

## LDA measurements of non-Newtonian liquids in pipe flow.

**Robert J. Poole, Sergio Rosa, Marcel P. Escudier**

Department of Engineering, The University of Liverpool, Liverpool L69 3GH, UK, robpoole@liv.ac.uk  
s.rosa@liv.ac.uk, m.p.escudier@liv.ac.uk

---

**Abstract** In this paper we report measurements of mean and fluctuating axial velocities, measured using a laser Doppler anemometer, for a 0.125% solution of a polyacrylamide, Separan AP 273 E, in fully-developed pipe flow. Although the results cover the laminar, transitional and fully turbulent regime, particular attention is placed on the transition regime, where, as has been observed previously, the mean velocity profiles exhibit a stable, and repeatable, asymmetry. Radial distributions of axial velocity at three axial locations, and for various azimuthal angles, highlight the three dimensional nature of this asymmetry.

---

### 1. Introduction

In the last decade or so considerable advances have been made in understanding the transition mechanism from laminar to turbulent flow for Newtonian liquids in pipes. Important experimental studies conducted by Mullin and collaborators using a unique syringe-pump device (Darbyshire and Mullin (1995), Hof, Juel and Mullin (2003)) have provoked considerable theoretical advances (Walaffe (1997,2003), Faist and Eckhardt (2004)) as have the experiments of the 'Delft' group led by Nieuwstadt (Draad et al (1998), Hof et al (2004), Hof et al(2005)). For non-Newtonian liquids however, perhaps unsurprisingly given the inherent additional complexities involved, little is known. Aside from a handful of papers, which we discuss below, there is virtually no data about the transitional flow of such non-Newtonian liquids. Although limited, the existing literature for the transitional pipe-flow of non-Newtonian liquids reveals an interesting, and as yet unexplained, effect: above a certain Reynolds number the flow develops a stable asymmetry. For laminar and fully turbulent flows the profiles are symmetric. Independent observations of the same stable asymmetry have been observed in the UK (Escudier and Presti (1996)), France (Peixinho et al (2005)) and Australia (Pullam (2005)). We have jointly published these, and additional, observations recently (Escudier et al (2005)) to highlight the effect. In the current paper we extend these results by recording the three-dimensional structure of such asymmetrical velocity profiles.

### 2. Experimental facility and Instrumentation

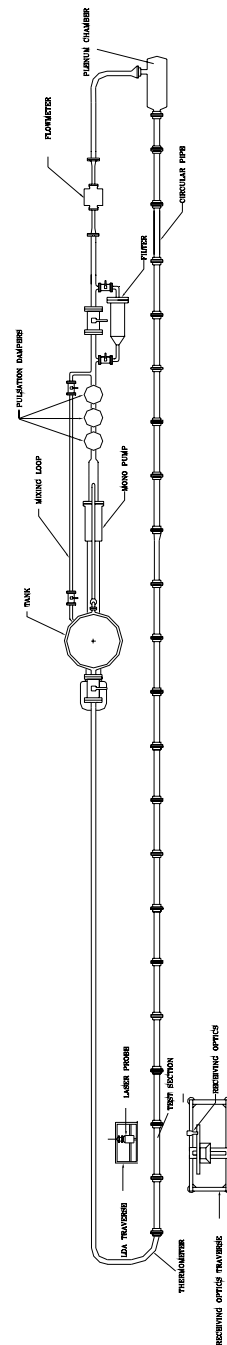
The flow loop used for the present experiments, shown in **Figure 1**, is a modified version of that used by Escudier and Presti (1996) for their pipe-flow investigation of Laponite, a synthetic clay, and so only the briefest details are given here. In the current set-up, immediately upstream of the pipe test section, a cylindrical plenum chamber, 70l in capacity (720mm in length, inner diameter 354mm), was installed to replace the original inlet bend to the test section. The plenum chamber was intended to minimize any asymmetry in the flow entering the test section. Within the plenum chamber was a disc of the same diameter equal to the inner diameter of the plenum chamber, with a series of symmetrically-placed holes which combine to give an open area twice that of the plenum chamber exit area ( $7.85 \times 10^{-3} \text{ m}^2$ ). Immediately downstream of the plenum-chamber

inlet was a 90° bend within the plenum interior that directed flow to the rear wall of the chamber. A crossbeam flow straightener was located at the plenum-chamber outlet to suppress any residual swirling motion in the fluid entering the test section. In addition to the inclusion of a plenum chamber, the original pipe flow test section has been extended and now consists of twenty-two precision bore borosilicate glass tubes (ID=100.4±0.1 mm), each of which was assembled into a module with matched male/female stainless steel flanges at alternate ends, providing an overall test-section about 23m in length. Velocity profiles for a 0.125% solution of a polyacrylamide, obtained using a laser Doppler anemometer (LDA), are measured at axial locations corresponding to approximately 15, 65 and 220 diameters downstream of the inlet plenum. Distributions of axial velocity were obtained initially along a horizontal radial line with additional profiles being obtained for various azimuthal angles for a profile exhibiting a high degree of asymmetry (Re=8230).

