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TURBULENT PIPE FLOW CHARACTERISTICS OF LOW MOLECULAR WEIGHT SHEAR-THINNING FLUIDS

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ABSTRACT

A miniaturised fibre optic Laser-Doppler anemometer and a differential pressure transducer were used to carry out detailed hydrodynamic measurements in a fully developed turbulent pipe flow with 0.4% to 0.6% by weight shear-thinning aqueous solutions of a methylhydroxil cellulose of molecular weight equal to 6,000 kg/kmole (Tylose MH 10000K from Hoechst).

In spite of undetectable elasticity in oscillatory and creep flow tests and of their low molecular weight, these solutions exhibited drag reductions of up to 35% relative to a newtonian fluid flow at the same wall Reynolds number, and of about 25% relative to the inelastic shear-thinning friction correlation of Dodge and Metzner (1959) at the same generalised Reynolds number, respectively.

The low molecular weight polymer solutions were also observed to delay transition from the laminar to the turbulent regime as intensively as reported before by Pinho and Whitelaw (1990) with heavier and more elastic solutions of cellulose, and we may tentatively conclude that this transition delay is a shear-thinning rather than an elastic effect.

1. INTRODUCTION

In the past the investigation of non-Newtonian wall-dominated flows has been mostly concerned with the study of the drag reduction phenomena and the understanding of the effects of elasticity and variable viscosity on their turbulent characteristics, but the fluids under scrutiny normally were made with additives of molecular weight over 10^5 kg/kmole (Berman (1978), Allan *et al* (1984) at very dilute concentrations. More recently Pinho and Whitelaw (1990) and Escudier *et al* (1992) investigated the turbulent pipe flow of shear-thinning polymer solutions with viscosity power law indices between 0.39 and 0.90 which also showed drag reduction and the validity of Virk's asymptote for variable viscosity fluids.

Elasticity in turbulent pipe flow manifests itself in a reduction of the friction coefficient, and according to Hinch (1977), Tabor *et al* (1989) and more recently Kostic (1994) amongst others, this is related to a strong strain imposed elongation of the molecules and its effect on the extensional viscosity, thus leading to an anisotropic viscosity. Therefore, it is logic to expect that small light molecules may be inelastic and will show no drag reduction. The experiments of Lodes and Macho (1989) with aqueous solutions of a 19,000 kg/kmole partially saponificated polyvinylacetate with different degrees of hydrolysis have reported drag reductions close to the maximum predicted by Virk's asymptote (Virk *et al*, 1970), but did not report any turbulence field data, and the authors speculated on a different origin for the elastic behaviour of the fluid without proper evidence. Therefore, the purpose of this work is to investigate the turbulent characteristics of shear-thinning fluids, of molecular weight lower than 10,000, in a pipe flow.

2. EXPERIMENTAL SET UP

The flow configuration, fully described in Pereira (1993), consisted of a long 26 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 100 litre tank through 90 diameters of pipe to the transparent acrylic test section of 232 mm of length, and a further 27 diameters down back to the tank, with the flow controlled by two valves. A 100 mm long honeycomb was located 90 diameters upstream of the test section to help to ensure a fully developed flow in the plane of the measurements.

Four pressure taps 65 mm apart were drilled in the test section and the upstream pipe and were used for the pressure loss measurements. Equal longitudinal pressure gradients were measured between any two consecutive taps, thus ensuring that the connection between the brass pipe and the test section was well done and within the machining tolerances of ± 10 μm, and caused no detectable harm to the flow condition. This, together with equal velocity measurements at two different far apart within the test section, confirmed a fully developed flow situation there.

The pressure drop was measured by means of a differential pressure transducer from Rosemount, model 1151 DP 3S and its output was sent to a computer via a data acquisition board Metrabyte DAS-8 interfaced with a Metrabyte ISO 4 multiplexer, both from Keithley. The overall uncertainty of the pressure measurements was less than 1.2 Pa, which is about 1.6% and 5% for high and low pressure differences, respectively.

