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OBSERVATION OF ELASTIC EFFECTS IN CONFINED SWIRLING FLOW OF VISCOELASTIC FLUIDS

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ABSTRACT

The effect of elasticity on the secondary motion of viscoelastic fluids due to swirl was analysed using flow visualisation. A closed cylinder containing a rotating base was used to induce the swirling motion of a flexible polymer Boger fluid. The secondary motion is observed to flow in the opposite direction to that for Newtonian fluids at low rotation rates. As the rotation rate is increased an instability is observed where the vortex core is seen to spiral with the primary motion of the fluid and an asymmetrical ring vortex appears on the centre of the rotating base.

INTRODUCTION

The observation of the effects due to elasticity for the flow of viscoelastic fluids is both interesting and exciting. The flow behaviour of Newtonian fluids can be fully characterised using the Navier-Stokes equations if the viscosity, density and boundary conditions are specified. However, only a few of the many instabilities and phenomena associated with viscoelasticity have been predicted numerically. Viscoelastic flows which can be predicted at least qualitatively include: laminar jet flow, elastic instability in Taylor Couette flow, squeeze film flows, elastic instability in cone and plate flow and elastic instability in parallel plate flow. Classic test problems such as circular entry flows and creeping flow around a sphere are still to be correctly predicted numerically. The difficulty associated with the prediction of the flow behaviour of viscoelastic liquids is that there is no single non-Newtonian equivalent to the Newtonian Navier-Stokes equations. This is due to no universal constitutive equation being known in viscoelastic fluid mechanics. The number of constitutive equations developed for the prediction of the flow of viscoelastic fluids has been numerous and yet many phenomena observed in flow fields with elastic liquids cannot be predicted. The only way to test proposed constitutive equations is to compare the results of simulations to experimental observations.

The flow behaviour of liquids in a cylindrical vessel containing a rotating base provides a complex flow field where the boundary conditions are precisely specified and axial symmetry can be maintained. Indeed, this geometry has been used for the accurate observation and simulation of 'vortex breakdown' of Newtonian fluids by several authors including Escudier (1984, 1988), Lopez (1990), Brown and Lopez (1990) and by Böhme et al (1992) for shear thinning non-Newtonian fluids. Hence this flow may be a good test case for comparison with numerical studies of the flow of elastic liquids. Therefore, at least qualitative experimental observations of the secondary flow patterns produced in this cylindrical geometry are required.

The first research into the confined disk and cylinder system for viscoelastic non-Newtonian fluids was conducted by Hill et al (1966) who observed the secondary flow of elastic fluids at low rotation rates to be in the opposite direction (i.e. 'reverse' flow) to that for Newtonian fluids. Hill et al (1966) believed that the direction of circulation was dependent on the primary/secondary normal stress differences and envisaged that this system may be useful in estimating the importance of normal stresses in a given fluid. As the rotation rate was increased, Hill (1972) observed complex patterns with the development of a 'ring' vortex at the edge of the rotating disk, rotating counter to the main vortex structure. A highly unsteady pattern was observed at very high rotation rates where the flow changed direction in a confused manner. A vortex was also observed to form near the centre of the rotating disk which was 'spun off' into the main body of the fluid and subsequently reformed on the disk. Hill (1972) used polyacrylamide in a solvent of glycerol and water which formed a range of shear thinning elastic liquids. Day et al (1994) used an aqueous shear thinning elastic fluid and also observed 'reverse' flow at low rotation rates. As the rate of rotation increased, an instability was observed with the formation of a spiral vortex flowing away from the rotating disk.

Numerical work into the prediction of the secondary flow patterns for the confined swirling flow of viscoelastic non-Newtonian fluids has been conducted by Kramer and Johnson (1972) and more recently by Nirschl and Stewart (1984) and Chiao and Chang (1990). A global spectral method was used by Chiao and Chang (1990) while an orthogonal collocation method was used by Nirschl and Stewart (1984) with both methods using the Criminale-Ericksen-Filbey constitutive equation. In both cases the fluid was assumed to be shear thinning and elastic using rheological data for aqueous polyacrylamide solutions provided by Hill (1972) with the Carreau A model used to describe viscosity and the primary normal stress coefficient. Kramer and Johnson (1972) used a perturbation theory for a weak secondary flow superimposed on an arbitrary primary flow using the WJFLMB constitutive model and assuming both a constant viscosity and a constant primary normal stress coefficient.