A Dantec Fibreflow laser Doppler anemometer system was used for the velocity measurements and comprised a Dantec 60X10 probe and a Dantec 55X12 beam expander in conjunction with a Dantec Burst Spectrum Analyzer signal processor (model 57N10). The beam separation at the front lens was 51.5 mm and the lens focal length 160 mm which produced a measurement volume in water with principal axis of length 0.21 mm and diameter 0.02 mm. In view of the small diameter of the measuring volume, no correction was applied for the effect of velocity-gradient broadening. As recommended by Tropea (1995), transit-time weighting was used to correct the velocity measurements for the effects of velocity bias. At each location, nominally 20000 velocity samples were collected which resulted in a maximum relative statistical error, for a 95% confidence interval, of approximately 0.5% in the mean velocity and 1.4% in the turbulence intensity (Yanta and Smith (1978)). The total uncertainty in the mean velocity is estimated to be in the range 3-4% and in the range 6-7% for the turbulence intensities.

A platinum-resistance thermometer mounted in the final module of the test section was used to monitor the fluid temperature to an accuracy of ±0.1°C. The bulk flow rate  $\dot{Q}_F$  was measured using a Endress and Hauser Coriolis flowmeter (model Promass 63) incorporated in the flow loop upstream of the test section with the flowmeter output signal recorded via an Amplicon PS 30AT A/D converter.

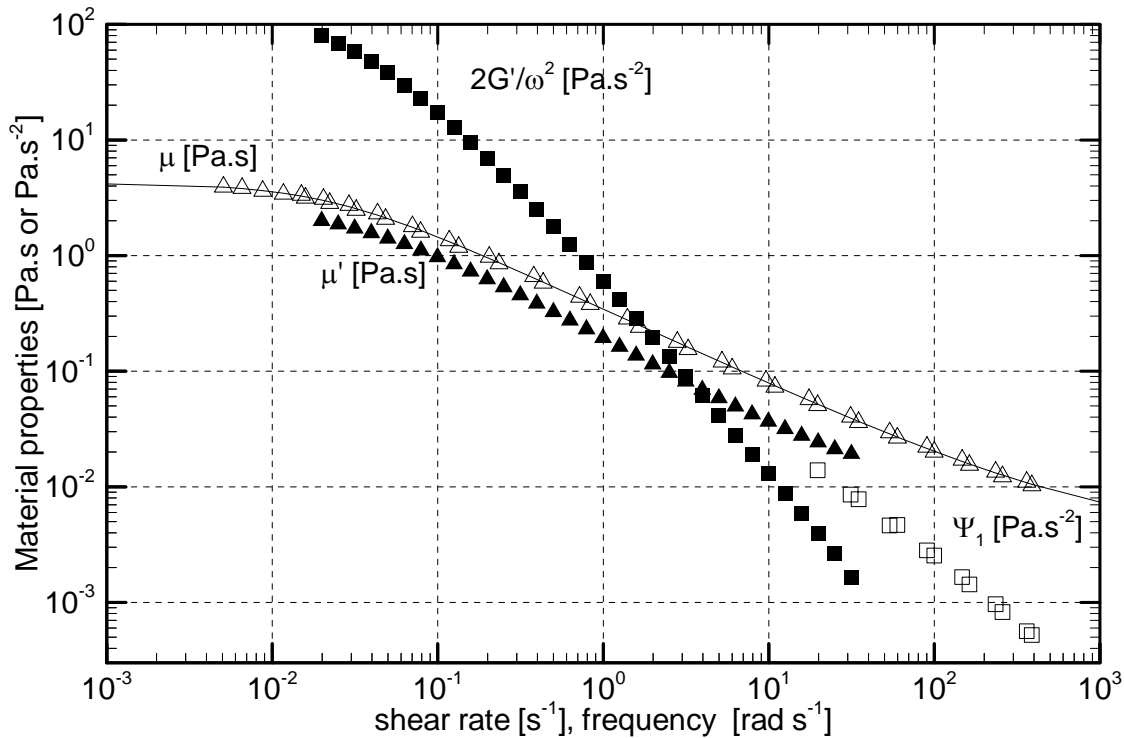
Steady shear and oscillatory shear rheological measurements were carried out using a TA Instruments Rheolyst AR 1000N controlled-stress rheometer at a temperature of 20 °C which was also the average temperature of the fluid within the flowloop for the duration of the experimental runs. Temperature control of the rheometer is achieved via a plate that uses the Peltier effect to control the temperature of the sample to within ±0.1 °C. The rheological characterization included measurements of shear viscosity  $\mu(\dot{\gamma})$ , the first normal-stress difference  $N_1$ , the storage modulus  $G'$  and the loss modulus  $G''$ .



