FOURTH INTERNATIONAL SYMPOSIUM
ON
APPLICATIONS OF LASER ANEMOMETRY TO FLUID MECHANICS

July 11th to 14th, 1988
Lisbon
Portugal

FLOW CHARACTERISTICS OF A NON-NEWTONIAN FLUID

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ABSTRACT

A solution of CMC (sodium carboxymethil cellulose) in water has been pumped through a 25.4 mm diameter pipe, without and with a flat disk located on the axis of symmetry and velocity characteristics measured with a laser velocimeter. The solution has power law and consistency indices of 0.67 and 0.195 Pa.s $^{0.67}$ respectively and an apparent viscosity some twenty to thirty times larger than that of water. The maximum Reynolds number achieved in the pipe was 4400 and the mean axial velocity and normal stress suggest transitional flow with a limited logarithmic near wall region. The flow downstream of the disk was found to be asymmetric in the Reynolds number range from 400 to 5600, with a tendency towards symmetry for higher and lower values: the energy spectrum showed evidence of a dominant frequency which may induce the asymmetry with the non-Newtonian nature of the flow augmenting the effect.

INTRODUCTION

The extensive use of non-Newtonian fluids, particularly in the chemical and processing industry, means that they have to be pumped and mixed with minimum consumption of power. Here, we have examined two flows for which detailed knowledge of the flow characteristics is available for Newtonian fluids at high Reynolds numbers and consider the problems associated with the use of a non-Newtonian fluid. The choice of fluid was made so that it would allow the use of laser velocimetry for the measurement of velocity characteristics and its viscosity could be represented by a power law, which is convenient to describe the almost inelastic nature of the fluid. It is well known that non-Newtonian fluids can be considerably more viscous than Newtonian fluids so that a reduction in Reynolds number relative to that achieved with water in the same flow circuit, was anticipated.

The first flow corresponds to fully developed pipe flow for which detailed knowledge is available for laminar and turbulent flow, though uncertainties can exist at transitional Reynolds numbers. The second corresponds to the confined flow around a disk for which Taylor and Whitelaw (1984) have provided detailed information at a Reynolds number, based on the disk diameter and annular bulk velocity, of 57,700 The first corresponds to a geometrically simpler flow for which the local stresses are modest with comparatively smooth gradients and the second to a more complex flow for which local regions of high stress and gradients are known to exist.

FLOW CONFIGURATIONS AND MEASUREMENT TECHNIQUES

The results presented in the following section were made in a section of a long pipe manufactured from perspex with a square outer cross section to reduce diffraction of light beams. The flow was delivered from a constant head tank, 70 diameters from the plane of measurements in the pipe. A 50% area blockage disk was located in this plane for some of the measurements and secured with uncertainty of less than 0.015 mm by four streamlined pylons attached to the sting. The maximum width of the ~~sting~~ pylons was 1 mm and their downstream ends were 40 maximum thicknesses upstream of the disk.Measurements were obtained first with water and resulted in Reynolds numbers of 54,000 and 41,000 for the pipe and disk flow respectively. Measurements of longitudinal velocity confirmed fully developed turbulent flow in the pipe and that the disk flow corresponded closely to that of Taylor and Whitelaw (1984).

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15μm but ±

Measurements of the properties of a number of non-Newtonian fluids led to the use of a 0.4% by weight solution of CMC (sodium carboxymethyl cellulose) in water with 0.07% kathon CG to prevent bacteriological degradation. A plate and cone viscometer was used to measure a power law with index 0.67 and a consistency index of .195 Pa.s$^{0.67}$ at 25° C in a range of strain rates from 2.3 to 10,500 s^{-1}, Pinho (1987); it was also shown that the viscometric viscosity decreased by around 10% if the fluid was pumped through the rig for 6 hours.

