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CHARACTERISTICS OF NON-NEWTONIAN RECIRCULATING FLOWS AT LOW AND MODERATE REYNOLDS NUMBERS

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ABSTRACT

Velocity characteristics of the flow of aqueous solutions of CMC (carboxymethyl cellulose) downstream of a 50% area blockage disk located on a 25.4 mm diameter pipe have been measured with a laser-Doppler velocimeter. The polymer solutions, at concentrations of 0.2 and 0.4% by weight, were weakly elastic and shear-thinning and a viscous Newtonian fluid with a viscosity ten times that of water was also investigated for comparison. The asymmetry and unsteadiness of the flow in the near wake of the body, previously reported by Pinho and Whitelaw (1988), was confirmed and the dominant frequency of the bubble oscillation decreased with polymer concentration at Reynolds numbers between 400 and 5,600. Below 400, the flow was symmetric, the axial turbulence generated in the shear layer was quickly suppressed and the recirculation bubble length varied almost linearly with Reynolds number with the 0.4% CMC solution. At Reynolds numbers in excess of 7,500, the flow was symmetric again and the turbulence was dampened proportionally to the polymer concentration so that, with a 0.4% CMC solution, the maximum turbulent kinetic energy was 45% lower than with a Newtonian fluid.

Introduction

Detailed velocity information on Newtonian fluid stirring flows has been provided by Popiolek, Yianneskis and Whitelaw (1987) and Nouri (1988) but little is available for non-Newtonian fluids. An investigation is in progress, Hockey (1990), and was preceeded by the investigation of turbulent pipe flow with polymer solutions of Pinho and Whitelaw (1990), who quantified the delay in transition from laminar to turbulent flow and showed the supression of turbulent fluctuations, particularly in the radial and tangential directions, thus providing information to assist understanding of the flows over the impeller blades in stirred vessels.

The present investigation analyses the behaviour of non-Newtonian fluids in recirculating flows and is relevant to the understanding of the flow emanating from stirred vessel impellers. It follows that of Pinho and Whitelaw (1988), who reported asymmetric flow at Reynolds numbers between 400 and 5,600, regardless of fluid rheology, and showed evidence of bubble unsteadiness with a dominant frequency but, did not quantify the effects of shear-thinning intensity. Velocity characteristics of the symmetric flow at Reynolds numbers below 400 are also considered here as are those at Reynolds numbers in excess of 8,000 where the flow has some of the characteristics of fully developed turbulent flow.

Flow configuration, instrumentation and fluid properties

The flow configuration is similar to that of Pinho and Whitelaw (1989) and consisted of a long 25.4 mm inside diameter vertical pipe with a square outer cross section to reduce diffraction of light beams. The fluid circulated in a closed circuit, pumped from a 60 litre tank through 90 diameters of pipe to the transparent acrylic test section and through a further 30 diameters back to the tank. The flow was controlled with two valves and the velocity and pressure drop measurements monitored the flow rate within 10% between different days. The 50% area blockage disk was located inside the 75 mm long test section and secured on the axis, with an uncertainty of less than 0.015 mm, by four streamlined pylons of 1 mm width attached to the sting and their trailing edges were 40 maximum thicknesses upstream of the plane of the disk.

The polymer was sodium carboxymethil cellulose (CMC grade 7H4C manufactured by Hercules) at concentrations of 0.2 and 0.4% by weight with 0.05 and 0.07% of Kathon CG (Rohm and Haas) added to prevent bacteriological deterioration. The fluids circulated in the rig for periods of less than 6 hours during which the viscosity decreased by 10% due to mechanical degradation, see Pinho (1990). The viscometric viscosity of the weakly elastic shear-thinning CMC solutions is represented in figure 1 as a function of the shear rate at 25° C. The viscous Newtonian fluid was a 53.2% by volume solution of glycerol in water with a density, kinematic viscosity and refractive index of 1142Kg/m^3, 10.1cS and 1.4135 respectively at 25°C.