**Figure 1:** Schematic of experimental rig

### 3. Rheology

The working fluid used in this investigation was a 0.125% by weight aqueous solution of a polyacrylamide (PAA), Separan AP273 E supplied by Floerger. The solvent was filtered tap water with 100 ppm of 40% formaldehyde solution added to retard bacterial degradation. Approximately 0.25 gm of Timiron seeding particles were added to the working fluid, total volume 700 litres, to improve the LDA signal quality.



**Figure 2:** Rheological properties of the shear-thinning, viscoelastic test fluid (0.125% PAA) in steady shear flow ( $\square$ ,  $\triangle$ ) and small amplitude oscillatory shear flow ( $\blacksquare$ ,  $\blacktriangle$ ) including Carreau-Yasuda fit to shear viscosity data ( $\text{—}$ ).

The measured rheological properties are shown in **Figure 2**. The data obtained in steady shear, the shear viscosity and first normal-stress difference, are represented by hollow symbols ( $\triangle$ ,  $\square$ ) and that obtained in oscillatory shear, the ‘dynamic’ viscosity (i.e.  $\eta' = G''/\omega$ ) and the dynamic rigidity ( $=2G'/\omega^2$ ), by filled symbols ( $\blacktriangle$ ,  $\blacksquare$ ). In the limit of zero shear rate/frequency the shear viscosity should equal the ‘dynamic’ viscosity. In the current measurements we could not go to low enough frequencies to confirm this but the agreement can be regarded as satisfactory. Included with the experimental data is the Carreau-Yasuda model fit to the shear viscosity data:

$$\mu_{CY} = \mu_{\infty} + \frac{\mu_0 - \mu_{\infty}}{\left(1 + (\lambda_{CY} \dot{\gamma})^a\right)^{n/a}} \quad (1)$$

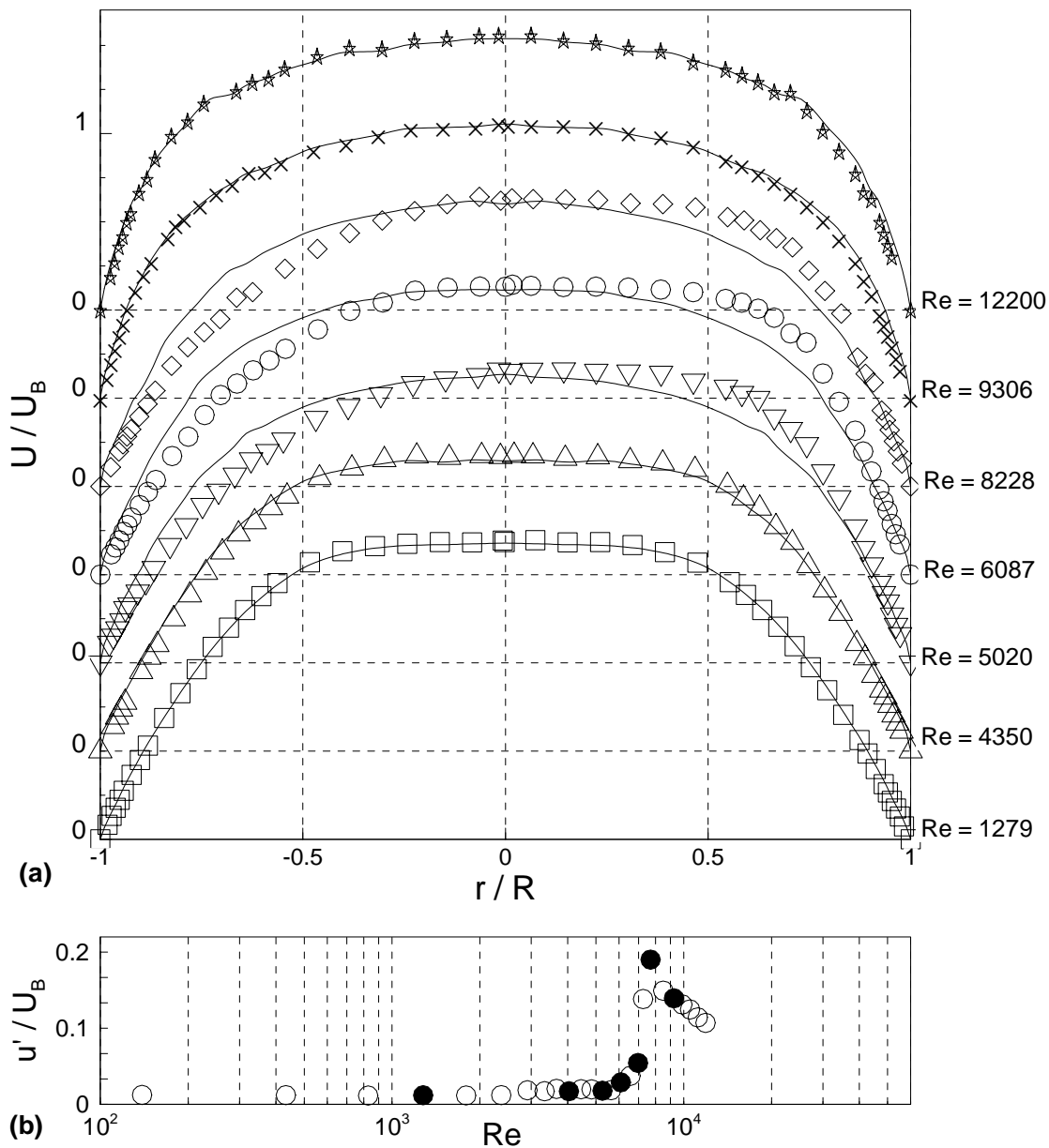
$\mu_0 = 4.22$  Pa.s being the zero-shear-rate viscosity,  $\mu_{\infty} = 0.00372$  Pa.s the infinite-shear-rate viscosity,  $\lambda_{CY} = 45.8$  s a constant which represents the onset of shear-thinning,  $n = 0.66$  a power-law index and  $a = 1.25$  a parameter introduced by Yasuda et al (1981). The parameters were determined using the least-squares-fitting procedure outlined by Escudier et al (2001).