A fiber optic laser-Doppler velocimeter from INVENT, model DFLDA was used for the velocity measurements, with a 30 mm probe mounted on the optical unit. Scattered light was collected by a photodiode in the forward scatter mode, and the main characteristics of the anemometer are listed in table I and described by Stieglmeier and Tropea (1992). The signal was processed by a TSI 1990C counter interfaced with a computer via a DOSTEK 1400 A card, which provided the statistical quantities. The data presented in this paper has been corrected for the effects of the mean gradient broadening and the maximum uncertainties in the axial mean and rms velocities at a 95% confidence level are of 2% and 3.1% on axis respectively, and of 2.8% and 7.1% in the wall region. The uncertainty of the radial and tangential rms velocity components is 4.1% and 9.4% on axis and close to the wall, respectively.

The velocimeter was mounted on a milling table with movement in the three coordinates and the positional uncertainties are of ± 200 and ± 150 μm in the axial and transverse directions, respectively.

Table I - Laser-Doppler characteristics

Laser wavelength	827 nm
Laser power	100 mW
Measured half angle of beams in air	3.68
Size of measuring volume in water at e^{-2} intensity	
minor axis	37μm
major axis	550μm
Fringe spacing	6.44μm
Frequency shift	2.5 MHz

3. FLUID PROPERTIES

Aqueous solutions of a methil-hydroxil cellulose from Hoechst, Tylose MH 10000K, with a molecular weight of 6,000 kg/Kmole were investigated. Prior to the hydrodynamic measurements, the 0.4%, 0.5% and 0.6% by weight concentration Tylose solutions were characterised for their transparency, viscometric viscosity, dynamic viscosity, creep compliance and resistance to degradation. The biocide Kathon LXE from Rohm and Haas was added at 0.02% by weight to prevent bacteriological deterioration and the solutions were prepared with tap water.

The rheological characterisation of the fluids was carried out in a rheometer from Physica, model Rheolab MC 20, made up of an universal measurement unit UM/MC fitted with a low viscosity double-gap concentric cylinder system and a cone-plate system. The rheometer could be both stress and shear rate controlled and viscosities up to the maximum shear rate of 5230 s^{-1} could be measured, with an uncertainty of less than 3.5%.

The viscometric viscosity of the three solutions at 25°C are plotted in figure 1 together with the fitted Carreau viscosity model and its parameters are listed in Table II.

$$\mu = \mu_0 \left[1 + (\lambda\dot{\gamma})^2\right]^{\frac{n-1}{2}} \quad (1)$$

Table II- Parameters of the Carreau model for the viscosity of the Tylose MH 10000K solutions at 25° C.

Concentration	μ_0 [Pa.s]	λ [s]	n	$\dot{\gamma}$ [s^{-1}]
0.4%	0.0208	0.0047	0.725	6.1 a 4031
0.5%	0.0344	0.005	0.660	6.1 a 4031
0.6%	0.0705	0.0112	0.637	6.1 a 4031

The fluids circulated in the rig for periods of less than 21 hours, during which the viscometric viscosity decreased by 10% due to the mechanical deterioration. The resistance to mechanical degradation of Tylose was three times longer than the lifetime of the CMC solutions, of molecular weight of 300,000, used by Pinho and Whitelaw (1990), under similar conditions.

The oscillatory and creep tests that were carried out could not detect any elasticity within the instrument accuracy.

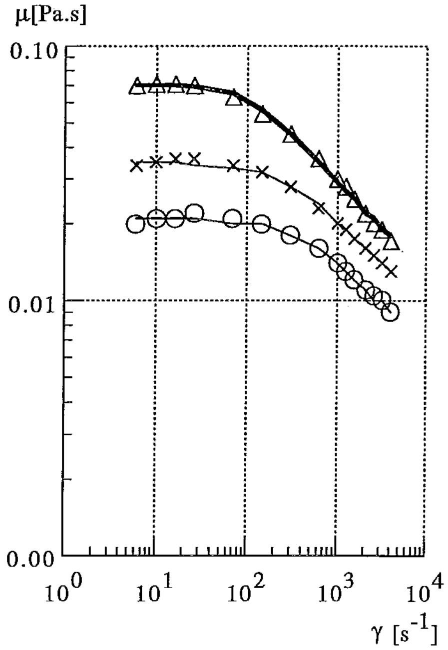

Figure 1- Viscosity and ajusted Carreau model to the 25° C Tylose solutions data. O- 0.4%; x-0.5% and Δ- 0.6%.

