Polymer drag reduction in Taylor vortices

THE Toms effect[1], whereby the addition of small quantities of polymer can typically produce 50% reduction in drag, occurs in turbulent flow systems. We report preliminary observations of a similar drag reduction behaviour observed in a Couette apparatus when toroidal Taylor vortices[2] are generated by rotating the inner of two concentric cylinders at sufficient speed; in this case the flow field is well understood and does not vary with time.

Simple shear alone as generated by normal Couette flow has little effect on deforming flexible polymer molecules and can be expected to exhibit no drag reducing effect; however, extensional flows such as pure shear, axial extension and compression do have the ability to extend molecules and the extensional viscosity when polymers are present may be orders of magnitude greater than the shear viscosity[3]. If this class of flow is present significant effects can be expected when polymers are added. In Taylor vortices the existence of extensional flow regions between each counter rotating vortex has already been identified[4] as the cause of nucleation of extended chain polymer crystals.

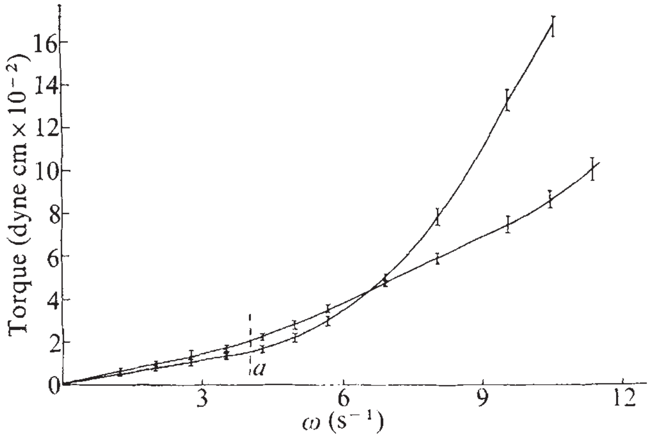


Fig. 1 Graph of torque as a function of angular velocity for a Couette apparatus 30 cm long, of inner cylinder diameter 2.0 cm and gap width 0.37 cm.

With a Couette apparatus we have measured the torque on the stationary outer cylinder using a fine torsion wire suspension. Figure 1 shows the torque measured for different rates of rotation of the inner cylinder using both water and polymer doped solutions. The polymer was polyethylene oxide (Union Carbide WSR301) of molecular weight $M_W \simeq 4\times10^6$. The solution was renewed before each series of measurements to minimise the effect of possible shear induced degradation. For a low angular velocity of the inner cylinder when the flow is simple shear, the torque against ω curve obeys an essentially linear relationship for both solutions where the gradient of the line gives the shear viscosity, which is about 20% higher for the 50 p.p.m. polyethylene oxide (WSR301) water solution. At a critical speed (*a* in Fig. 1) the torque starts to increase non-linearly. This speed corresponds well with that predicted by Taylor[2] at which the secondary Taylor vortex pattern develops. Above this critical speed we assume that subsequent differences in the measured torque curve from the extrapolated straight line represent the additional drag caused by the secondary Taylor vortex flow. When Taylor vortices are well developed we see that the drag as measured by the torque is significantly reduced when polymer is present.

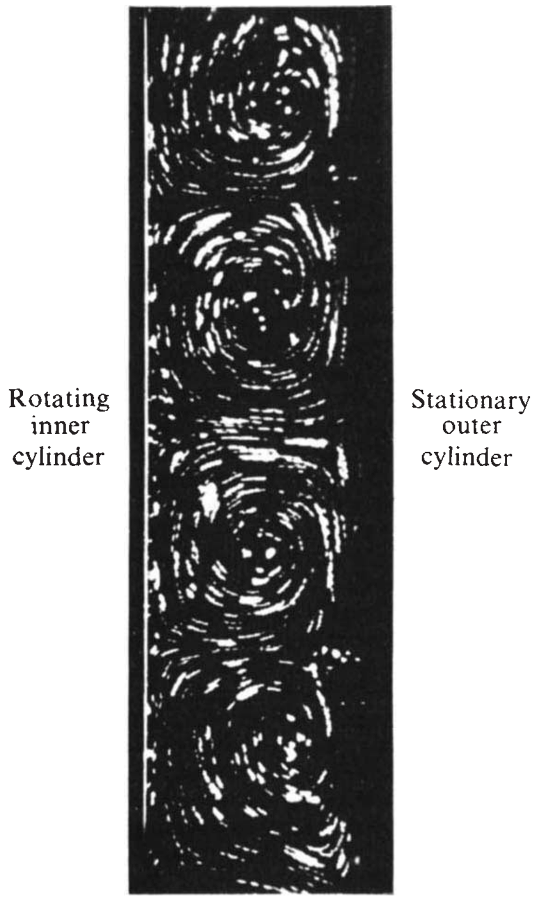
From our torque measurements we cannot say with precision if there is a change in the onset of instability with the addition of polymer; however, our results do indicate that this change if present is not large. Changes in the onset of instability have been examined in detail by others[5-8], however, these studies were confined to rates of rotation close to the critical region (*a* in Fig. 1). The large drag reducing effects we are concerned with, occur at greater rates of rotation well removed from this critical region.

By illuminating the gap between the two cylinders with a plane beam of light directed vertically along the radius and passing through the glass outer cylinder, the nature of the Taylor vortices could be examined in profile by observing scattered light from small tracer particles put into the solution.