## 4. Results and Discussion

The axial velocity profiles shown in **Figure 2** cover a range of Reynolds numbers which span the three flow regimes. The definition adopted here for the Reynolds number is

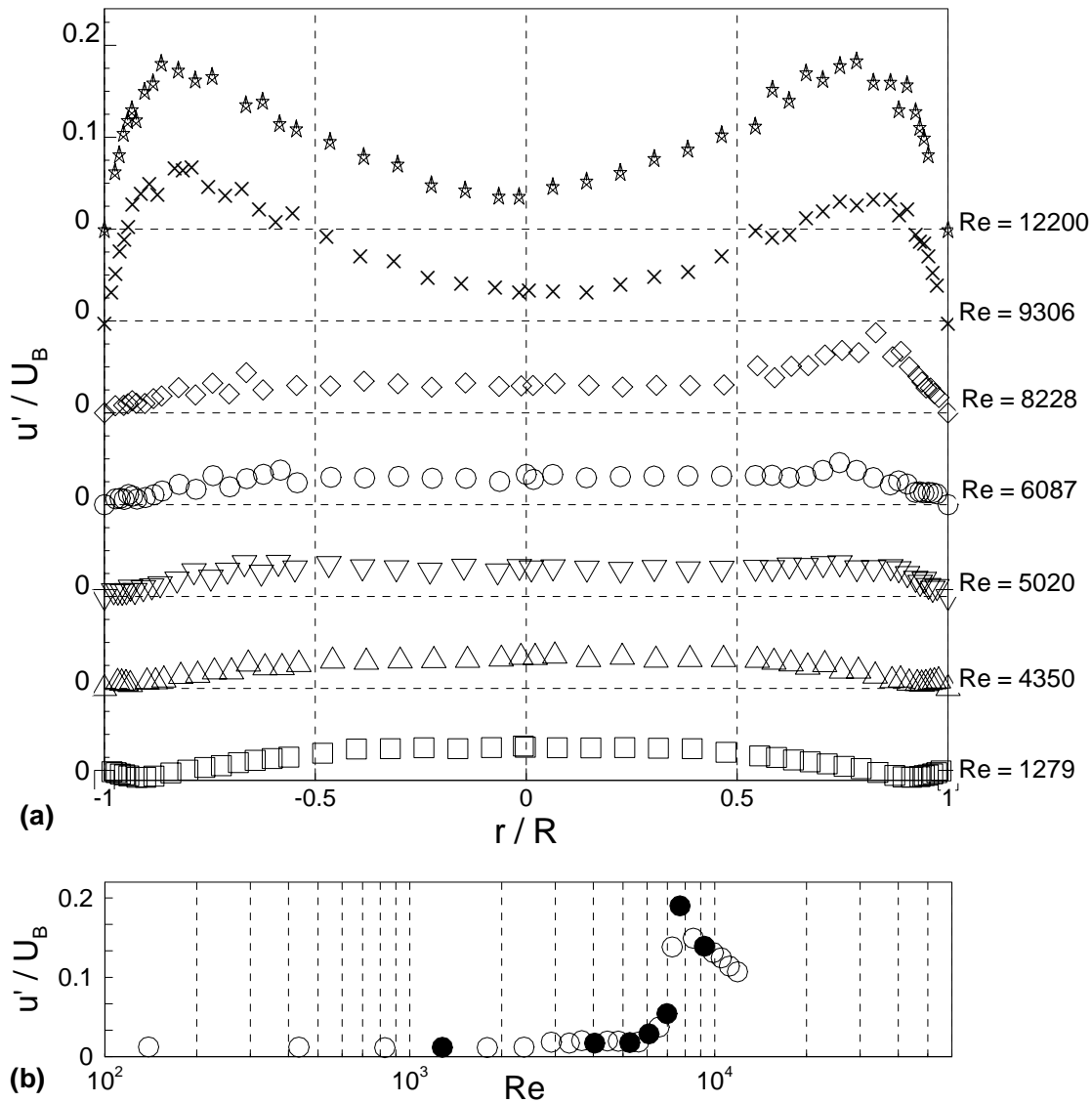
$$Re = \frac{\rho U_B D}{\mu_w} \quad (2)$$