4. RESULTS AND DISCUSSION

Figures 2 and 3 show the Darcy skin-friction coefficient ($f_D=2\Delta p D/\rho U_b^2 L$) versus generalised and wall Reynolds numbers respectively, and illustrates the behaviour of the non-Newtonian solutions under laminar, transitional and turbulent flow conditions. The use of the generalised Reynolds number, as defined by Dodge and Metzner (1959), is appropriate in laminar flow and collapses the experimental data on the Newtonian relationship $f_D=64/Re_{gen}$ within the experimental uncertainty (figure 2). The Darcy friction (f_D) coefficient law for inelastic shear-thinning fluids based on the generalised Reynolds number (equation 2), is also included for comparison and shows that a drag reduction exists for the Tylose solutions.

$$\sqrt{\frac{1}{f_D}} = \frac{2}{n^{0.75}} \log\left[Re_{gen} f_D^{\frac{2-n}{n}}\right] - \frac{1.204}{n^{0.75}} + 0.602\, n^{0.25} - \frac{0.2}{n^{1.2}} \quad (2)$$

However, for the turbulent regime the wall viscosity is a preferred parameter to define the Reynolds number, because it is in the wall region that viscous forces are most important. The same data of figure 2 is plotted again in figure 3 using the wall Reynolds number together with the newtonian Prandtl-Kárman law and Virk's (1975) maximum drag reduction asymptote. The newtonian data is consistent with previous results and confirms that the flow is close to being fully developed at high Reynolds numbers. Although not conclusive, the drop of the ratio of centreline to bulk velocity (U_0/U_b) with Reynolds number of figure 4 indicates that the flow condition is fully developed, or close to it, for the maximum flow rate with the various polymer solutions.

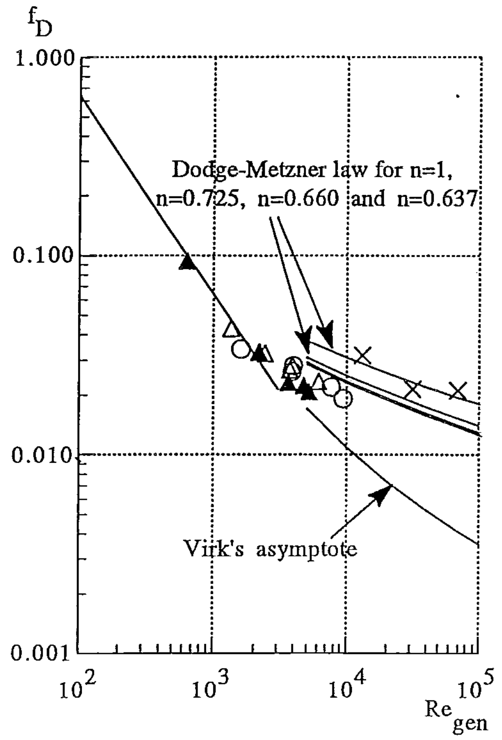

Figure 2- Darcy friction factor versus generalised Reynolds number. X Water, O Tylose 0.4%, Δ Tylose 0.5% and ▲ Tylose 0.6%. n - viscosity power law index.