Velocity measurements were obtained with a laser velocimeter which had the optical characteristics of Table I. Light was collected at 25 degree to the axis to reduce the size of the measuring volume. Moments of the velocity signal were calculated from the signal processed by a counter, Heitor et al (1984), and energy spectra were obtained from the demodulated signal from a Cambridge Consultants tracking filter (model CC0 8) and a frequency analyzer (Spectral Dynamics SD340). The averages of the velocity signal were corrected for gradient broadening. The longitudinal mean velocity is expected to be accurate within 1 % and the corresponding rms within 5%. The temperature was maintained at 25° C within 0.1° C during all the tests.

Table I- Characteristics of the LDA system

	Pipe flow	Baffle flow
10mW He-Ne laser		
Focal length of lenses		
Imaging lens (nominal)	100 mm	60 mm
Collimating lens (nominal)	300 mm	300 mm
Focusing lens (nominal)	200 mm	200 mm
Measured half angle of beams in air	8.90°	8.90°
Calculated half angle in water and CMC	6.67°	6.67°
Fringe spacing	2.045 μm	2.045 μm
Calculated dimensions of measuring volume in water		
minor axis at e^{-2} intensity	83 μm	50 μm
major axis at e^{-2} intensity	712 μm	424 μm
Calculated number of fringes	40	24
Frequency shift (MHz)	1.534	1.534 and 3.124
Short term stability of shift controller	0.3 %	0.3 %

RESULTS AND DISCUSSION

The maximum average velocity in the pipe was 3.59 m/s which corresponds to a generalized Reynolds number, see Dodge and Metzner (1959), of

$$Re_g = \frac{\rho D^n U^{2-n}}{K 8^{n-1}\left(\frac{3n+1}{4n}\right)^n} = \frac{\rho D U}{\eta_{app}} = 4{,}400$$

The mean velocity profiles for this and lower Reynolds numbers are shown in figure 1 and those at 1100 and less agree well with the theoretical profile

$$\frac{u}{U_o} = 1 - \left(\frac{r}{R}\right)^{\frac{n+1}{n}}$$

which is also shown in the figure. The profiles of normalized rms of the velocity fluctuations increase with Reynolds number and, at 4400, show a maximum value of 5.5% with a slope which is tending towards that of a turbulent flow of a Newtonian fluid. Examination of the near-wall flow, however, shows that the flow has not established a logarithmic region and the deviations, from the theoretical laminar profile stem in part from the need for development length of 0.09 Reg, as indicated by Ramamurthy and Boger (1971).

The pipe flow results show the difficulties associated with arranging a turbulent flow of a non-Newtonian fluid, especially since a closed circuit with a large capacity pump would result in more rapid degradation of the fluid.

A preliminary visualisation of the flow of the non-Newtonian fluid, using dye trace technique in the disk geometry, showed asymmetry and this is recorded in figure 2 which shows the evolution of flow patterns from the symmetric to asymmetric as the maximum annular velocity is increased from 0.1 to 1.0 m/s. Measurements of axial velocity and normal stresses for water flow at Reynolds numbers of 600, 2,700 and 33,000 also indicates asymmetry at the lowest Reynolds number which is replaced by flow symmetry, within the measurement accuracy, at 33,000.

With the flow of non-Newtonian fluid in the disk geometry, a Reynolds number (Re_b) can be defined with the apparent pipe flow viscosity and with the average annular velocity (U_b) and disk diameter (D_b) representing the velocity and length scales. Alternatively the viscosity may be replaced by a value determined from the power law and a characteristic shear rate

$$\dot{\gamma}_{char} = \left(\frac{u_{max} - u_{min}}{\Delta}\right)_{max}$$

where u_{max} and u_{min} are maximum and minimum velocities at locations separated by a distance ,Δ. The second approach yielded higher values within 10% of the first method with a tendency for the difference to increase with reducing Reynolds number. Then, the flow of non-Newtonian fluid with maximum annular velocities of 0.73, 1.0, 2.0 and 6.6 m/s corresponded to Reynolds numbers of 300, 450, 1,130 and 5,600. The magnitude of the asymmetry attains a maximum at a Reynolds number around 1,000 and decreases afterwards as can be deduced from figure 4.

