CIRCULAR COUETTE FLOW AND TAYLOR VORTICES
IN SHEAR-THINNING LIQUIDS

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Abstract The flow structure in a concentric annular geometry with a large aspect ratio and a radius ratio of 0.506 has been investigated for inner cylinder (centrebody) rotation for one Newtonian and two non-Newtonian liquids: glucose, Xanthan gum and a blend of Laponite and CMC. Tangential velocity distributions have been measured for circular Couette flow (i.e. sub-critical Taylor numbers) and found to be in excellent agreement with theory. Tangential and axial velocity components have been measured for high-Taylor numbers to reveal the internal structure of the Taylor vortices. The axial-velocity data have been used to construct streamline plots of the radial-axial flowfields. The shear-thinning nature of the two non-Newtonian fluids is shown to have a strong influence on both the Couette flow and also the Taylor cell structure. Axial drift of the Taylor cells for the two non-Newtonian liquids is attributed to differences in their rheological characteristics (viscoelasticity versus thixotropy).

1. Introduction

The cellular motion that develops in the fluid contained between two concentric cylinders when the rotation speed exceeds a critical value, strongly dependent upon the radius ratio, was discovered and analysed theoretically and experimentally by Taylor in 1923. The review of Stuart (1986) lists nearly a hundred subsequent papers concerned in one way and another with Taylor-vortex flows whilst Koschmieder (1993) puts the total at about three hundred. Although some quite remarkable experiments have been reported, starting with those of Taylor himself and including the definitive work of Donnelly (1958) and Coles (1965), almost all have been limited to either torque measurements or visualisation of flow structures through the outer cylinder wall with considerable emphasis on transitions between flow states rather than the internal details of a particular flow state. Hot-film, laser Doppler anemometer and electrochemical current measurements of power spectra have also been employed to detect departures from the axisymmetric structure of the primary Taylor state to increasingly complex wavy vortices as the Taylor number is increased. In view of the interest in Taylor vortex flow which has continued
for more than 70 years, it seems remarkable that only limited measurements of the internal structure of Taylor vortices have been reported hitherto.

So far as non-Newtonian fluids are concerned, the Taylor-vortex literature is very limited. Recent theoretical work includes the finite-element study of the stability of inelastic non-Newtonian fluids in Couette flow by Lockett et al (1992) based upon the far more extensive numerical work of Lockett (1992) which also includes the influence of an imposed axial flow and eccentricity. The latter topics are also being investigated experimentally in the wider research programme of which this study of Taylor vortices is a part (Escudier et al 1994a, Escudier and Gouldson 1994). Previous experimental work on non-Newtonian liquids has been limited to either detecting the critical rotation speed for the onset of Taylor motion or using the critical speed to determine rheological properties.

As was Lockett’s (1992) work, the present study was motivated by the need for a more complete understanding of the flow of drilling fluids in the annulus created between drillpipe and wellbore during oil- and gas-well drilling operations. The selection of the two non-Newtonian fluids used for the work described here was strongly influenced by the viscometric characteristics of a typical drilling fluid: shear thinning, thixotropic, viscoelastic and formulated to gel below a critical shear (yield) stress. To permit the use of laser Doppler anemometry for the detailed flow measurements, it was essential that the fluids were also optically transparent. Of the two fluids selected, one, Xanthan gum, is shear thinning and elastic whilst the other, a Laponite/CMC blend, is shear thinning with a low yield stress and is also thixotropic. A second aspect of the present work which was influenced by the relevance to drilling situations is the geometry of the apparatus. The radius ratio is 0.506 and the aspect ratio (i.e. annulus length/gap width) is 233:1, which is considerably higher than any previous wide-gap Taylor-vortex apparatus. Such a high aspect ratio was essential since the main aim of the research programme was the investigation of fully developed flow through the annulus.

The present measurements reveal the influence of fluid rheology on circular Couette flow and on the internal structure of Taylor cells. Variations in the internal vortex structure with increasing Taylor number are investigated by determining the changes in the radial distributions of the maximum and minimum axial velocities within a Taylor cell.

2. Experimental Rig and Instrumentation

The annular test section comprises six precision-bore borosilicate glass tubes (ID 100.4 ± 0.1mm) with a 50.8mm diameter thin-wall stainless steel inner tube giving a radius ratio of 0.506. There are five modules each of 1.027m length