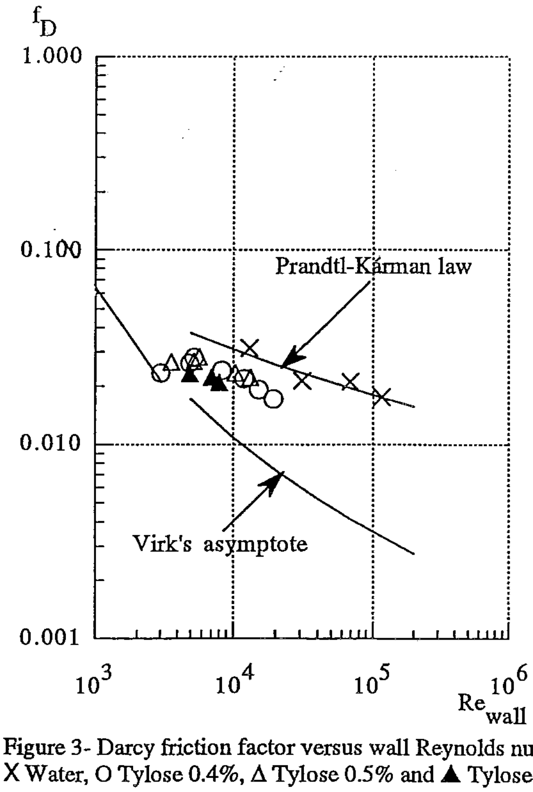

Figure 3- Darcy friction factor versus wall Reynolds number. X Water, O Tylose 0.4%, Δ Tylose 0.5% and ▲ Tylose 0.6%.

Figures 2 and 3 clearly emphasize the main conclusion of this work; in spite of the very low molecular weight of Tylose the aqueous solutions of this polymer exhibit drag reduction and this is consistent with the mean velocity profiles in wall coordinates shown below. The reduction of the friction factor is not a consequence of the shear-thinning characteristic of the polymer solutions, as can be seen in the comparisons figure 2 with Dodge and Metzner (1959) friction law for inelastic shear-thinning fluids. Maximum drag reductions of 30% to over 35% were measured relative to a newtonian flow at constant wall Reynolds number for the 0.4 and 0.6% Tylose solutions, which corresponded to about 20 to 27% if compared on the basis of a constant generalised Reynolds number. The drag reduction of Tylose was about half that reported to occur with the low elasticity shear-thinning high molecular weight CMC solutions of Pinho and Whitelaw (1990) which reached Virk's asymptote.

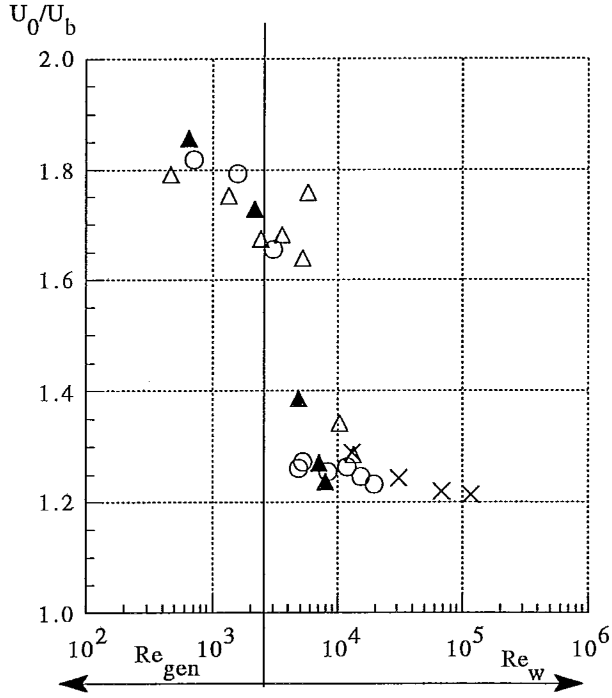

Figure 4- Ratio of centreline to bulk velocity versus generalized and wall Reynolds number for X Water, O Tylose 0.4%, Δ Tylose 0.5% and ▲ Tylose 0.6%.

Local measurements of the mean velocity and of the root-mean-square of the velocity fluctuations of the 0.4% by weight Tylose MH 10000K solution are shown in figures 5 to 7 which include some non-newtonian data taken from Pinho and Whitelaw (1990) concerning aqueous solutions of CMC (sodium carboxymethil cellulose) grade 7H4C from Hercules, with a molecular weight of around 3×10^5, i.e., about 50 times heavier than the Tylose solutions used in this work.