It is well known, see for example Walters and Webster (1982), that non-Newtonian fluids can amplify asymmetries at very low Reynolds numbers but information of the present flow with its moderate Reynolds numbers is unknown. On the other hand, the measurements of Calvert (1967) and Ko and Chan (1979) have shown that the flow around disks, or other bluff bodies, gives rise to a predominant frequency, and Sivasegaram and Whitelaw (1985) have shown that confined disk flows can also involve periodicity, although with reduced amplitude. Spectral analysis of the axial velocity signal from the velocimeter showed a periodicity corresponding to a Strouhal number of 0.07 based on the definition

$$St = f\, D_{baffle} / U_{annular}$$

In contrast to the results of Sivasegaram and Whitelaw, the periodicity signal was more prominent within the region of separated flow but it could be detected everywhere except in the annular jet where more random fluctuations were of greater amplitude. The Strouhal number is less than that of Sivasegaram and Whitelaw who measured a value of around 0.3 and, since the geometry is similar, the differences may be due to the nature of the velocity profiles in the plane of the disk which will have different shapes due to different velocities and viscosities. It remains to be determined if the same phenomena can be observed in a Newtonian fluid with Reynolds numbers similar to these examined here with a non-Newtonian fluid. Certainly, similar time-dependent induced asymmetry has been observed, for example by Cherdron, Durst and Whitelaw(1977), at moderate Reynolds numbers with a Newtonain fluid.

CONCLUSION

Measurements of the velocity characteristics of the flow of a non-Newtonian fluid in a pipe have quantified problems associated with pumping and mixing. Thus, due to the high apparent viscosity of the non-Newtonian fluid, the maximum Reynolds number was more than ten times less than that which could be achieved with water for the same pressure head and a fully turbulent flow could not be established. The confined flow about a disk was asymmetric at the largest Reynolds number which could be achieved and this may have its origins in the measured periodicity of the flow. It remains to determine if the same phenomena is observed with a Newtonian flow at the same Reynolds number.

ACKNOWLEDGMENTS

The authors are grateful to the European Commission, Imperial Chemical Industries and Unilever for financial support through a BRITE award and for their continuing help and encouragement.