where the viscosity  $\mu_w$  was determined from the Carreau-Yasuda model fit at a shear stress determined from pressure drop measurements. Also included in **Figure 3(a)** are reference curves corresponding to an average of the velocity data on either side of the centreline. Below the



**Figure 3** (a) Mean velocity profiles for 0.125% PAA (including average data line)  
 (b) Velocity fluctuation levels at  $r/R = 0.8$  to indicate transition.

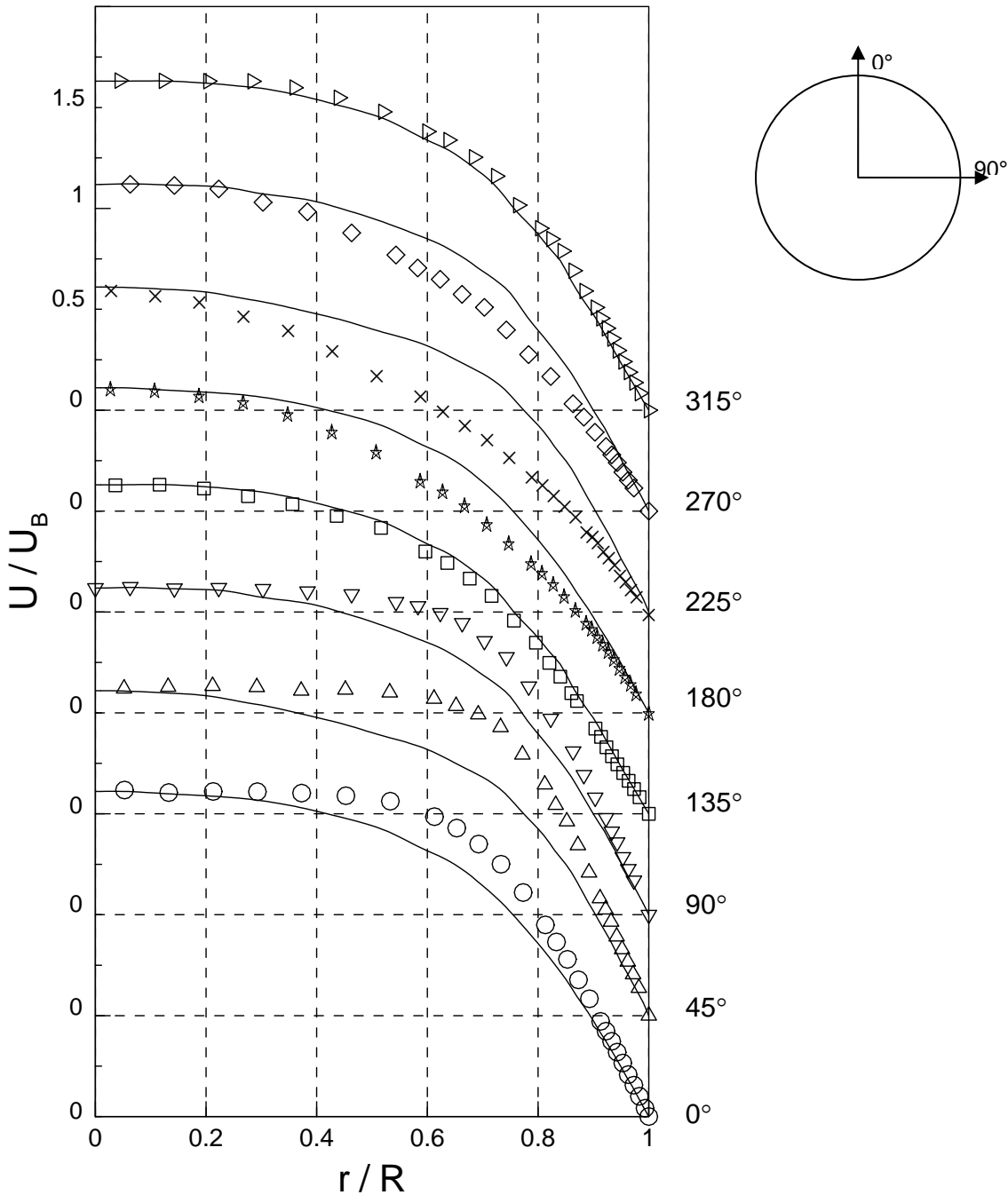
velocity profiles, in **Figure 3(b)**, is the variation of the near-wall ( $r/R = 0.8$ ) axial-velocity fluctuation level  $u'$  (rms) which Escudier and Presti (1996) showed is a reliable indicator of the flow regime. At the lowest  $Re$  the flow is laminar and the profile symmetric. As  $Re$  is increased a progressive asymmetry develops. In agreement with previous observations (Escudier et al (2005)), a return to symmetric flow is observed at higher Reynolds numbers. In **Figure 4** we plot the corresponding axial turbulence intensities. For the lowest Reynolds number studied ( $Re = 1279$ ) the flow is laminar and the “turbulence” levels are an indication of the inherent noise within our LDA system.