The axial mean velocity profile of the 0.4% Tylose at a Reynolds number of 3,030 in figure 5 is clearly not turbulent. The flow at the Reynolds number of 4,920, in spite of a low value of the ratio U_0/U_b in figure 4 and the mean velocity profiles of figures 5 and 6 which could indicate turbulent flow, does not seem to be under such flow condition as the exceedingly high velocity fluctuations of figures 7a) to c) suggest. For this flow condition the turbulence is much higher than that for higher Reynolds numbers, and this can be associated with flow intermittency. Normal Reynolds stresses are known to increase gradually with the decrease in Reynolds number, Wei and Willmarth (1989), but for this low Reynolds number range the variations should not be so intense as observed here, unless the flow is within a transitional condition with intermittency contributing decisively to turbulence broadening. Actually this seems to be the case here as confirmed in figure 4 which shows a delayed transition with the non-newtonian fluids, a behaviour beautifully investigated by Wójs (1993).

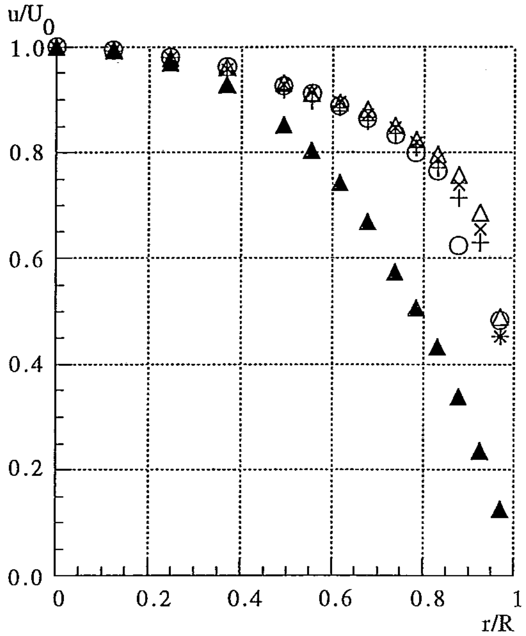

Figure 5- Axial mean velocity profile in physical coordinates for the 0.4% Tylose solutions. ▲ Re_w= 3030, O Re_w= 4920, + Re_w= 11930, X Re_w= 15400 and Δ Re_w= 19570.

The axial mean velocity profiles in wall coordinates of the 0.4% Tylose solutions in figure 6 are consistent with the drag reduction because they are shifted upwards from the newtonian log law, in a way which is proportional to the drag reduction intensity. This is better understood from the comparison with the 0.1% and 0.2% CMC data of Pinho and Whitelaw (1990) which were reported to have drag reductions of 47% and 64%, respectively. The more intense drag reductions of these heavy polymers imply a larger shift from the newtonian log law than that of the light Tylose solutions. Figure 6 also shows that the slope of the velocity profiles become steeper with drag reduction, especially at higher values of drag reduction, close to Virk's asymptote.

The normal Reynolds stresses of the Tylose solutions have a behaviour which is intermediate to the newtonian and the high molecular weight and intense drag reducer CMC solutions. The axial component of the Reynolds stress of the 0.4% Tylose solutions is not so high close to the wall as with the 0.2% CMC solutions, the one that is closer to the 0.4% Tylose in terms of viscous characteristics, and at the centre of the pipe the turbulence is not so damped, as shown in figure 7 a). Drag reduction is known to intensify axial turbulence close to the wall (Allan *et al* (1984) and is associated with a decrease of transverse turbulent transport. With drag reductions which are intermediate between those of the CMC solutions and the