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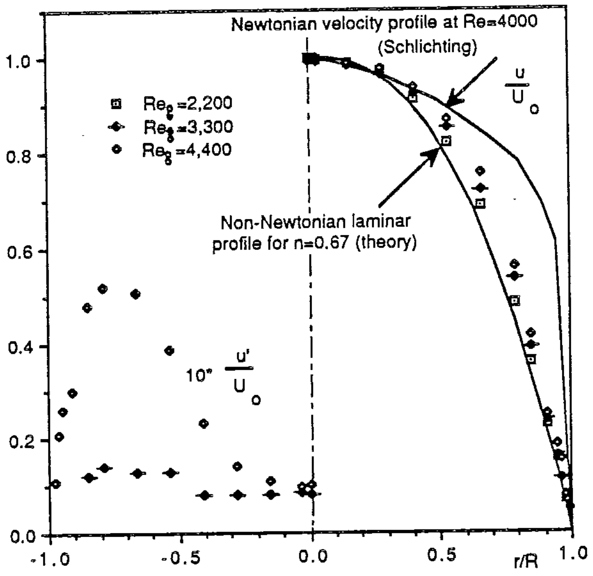
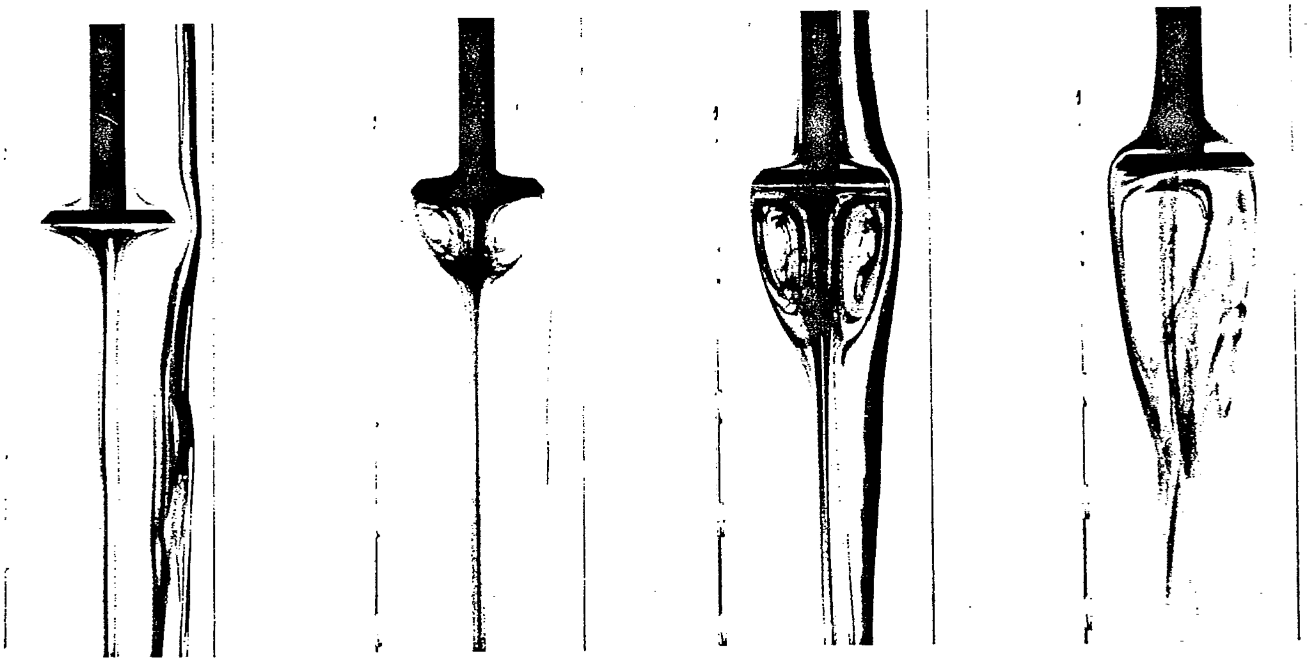


Figure 1- Axial mean and rms velocities normalised with the velocity at the axis for CMC