**Figure 4** (a) Profiles of fluctuating axial velocity for 0.125% PAA  
 (b) Velocity fluctuation levels at  $r/R = 0.8$  to indicate transition.

For the  $Re = 1279$  profile the maximum level of this fluctuation was about 3.5% when normalized by  $U_B$ : this figure reduces to about 2% when normalized by the *local* fluid velocity. Based on these profiles, remembering that for the higher  $Re$  profiles they only represent a single “cut” through a non-axisymmetric flowfield, it appears that the flow remains laminar up to Reynolds numbers of about 5000. Although the oft-quoted value of transition to turbulence for Newtonian pipe flows of  $Re \approx 2200$  is, in fact, not universal (with great care, transition to

turbulence in a pipe can be delayed to extremely high values of the Reynolds number ( $O(100,000)$ ) in the current experimental rig transition was seen to occur at about this value of  $Re$  (Escudier et al (2005)). Our results thus suggest that polymer solutions delay the onset of turbulence in agreement with the earlier work of Draad et al (1998) for a much lower concentration of polyacrylamide.



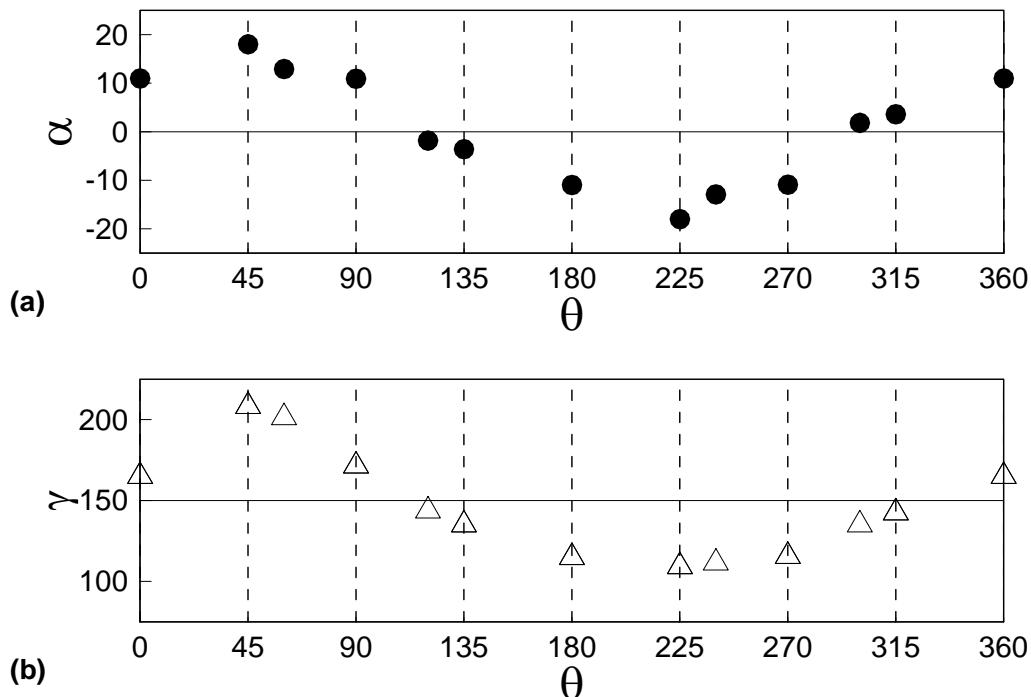
**Figure 5:** Radial variation of mean axial velocity for various azimuthal angles  $\theta$  for  $Re = 8230$  at an axial location  $220 D$  downstream of inlet.

