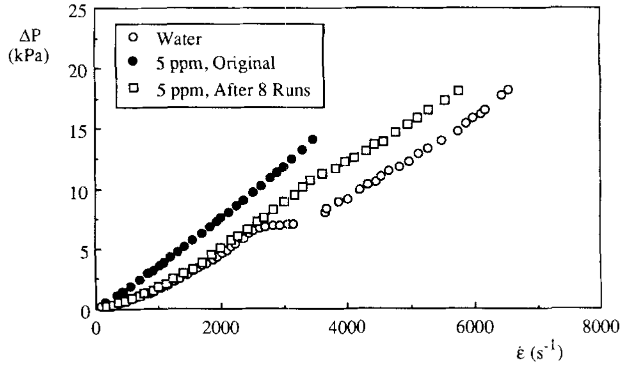

Figure 5. Pressure drops for water and HPAA in deionized water.

When the HPAA molecule is dissolved in deionized water, it adopts a highly expanded conformation since there is repulsion among the unscreened ions in the molecule; it thus behaves as a semirigid molecule. This causes a high degree of friction between the molecule and the solvent, an effect that is enhanced by the possible existence of transient entanglements (Odell et al., 1988). As a consequence of this effect, the solution has a viscosity that is appreciably larger than that of the pure solvent. This increased viscosity results in larger pressure drops in the laminar regime, as shown in Figure 5. The difference between the two original HPAA curves (Figures 4 and 5) can then be attributed to the polyelectrolitic nature of the HPAA. The degradation behavior of the HPAA solution in deionized water (Figure 5) is analogous to that observed with the HPAA in brine (Figure 4). In this case degradation also results in a decrease in the shear viscosity of the solution. After a certain number of passes, the solution eventually resembles pure water.

Conclusions

We have shown that the addition of small amounts of polymers to a Newtonian solvent delays the onset of turbulence in opposed-jets flows. This delay occurs independently of the equilibrium conformation of the macromolecules in solution, since it is exhibited by both flexible and semirigid polymers. Furthermore, for both types of molecule, the polymer gradually degrades in the flow field as it suppresses turbulence. After a certain degree of degradation, the turbulence suppression effect disappears. These results illustrate that the effect of small amounts of polymers in turbulent flows depends on the nature of the time-averaged flow field: in shear flows, drag reduction is observed, whereas in elongational flows, such as the one considered here, turbulence suppression and its consequent drag increase occur.

Acknowledgments

We gratefully acknowledge the financial support of the European Community through EC Cooperative Award No. CI1-CT91-0887. We also thank Ms. A. C. Gamboa for helping with data processing.

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Manuscript received Apr. 25, 1994, and revision received Aug. 1, 1994.