Streamlines of the vortices observed at right angles to the incident beam are shown in Fig. 2. No detectable difference could be found in their profile with the addition of polymer, but examination of velocities using short time exposure photographs indicated that the speed of the vortices measured in a region where the vortices meet midway in the gap between cylinders, increased by up to 10% at $\omega = 13\ s^{-1}$ with the addition of polymer. This result is contrary to the expectations of some theories[9] of drag reduction and indicates that drag reduction in Taylor vortices does not occur by suppression of vorticity; indeed the horizontal components of vorticity as represented by the secondary flow pattern of our experiments is enhanced.

We have shown that addition of polymer does not change significantly the onset of the secondary flow or suppress its vorticity and thus other mechanisms must be explored to explain the origin of the effect. We believe chain extension occurs near the cylinder walls in regions of compression where the vortex flow approaches either inner or outer wall. The possibility of

Fig. 2 Photographic profile view of Taylor vortex pattern generated in Couette apparatus; inner cylinder diameter 4 cm and gap width 1.0 cm.



chain extension occurring in the regions of extension where the vortices move away from the walls is not thought likely because related experiments firing a jet of polyethylene oxide solution at right angles to a flat surface showed localised birefringence corresponding to chain extension, near and parallel to the wall for jet outflow (axial compression) but no visible birefringence for the reverse flow direction when fluid was sucked into the jet (axial extension). We therefore conclude that in regions of compression in which chain extension occurs the extensional viscosity can be expected to increase significantly. As no drag reducing mechanism can be seen in the vertical plane we conclude that either the primary or secondary flow must be modified in the horizontal plane in such a way as to cause the reduction in overall momentum transfer to the outer wall. Further velocity profile and additional birefringence experiments viewing the horizontal plane of the Taylor vortex flow system will be carried out to establish this point.

At this stage certain generalisations concerning conditions for drag reduction may be proposed: an elongational flow system is required to produce chain extension; and the chain extension thus achieved should then be capable of reducing the momentum transfer (which is the cause of the drag) in a manner not specified in detail at the moment. This reduction of momentum transfer, however should not eliminate the elongational flow field which has produced the chain extension in the first place; its continued survival is a prerequisite for the whole effect.

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Acoustic Bragg diffraction from human tissues

ANALYTICAL methods based on the use of ultrasonic beams are potentially of interest for the remote, *in vivo* characterisation of the mechanical structure of human tissues[1,2]. We have investigated, from this point of view, the relationship, for a specific volume of tissue, between the recorded ultrasonic backscattering amplitude and the orientation of the tissue structure to the ultrasonic beam. Experimentally this measurement is closely analogous to Bragg's X-ray crystallography arrangement except that we use 180° backscattering geometry.

Our early observations suggested qualitatively that the acoustic Bragg traces obtained were indeed characteristic of the particular tissues examined[3] and modelling calculations have shown that the data are consistent with the hypothesis[4] that diffraction arises predominantly from the connective tissue microstructure of the organs involved, for example the lobular network in liver tissue[5]. Here we present quantitative evidence that the method can provide objective characterisation of tissue structure.

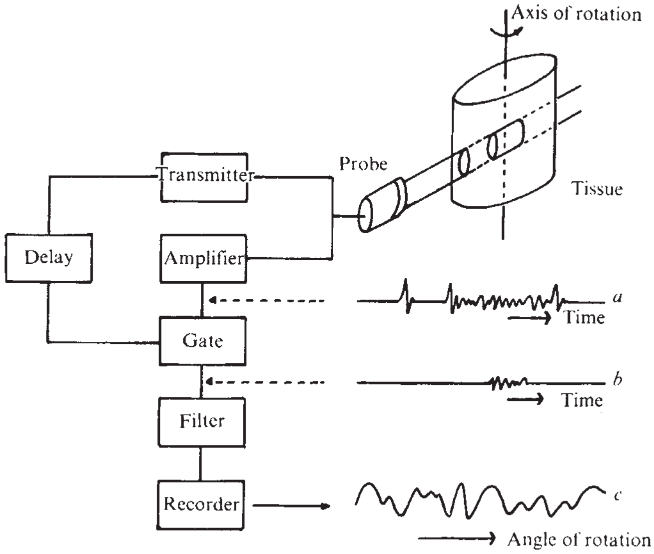

Fig. 1 Schematic diagram of the experimental arrangement for investigation of the backscattered Bragg diffraction characteristics of human tissues: *a*, received echo train from tissue specimens: *b*, gated output of received echo train; *c*, diffraction pattern obtained by frequency filtering the gated output while rotating the specimen.

Experimentally the apparatus is that of a conventional ultrasonic pulse–echo system (Fig. 1) in which an approximately cylindrical tissue specimen is positioned in a water-filled sound tank so as to lie directly in the sound beam, its long axis being normal to the direction of the beam. The sample is then rotated about this axis to enable backscattering amplitude measurements to be made from all angles. A time gate centred on this axis of rotation selects a portion of the returning echo train such that the total received echo amplitude corresponds to the backscattering from a specific volume of tissue, determined by the beam width, pulse length and appropriate time gate. Following frequency filtering of the returned echo train, plots of echo amplitude as a function of angle of rotation are obtained for one complete rotation. Some limited examples (0–50°) are shown in Fig. 2. An interesting feature of these diffraction patterns is that they seem to be characteristic of the particular tissue and presumably reflect corresponding differences between the respective tissue structures.

Evidently, several possible analytical approaches could be taken towards establishing the significance of differences or similarities between such traces and we report here the results of one of these, in which we have computed, by the fast Fourier transform method, the distributions of angular frequency

Fig. 2 Observed Bragg diffraction patterns from three types of human soft tissue, examined at 1.0 MHz. *a*, Liver; *b*, brain; *c*, spleen.