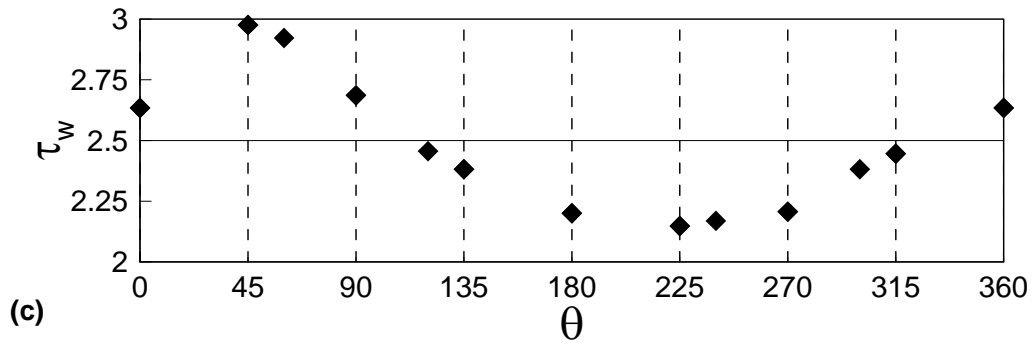
To highlight the three-dimensional structure of the flow, in **Figure 5** we plot radial distributions of the mean axial velocity for various azimuthal angles  $\theta$ , for  $Re = 8230$ . As

highlighted in the schematic which accompanies the figure the angle is measured with respect to the vertical “looking” downstream. The two halves of the corresponding horizontal profile in **Figure 2** are represented here by the profiles at 90° and 270°. Once again, the reference curves represent the average of the velocity data on either side of the centreline (i.e. X° and (X+180)°). It is clear that the ‘peak’ velocity is shifted to the top right quadrant of the pipe (i.e. between 0° and 90°), with a corresponding maximum negative shift in the velocity profile in the bottom left quadrant. The degree of asymmetry varies smoothly with azimuthal angle with the profiles at 135° and 315° being practically symmetric. To quantify the degree of asymmetry we define the following asymmetry parameter,  $\alpha$ :

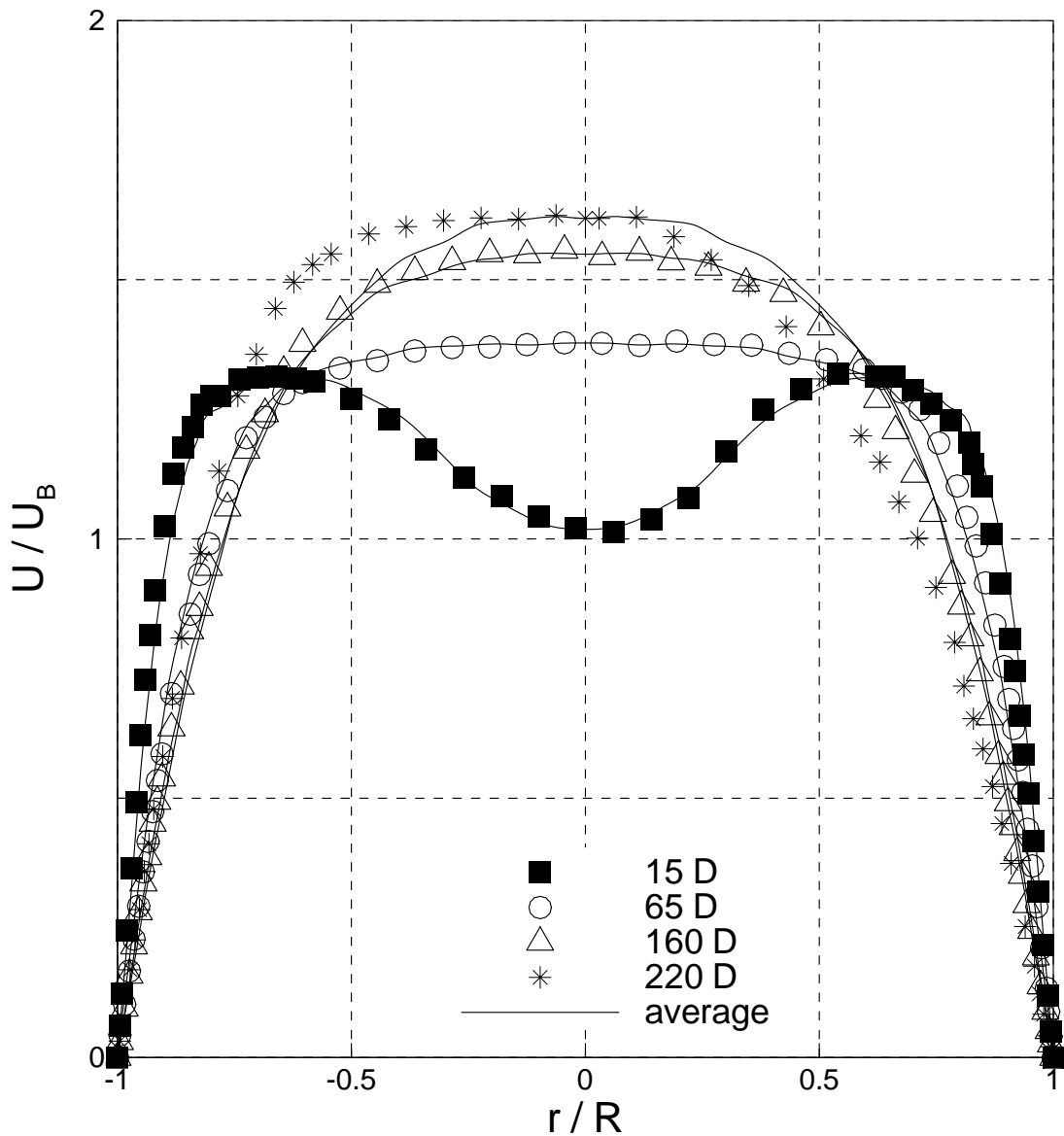
$$\alpha = \frac{\int_0^R (U - \bar{U})r.dr}{\int_0^R \bar{U}.r.dr} \quad (3)$$