Velocity measurements were obtained with a laser velocimeter operating in the forward scatter mode and with the characteristics of table 1. The signal was processed by a counter, Heitor *et al* (1984), interfaced with a computer which provided all the moments of velocity whereas 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 maximum uncertainties in the mean and rms velocities at a 95% level of confidence were 2% and 7% respectively, in regions of high turbulence and the temperature of the fluid was maintained at 25 °C within 0.1° C during all tests. In the absence of the baffle, the flow in the test section gave rise to a linear pressure distribution for all flows considered, and gradient broadening effects existed only in the

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immediate vicinity of the pipe wall.

Table 1- Principal characteristics of the Laser-Doppler velocimeter

Beam diameter of laser at e^{-2} intensity	0.65 mm
Focal length of lenses	
Imaging lens (nominal)	60 mm
Collimating lens (nominal)	300 mm
Focusing lens (nominal)	200 mm
Measured half angle of beams in air	8.90 °
Calculated half angle of beams in	
CMC solutions	6.67 °
viscous Newtonian fluid	6.41 °
Fringe spacing	2.039 µm
Calculated dimensions of control volume at e^{-2} intensity	
for CMC	
minor axis	50 µm
major axis	424 µm
for viscous Newtonian fluid	
minor axis	50 µm
major axis	442 µm
Calculated number of stationary fringes	24
Frequency shift [MHz]	0.9 to 6.89

The effective viscosity was calculated for a shear rate defined as

$$\dot{\gamma}=\left[\frac{U_{max}-U_{min}}{\Delta r}\right]_{max} \quad (1),$$

that represents an average value in the recirculation and shear layer regions in a plane close to the center of the recirculation bubble. U_{max} and U_{min} are the maximum positive and negative velocities in the annular jet and recirculation regions and Δr is the radial distance between them. The viscosity obtained from this definition and the relationships of figure 1, together with the diameter of the disk and annular bulk velocity, formed the Reynolds number.

Results and Discussion

At Reynolds numbers between 400 and 5,600, the flow of Newtonian and non-Newtonian fluids in the near wake of the bluff body was asymmetric as shown in the diametral profiles of axial mean velocity and normal Reynolds stress of figures 2 and 3, with the glycerin and the 0.2% CMC solutions respectively at 1 baffle diameter downstream of the disk. However, the effect was larger with higher polymer concentrations with the asymmetry preserved at Reynolds numbers higher than 5,600. The flow was also unsteady in the centreline region close to the baffle, and a frequency analysis of the instantaneous axial velocity measured by a frequency tracker demodulator detected a frequency (f) of the oscillation which, when normalised by the baffle diameter and annular bulk velocity, defined a Strouhal number ($St=fD/U_0$) of 0.094 for Newtonian fluids, 0.079 for 0.2 % CMC and, as reported by Pinho and Whitelaw (1988) of 0.07 for 0.4 % CMC, all values with a maximum uncertainty of 0.005. The energy associated with the oscillations was high as shown in the large amplitude of the peaks of the frequency spectra of figure 4 with 0.2% CMC for Reynolds numbers between 1,045 and 5,520

At Reynolds numbers under 400 the flow was symmetric and laminar and, the axial turbulence generated in the shear layer between the recirculation bubble and annular jet was quickly dissipated as shown in the radial profiles of axial normal Reynolds stress of figure 5 with the 0.4% CMC solution at a Reynolds number of 210. The variation of the recirculation bubble length with Reynolds number was strong for all fluids so that, with a 0.4% CMC solution, the bubble did not exist at Reynolds numbers less than 20, figure 6 a). The irregular variation of the recirculation bubble length at Reynolds numbers between 500 and 6,000 in figure 6 b) is due to the fact that the length was measured along the centreline and the distortion of the bubble prevents its tip to be on axis, during the asymmetric flow. At Reynolds numbers in excess of 7,500 the flow was symmetric and turbulent with the turbulence levels depending on polymer concentration so that, for instance at a Reynolds number around 8,000 the maximum levels of normal Reynolds stresses were dampened by 30, 60 and 45% respectively in the axial, radial and tangential direction as the polymer concentration increased from 0 to 0.4% CMC.