All the computed flows were found to exhibit single or double vortices depending on the rotation speed and the polymer concentration. Elasticity driven 'reverse' flow was predicted using each method mentioned above at low rates of rotation. As the rate of rotation was increased, Chiao and Chang (1990) and Kramer and Johnson (1972) also predicted the centrifugully driven 'ring' vortex on the outer edge of the disk when the rate of rotation was increased which was also observed experimentally by Hill (1972). However, contrary to Hill's experiments, Nirschl and Stewart (1984) predicted a small counter rotating 'ring' vortex to form in the centre of the disk, as did Kramer and Johnson (1972) when the fluid elasticity was increased. Chiao and Chang (1990) also predicted a region of temporal instabilities and chaotic flow which were believed to be consistent with some observations made by Hill (1972).

The current research involves the use of constant viscosity elastic liquids known as Boger fluids (Boger, 1977/78). Boger fluids are used to eliminate the effects of shear thinning on the flow behaviour such that purely elastic effects can be observed. The isolation of elastic effects will assist in understanding the effect that elasticity has on the secondary flow patterns in this cylindrical flow geometry. Inertia is also made negligible by using low rotation rates and high viscosity fluids. Hence, the experimental conditions have been carefully controlled in order to simplify the problem. It is envisaged that the combination of the simple geometry and well characterised elastic liquids will make this flow field very suitable as a test case for numerical studies.

APPARATUS

The details of the experimental apparatus are shown schematically in Figure 1. The experimental rig consists of a polycarbonate cylinder situated in a rectangular perspex water bath. The water bath is designed to reduce errors due to parallax and to offset the effects of viscous heating in the working fluid. The base of the cylinder is made from stainless steel connected to a motor by a belt. The motor is controlled by a variable speed drive. The upper lid is movable and lockable and is positioned according to the height to radius ratio required. The temperature is held constant at approximately 21°C and can be monitored by inserting a thermocouple through the upper lid. Fluorescein dye is added to the system by inserting a capillary tube through the top lid and injecting a small amount of dye onto the base. Illumination of the secondary flow plane is with a blue-green argon-ion laser sheet produced by a cylindrical lens.

RHEOLOGY

A constant viscosity elastic fluid, or 'Boger Fluid', consisting of 0.025wt% polyacrylamide MG500 (supplied by Dow Chemical Ltd) in a solvent of 43°Be wheat syrup (supplied by Bunge Aust. Ltd.) and Milli-RO water was developed. A small amount of sodium azide was used as a biocide. The rheological properties of the fluid were determined using an R19 Weissenberg rheogionometer with a cone and plate geometry. The fluid has a constant viscosity of 3 Pa s and shows 'Newtonian-like' behaviour in terms of shear stress-shear strain data as shown in Figure 2. The primary normal stress difference (N_1) shows approximate quadratic behaviour at low shear rates and linear behaviour at high shear rates, as expected for a flexible polymer solution. Hence, the zero shear rate Maxwell relaxation time was determined from the data to be 0.36 seconds. Figure 3 shows the behaviour of N_1 and the Storage Modulus (G') with relation to shear rate. Figure 4 shows the behaviour of the relaxation time with shear rate. The specific gravity of the fluid was 1.33.