Re_b= 20 Re_b= 80 Re_b= 170 Re_b= 460

Figure 2- Evolution of the recirculation bubble with the Reynolds number for CMC

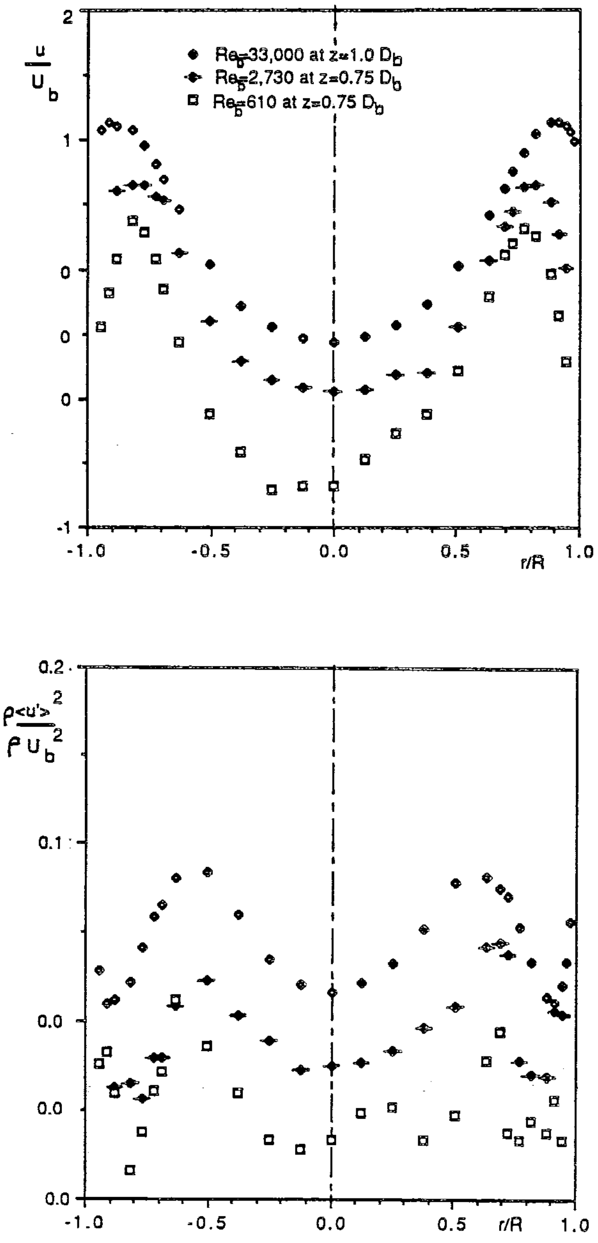


Figure 3- Axial mean velocity and normal stress normalised with annular bulk velocity for water in the disk flow (z=1.0 D means measurement at one disk diameter downstream of baffle)

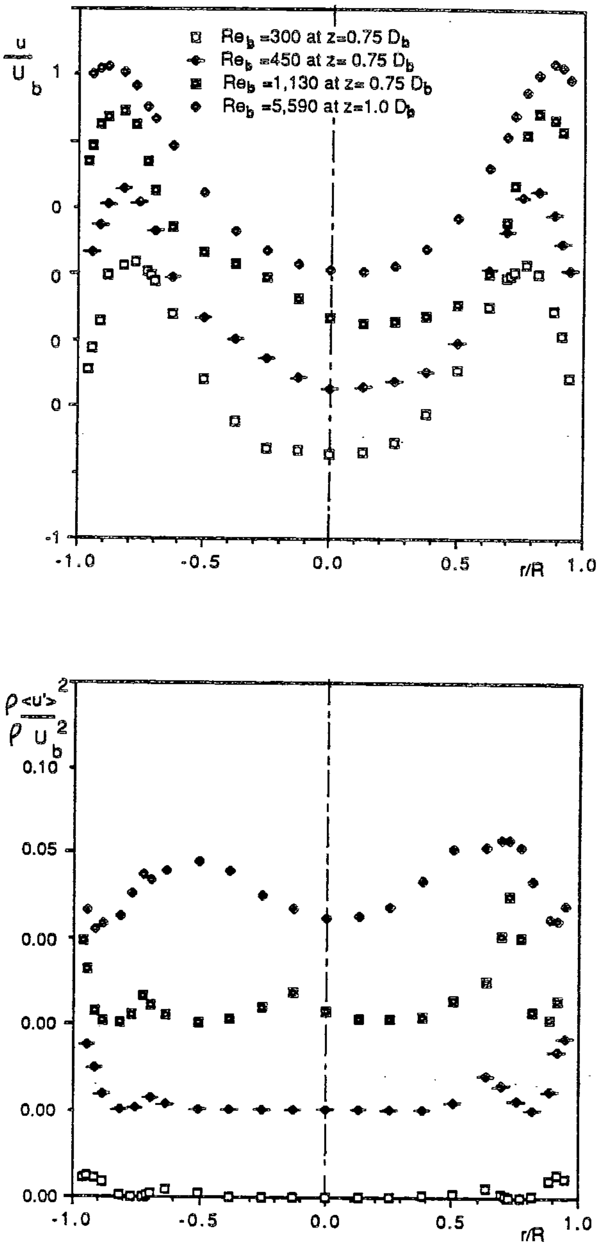


Figure 4- Axial mean velocity and normal stress normalised with annular bulk velocity for CMC in the disk flow.