The flow asymmetry at moderate Reynolds numbers seems similar to that found by Cherdron, Durst and Whitelaw (1978) in a sudden expansion at low Reynolds number, and is the result of the amplification of instabilities that are shed from the edge of the disk. The asymmetric nature of those instabilities creates an asymmetric flow that interacts with the recirculating flow and a low frequency periodic oscillation of the bubble is established, similar to the precession of the swirl centre in the recirculation region of a steady open cylinder flow behind an engine valve, Arcoumanis *et al* (1987). This frequency is two to three times lower than that of the oscillations in the shear layer due to vortex shedding from the baffle, Calvert (1967), which is not detected in the present case because confinement and the high blockage ratio conceals it in the overall flow oscillations, as shown by Sivasegaram and Whitelaw (1985).

The preservation of the asymmetric flow at higher Reynolds numbers with the more concentrated polymer solutions is similar to the delay in transition between laminar and turbulent flow observed in the pipe flow of Pinho and Whitelaw (1990) with the same fluids and is the result of a viscosity increase due to molecular stretching, a phenomena that affects the elongational viscosity rather than the viscometric viscosity used in the Reynolds number calculation. Simultaneously, a higher polymer concentration increases the degree of shear-thinning and the viscosity inside the recirculation bubble becomes larger because of the low local average strain rates.

At Reynolds numbers in excess of 7,500 the flows of Newtonian and non-Newtonian fluids are symmetric with characteristics of turbulent flow. Fully developed turbulent flow is achieved below a Reynolds number of 50,000, see Pinho and Whitelaw (1989) so that, at a Reynolds number of around 8,000, the increase in CMC concentration dampens the turbulence especially in the tangential and radial directions, figure 7 a), thus lengthening the recirculation bubble because of a decrease in radial momentum exchange, figure 7 b); the reduction in the maximum values of normal Reynolds stresses between 0.4% CMC and the glycerin solution was of 31, 60 and 43% for the axial, radial and tangential components respectively.

Many non-Newtonian fluids have viscosities high enough to prevent high Reynolds numbers, as shown in the pipe flow experiments of Pinho and Whitelaw (1990) where with a bulk velocity of 5 m/s Reynolds numbers of 111,000 and 7,700 were achieved with water and 0.4% CMC respectively. That, together with the ability of concentrated polymer solutions to preserve transitional flow characteristics at higher Reynolds number flows, leads to the possibility of having stirred vessel flows with transitional aerodynamic characteristics, possibly including flow unsteadiness, at Reynolds numbers where the Newtonian flows would be turbulent, symmetric and steady. This is consistent with the longer preservation of asymmetry and unsteady flow below Rushton impellers and of the radial flow emanating from pitched blade impellers at low Reynolds number, as reported by Hockey, Nouri and Pinho (1989). At

Reynolds numbers where the flow is turbulent and symmetric the turbulent kinetic energy can be reduced by up to 45% thus decreasing the quality of micromixing.

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References

Arcoumanis, C., Hadjiapostolou, A. and Whitelaw, J. H., 1987. Swirl centre precession in Engine flows. *Society of Automotive Engineers*, 870370.

Calvert, J. R. 1967. Experiments on the low speed flow past cones. *J. Fluid Mech.*, **27**, 273.

Cherdron, W., Durst, F. and Whitelaw, J. H. 1978. Asymmetric flows and instabilities in symmetric ducts with sudden expansions. *J. Fluid Mech.*, **84**, 13.

Hockey, R.M. 1990. *Turbulent Newtonian and non-Newtonian flows in stirred vessels.* PhD Thesis, University of London.

Nouri, J. M. 1988. *Single and two-phase flows in ducts and stirred reactors.* PhD Thesis, University of London.

Pinho, F. T. and Whitelaw, J. H. 1988 Flow characteristics of a Non-Newtonian fluid. *4th Int. Symp. on Applications of Laser Anemometry to Fluid Mechanics*, July 1988, Lisbon, Portugal.