The Reynolds number (Re_0) is defined as:

$$Re_0 = \rho \Omega R^2 / \eta_0$$

where

ρ = density (kg/m^3)
Ω = rotation rate (s^{-1})
R = disk radius (m)
η_0 = zero shear rate viscosity (Pa s)

The Weissenberg number (We_0) is defined as the ratio between the characteristic time of the fluid (relaxation time) and the characteristic time of the flow process (reciprocal of the rotation rate) as follows:

$$We_0 = \lambda_M \Omega$$

where

λ_M = zero shear rate Maxwell relaxation time (s)

OBSERVATIONS AND DISCUSSION

Figure 5 is a schematic diagram showing the secondary flow behaviour in a Newtonian fluid before the onset of vortex breakdown (Re< 160 for H/R = 1.3) (Escudier, 1984). The tangential velocity varies with the radius of the rotating disk, and is zero on the other enclosing surfaces. The resulting non-uniform centrifugal force will cause a secondary flow in the cylinder, moving outward along the rotating base, up the walls and down the central axis. At higher Reynolds numbers (depending on the aspect ratio), Escudier (1984) observed the central vortex core undergo vortex breakdown.

Figures 6 and 7 show two phenomena observed in the confined swirling flow of a constant viscosity elastic liquid (Boger Fluid) at an aspect ratio (H/R) of 1. Figure 6 shows the behaviour of the fluid at a rotation rate of 0.13 s^{-1} with a Reynolds Number of 0.32 and a Weissenberg Number of approximately 0.05. The secondary motion of the fluid is observed to flow in the opposite direction to that of a Newtonian fluid, i.e., the stable secondary flow direction is inward along the base, against centrifugal forces, and then upward along the central axis away from the rotating disk. This is due to the induced normal stresses created upon motion of the fluid. Increasing the rotation rate to 0.20 s^{-1}, with a Re_0 of 0.45 and We_0 of approximately 0.07, caused the core vortex to become 'wavy' near the stationary lid and a small ring vortex to form on the centre of the disk. An unsteady flow then develops as depicted in Figure 7. The original central vortex core is observed to spiral with the primary motion of the fluid. Several cross sections of the spiralling vortex can be seen as the laser sheet slices through the secondary flow field. An asymmetric 'ring' vortex, rotating counter to the main vortex, is also observed on the centre of the rotating base.

The instability observed is the same as that seen by Day (1994). However, through the use of a constant viscosity elastic liquid, it has been confirmed that it is an effect caused purely by the elastic nature of the fluid and is not caused by any shear thinning effects. The mechanism behind the instability is still unknown precisely but it is hoped to gain a better understanding of the mechanisms taking place through experiments to be conducted in the future.

CONCLUSION

The secondary flow patterns for a constant viscosity elastic liquid (Boger fluid) showed 'reverse' flow at low rotation rates when compared with a Newtonian fluid while at a slightly higher rotation an instability was developed. The instability comprised of a spiral vortex moving away from the rotating disk and spiralling with the bulk swirling motion of the fluid. Also observed was a small asymmetrical ring vortex on the centre of the disk. The disk and cylinder apparatus should provide a suitable test case for non-Newtonian fluid flow simulations due to the simplicity of the geometry and the complexities of the flow structure.

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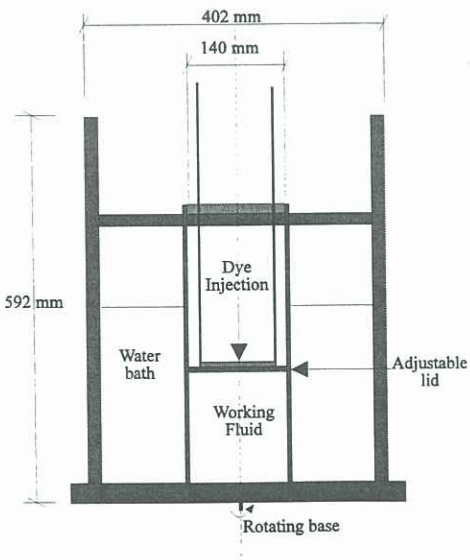