where  $U$  is the mean axial velocity and  $\bar{U}$  is the average of the velocity data on either side of the centreline. If the profile is symmetric,  $U = \bar{U}$  and  $\alpha = 0$ . The variation of  $\alpha$  with azimuthal angle is shown in **Figure 6(a)**: as was apparent from inspection of **Figure 5** the asymmetry is greatest at approximately 45° and 225°. **Figure 6(b)** and (c) shows the variation of wall shear rate (determined from the slopes of **Figure 5**) and wall shear stress ( $= \dot{\gamma}_w \mu_{CY}$ ) respectively. As can be seen, a positive degree of asymmetry (i.e. represented by a positive  $\alpha$ ) corresponds to an increase in the velocity compared to the average and a corresponding higher wall shear rate (and hence wall shear stress).





**Figure 6:** Azimuthal variation of (a) asymmetry parameter, (b) wall shear rate and (c) wall shear stress for 0.125% PAA  $Re=8230$ .



**Figure 7:** Mean velocity profiles for 0.125% PAA at various axial locations along a horizontal radial line (i.e.  $\theta = 90^\circ$  and  $270^\circ$ )



In **Figure 7** we show the variation of the velocity profile with axial distance along the pipe. The profiles correspond to a horizontal radial ‘cut’ through the pipe (i.e.  $\theta = 90^\circ$  and  $270^\circ$ ). The farthest upstream profile, at  $x = 15 D$ , has a velocity defect in the centre of the pipe which is a direct consequence of the disc within the plenum chamber immediately upstream of the inlet to the test section. Although this profile is far from an idealized ‘uniform’ inlet profile it is not strongly asymmetric.

## 5. Conclusion

We have reported LDA axial velocity measurements for a shear-thinning, viscoelastic polymer solution (polyacrylamide) flowing through a pipe. Our results cover the laminar, transitional and fully turbulent regimes. In the transitional regime, as has been observed previously, the mean velocity profiles exhibit a stable, and repeatable, asymmetry. Radial distributions of mean axial velocity for various azimuthal angles highlight the three dimensional nature of this asymmetry.

## 6. References

- [1] A Darbyshire and T Mullin (1995), *J Fluid Mech* 289 p83.
- [2] A Draad, G Kuiken and F Nieuwstadt (1998), *J Fluid Mech* 377 p267
- [3] M P Escudier and F Presti (1996), *J Non-Newt Fluid Mech*, 62, 1996.
- [4] M P Escudier, I W Gouldson, A S Pereira, F T Pinho and R J Poole (2001), *J Non-Newt Fluid Mech.* 97 p99.
- [5] M P Escudier, R J Poole, F Presti, C Dales, C Nouar, C Desaubry, L Graham and L Pullum (2005), *J Non-Newt Fluid Mech.* 127 p143.
- [6] H Faisst and B Eckhardt (2004), *J Fluid Mech* 504 p343.
- [7] B Hof, A Juel and T Mullin (2003), *Phys Rev Lett* 91 p244502.
- [8] B Hof, C van Doorne, J Westerweel, F Nieuwstadt, H Faisst, B Eckhardt, H Wedin, R Kerswell and F Waleffe (2004), *Science* 305 p1594.
- [9] B Hof, C van Doorne, J Westerweel, F Nieuwstadt (2005), *Accepted for publication in Phys Rev Lett*.
- [10] J Peixinho, C Nouar, C Desaubry and B Theron (2005), *J Non-Newt Fluid Mech.* 128 p172.
- [11] L Pullen (2005), private communication
- [12] C Tropea (1995), *Meas Sci Technol*, 6, pp605-619.
- [13] F Waleffe (1997), *Phys of Fluids* 9 p883.
- [14] F Waleffe (2003), *Phys of Fluids* 15 p1517.
- [15] W J Yanta, R A Smith (1978), in *11<sup>th</sup> Aerospace Science Meeting*, (Washington, AIAA paper 73, 1978), p.169.
- [16] K Yasuda, R C Armstrong and R E Cohen (1981), *Rheo Acta*, 20, pp163-178.