Pinho, F. T. and Whitelaw, J. H. 1989. Flow of non-Newtonian fluids over a confined baffle. *Fluids Section, Mechanical Engineering Dep., Imperial College,* London, report FS/89/23

Pinho, F. T. 1990. *Velocity Characteristics of polymer solutions in ducts.* PhD Thesis. University of London.

Pinho, F. T. and Whitelaw, J. H. 1990 Flow of Non-Newtonian fluids in a pipe, *J. Non-Newt. Fluid Mech.*, **34**, 129

Popiolek, Z., Yianneskis, M. and Whitelaw, J. H. 1987. An experimental study of the steady and unsteady flow characteristics of stirred reactors, *J. Fluid Mech.*, **175**, 537.

Sivasegaram, S. and Whitelaw, J. H. 1985. Vortex shedding in disk stabilized flames. *Fluid Section, Mechanical Enigineering Department, Imperial College*, London, report FS/85/1.

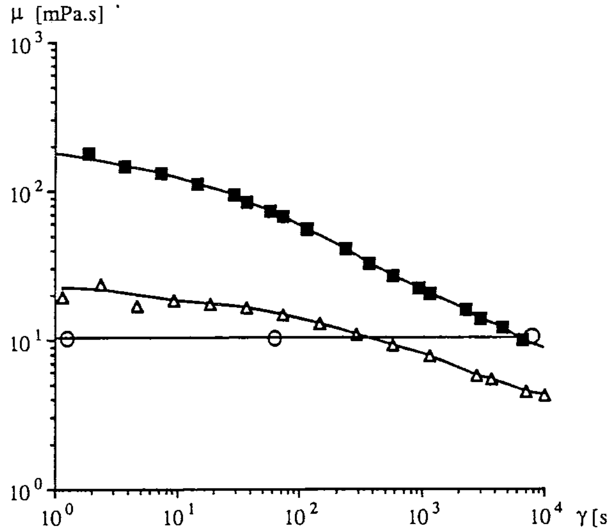

Figure 1- Viscosity of CMC at 25° C. O Glycerin-water solution; Δ 0.2% CMC; ■ 0.4% CMC by weight.

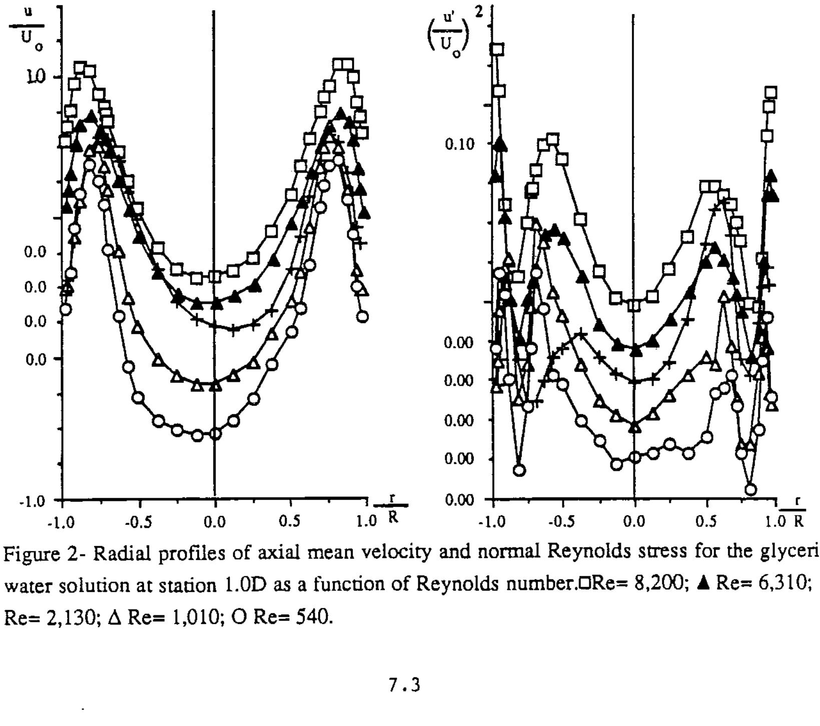

Figure 2- Radial profiles of axial mean velocity and normal Reynolds stress for the glycerin water solution at station 1.0D as a function of Reynolds number.□Re= 8,200; ▲ Re= 6,310; + Re= 2,130; Δ Re= 1,010; O Re= 540.