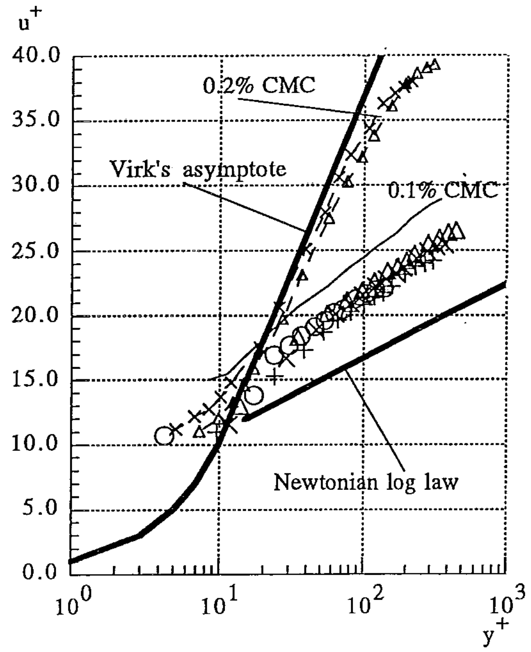

Figure 6- Axial mean velocity profile in wall coordinates for the 0.4% Tylose solutions. O Re_w= 4920, + Re_w= 11930, X Re_w= 15400 and Δ Re_w= 19570. From Pinho and Whitelaw (1990) -Δ- 0.2% CMC at Re_w= 18260,-x- 0.2% CMC at Re_w= 11770,—— 0.1% CMC at Rew= 16800.

newtonian fluid, it is expected that the profiles of the rms velocities reflect this behaviour, as happens here. The axial turbulence profiles show a small Reynolds number effect with the flow at a Reynolds number of 11,930 having marginally higher values than the flow at a higher Reynolds number.

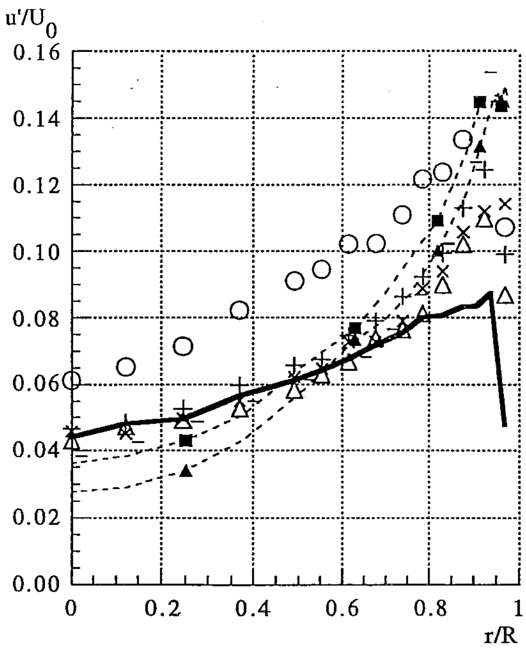

Figure 7a) Axial rms velocity profile in physical coordinates for the 0.4% Tylose solutions. O Re_w= 4920, + Re_w= 11930, X Re_w= 15400 and Δ Re_w= 19570.—— Water Re= 117500. From Pinho and Whitelaw (1990) -▲- 0.2% CMC at Re_w= 18260,- ■ - 0.2% CMC at Re_w= 11770, ∗ 0.1% CMC at Re_w= 16800.

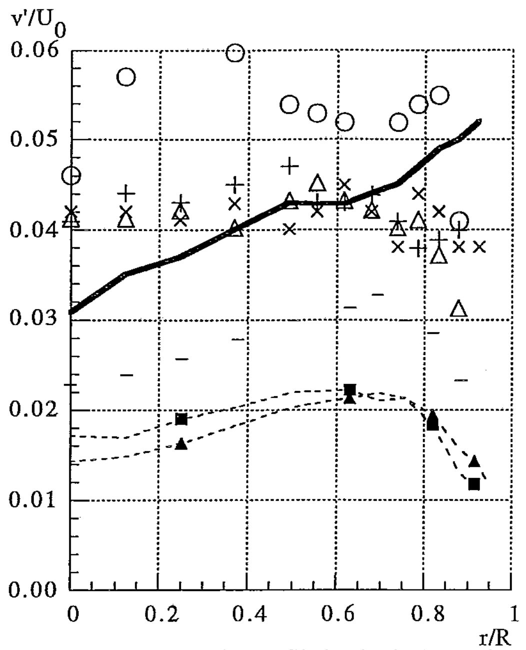

Figure 7b) Radial rms velocity profile in physical coordinates for the 0.4% Tylose solutions. O Re_W= 4920, + Re_W= 11930, X Re_W= 15400 and Δ Re_W= 19570. —— Water Re= 117500. From Pinho and Whitelaw (1990) -▲- 0.2% CMC at Re_W= 18260,- ■ - 0.2% CMC at Re_W= 11770, ∗ 0.1% CMC at Re_W= 16800.