FIGURE 1. CONFINED SWIRLING FLOW EXPERIMENTAL APPARATUS

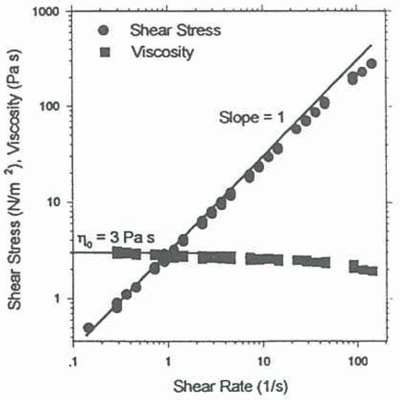

FIGURE 2. SHEAR STRESS AND VISCOSITY VERSUS SHEAR RATE FOR BOGER FLUID

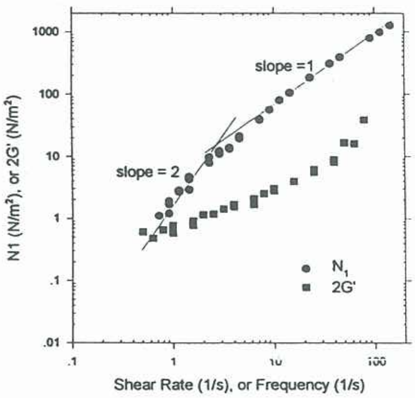

FIGURE 3. PRIMARY NORMAL STRESS DIFFERENCE AND STORAGE MODULUS VERSUS SHEAR RATE FOR BOGER FLUID

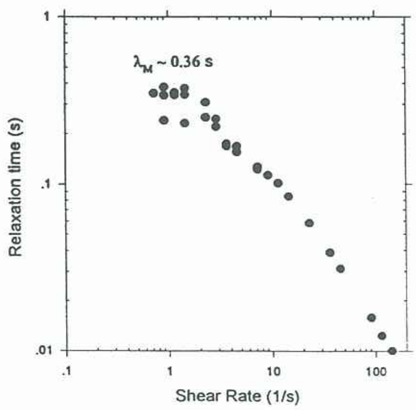

FIGURE 4. RELAXATION TIME VERSUS SHEAR RATE FOR BOGER FLUID

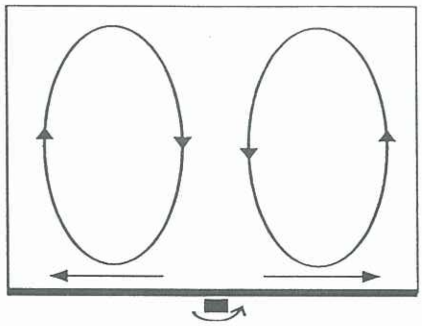

FIGURE 5. SCHEMATIC DIAGRAM OF THE SECONDARY FLOW FOR A NEWTONIAN FLUID AT LOW REYNOLDS NUMBER

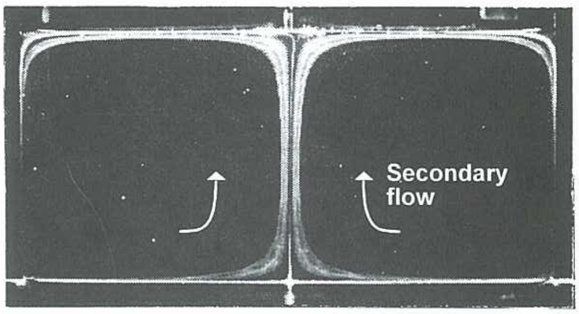

FIGURE 6. OBSERVATION OF 'REVERSE' FLOW FOR A BOGER FLUID AT A ROTATION RATE OF 0.13 s^{-1} (Re_0=0.32, We_0=0.05)

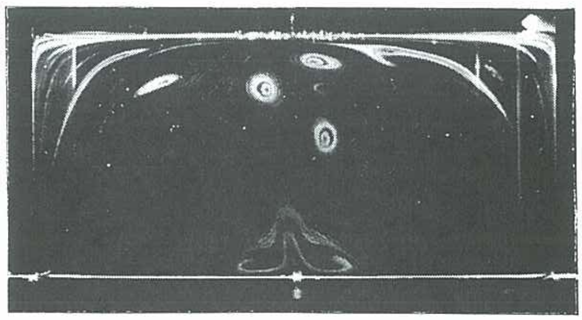

FIGURE 7. OBSERVATION OF SPIRAL VORTEX FOR A BOGER FLUID AT A ROTATION RATE OF 0.2 s^{-1} (Re_0=0.45, We_0=0.07)