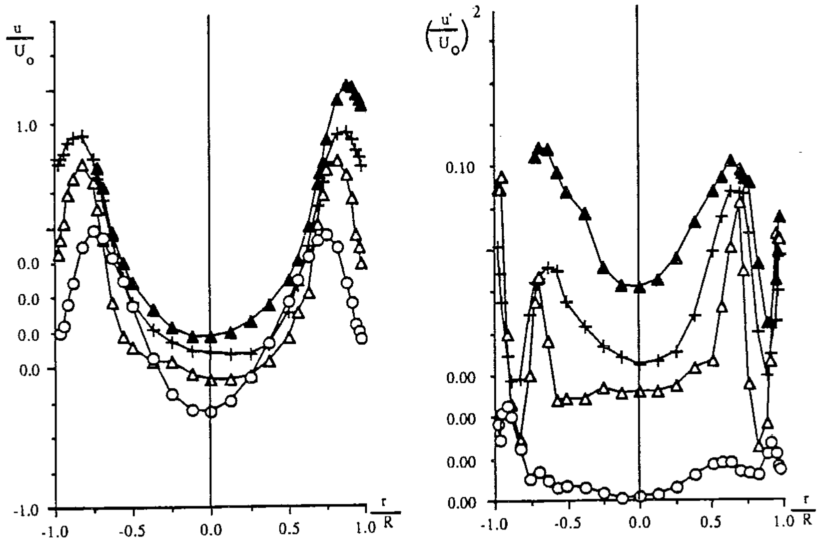

Figure 3- Diametral profile of axial mean velocity and normal Reynolds stress for 0.2% CMC solution at station 1.0 D. ▲ Re= 8,250; + Re= 5,520; Δ Re= 1,040; O Re= 220.

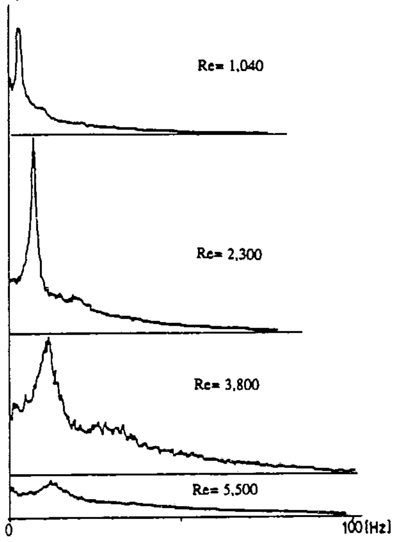

Figure 4- Frequency spectra of 0.2% CMC at z/D=0.5 and r=0 as a function of Reynolds number.

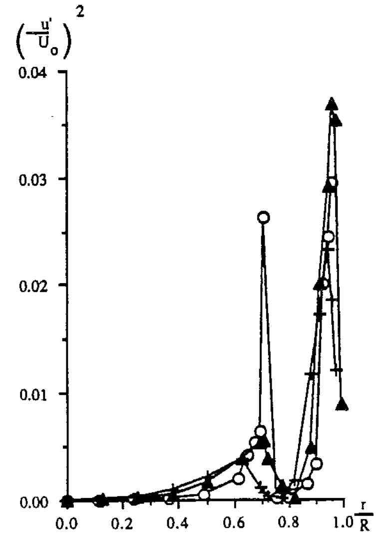

Figure 5a)- Radial profiles of axial normal Reynolds stress for 0.4% CMC at a Reynolds number of 210. O 0.25D; ▲ 0.5D; + 0.75D.