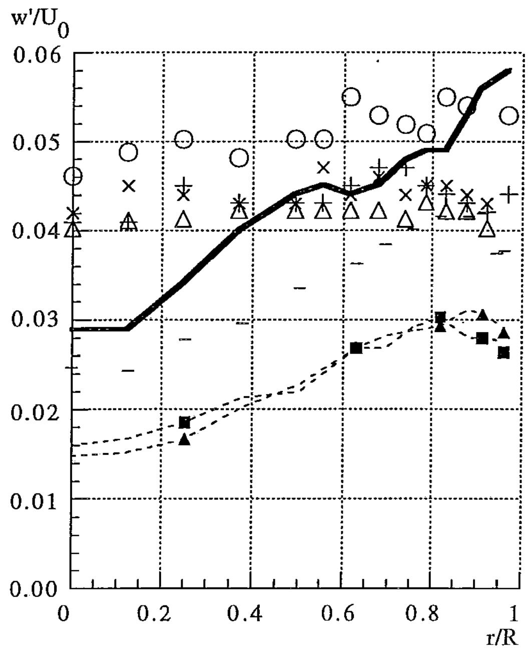

Figure 7c) Azimuthal rms velocity profile in physical coordinates for the 0.4% Tylose solutions. O Re_W= 4920, + Re_W= 11930, X Re_W= 15400 and Δ Re_W= 19570. —— Water Re= 117500. From Pinho and Whitelaw (1990) -▲- 0.2% CMC at Re_W= 18260,- ■ - 0.2% CMC at Re_W= 11770, ∗ 0.1% CMC at Re_W= 16800.

The radial and azimuthal components of the rms of the fluctuating velocity of the 0.4% Tylose fluids in figures 7 b) and c) agree with the previous observations, showing less dampening than those of the CMC solutions. However there is a major difference between the Tylose and the CMC curves: although intense dampening of the transverse turbulence is observed with the Tylose and CMC solutions in the near-wall region in relation to the water flows, in the centre of the pipe there is no reduction of turbulence with the Tylose, and in fact the opposite occurs. Radial and tangential rms velocities hardly increase from the centre of the pipe to the wall, remaining almost constant within 80% of the radius, and decreasing only on the final 20% near the wall. The high radial and tangential turbulence in the center of the pipe could be due to the reported delay in transition together with a Reynolds number effect. This means that Reynolds number and transitional effects with the non-newtonian Tylose solutions occur over a wider range of Reynolds numbers than with the water flows. For the water flows at Reynolds numbers between 30,000 and 117,500 the turbulence profiles hardly change, and agree well with data from Lawn (1971) indicating fully developed turbulent flow in all conditions. Besides, as already mentioned, Reynolds number effects with newtonian fluids are not so intense as observed here with the non-newtonian fluids.

It is clear that the effects of drag reduction on the turbulence characteristics of the low molecular weight polymers are localised in the wall region, whereas for the high molecular weight solutions they span over the whole pipe, and this effect is not restricted to the transverse components of turbulence. In the centre of the pipe the axial component of turbulence of the Tylose solutions is similar to the newtonian values whereas the CMC axial turbulence intensity is attenuated.

5. CONCLUSIONS

Aqueous solutions of a very low molecular weight polymer were rheologically characterised to be shear-thinning and inelastic in creep and oscillatory flows. In spite of this, they exhibited drag reductions of up to 35% in a turbulent pipe flow, as compared to the newtonian friction law and a delay in transition proportional to the polymer concentration.

The drag reduction was accompanied by a reduction of the turbulence, especially in the transverse directions. However, these effects were not so intense as previously observed with high molecular weight shear-thinning polymer solutions and were mostly concentrated on the wall region.

One has to conclude from this work that linear molecules suffer the effects of elongational viscosity increase, or any other mechanism that causes turbulent drag reduction and the decrease of transverse turbulence, even for very small molecular sizes.

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