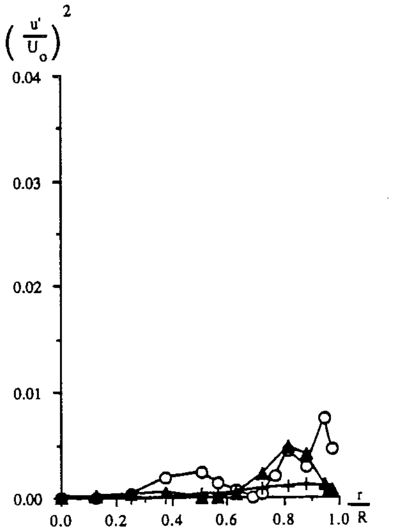

Figure 5b)- Radial profiles of axial normal Reynolds stress for 0.4% CMC at a Reynolds number of 210. O 1.0D; ▲ 1.407D; + 3.0D.

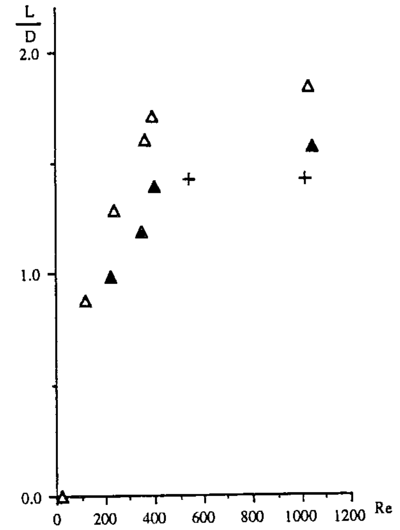

Figure 6a) Bubble length normalised by baffle diameter. Δ 0.4% , ▲ 0.2% CMC, + Newtonian fluid.

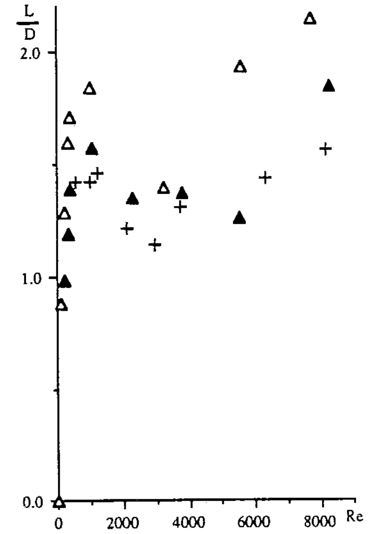

Figure 6b) Bubble length normalised by baffle diameter. Caption as in fig. 6 a).

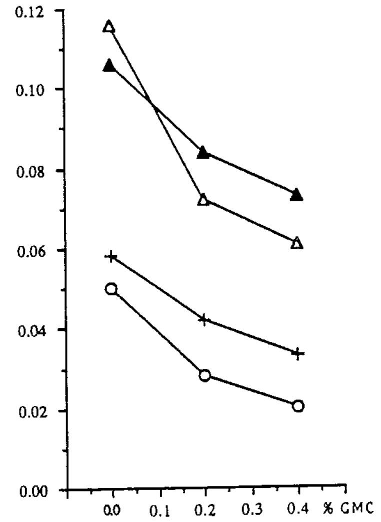

Figure 7a) Normalised axial (▲), radial (O) and azimuthal (+) Reynolds stress and TKE (Δ) as a function of CMC concentration at Re= 8,000.

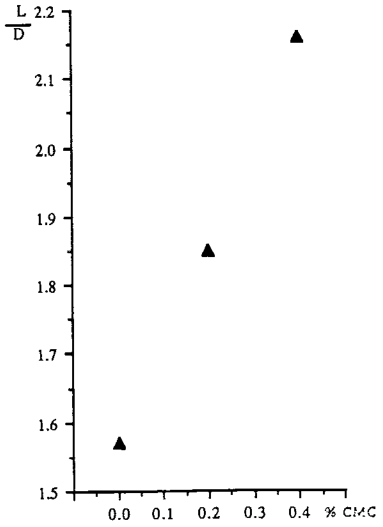

Figure 7b) Normalised recirculation bubble length as a function of CMC concentration at Re = 8,000.