Turbulent flow of viscoelastic shear-thinning liquids through a rectangular duct

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1 Introduction

Large reductions in turbulent frictional drag occur when high molecular-weight polymers, surfactants etc are added to a Newtonian solvent [1]. Recent advances in numerical modelling, especially Direct Numerical Simulations [2, 3, 4, 5] have enhanced our understanding of how the additives interact with and modify the turbulence and reduce the frictional drag. The purpose of this work is to provide for comparison purposes a more comprehensive experimental database for higher polymer concentrations than has been available hitherto for planar duct flow. Selected results are presented here.

2 Experimental arrangement and instrumentation

Complete details of the new experimental facility used will be given elsewhere. The duct consists of seven $1.2m$ long modules with a rectangular internal cross section of height $h = 25mm$ and width $w = 298\ mm$ (hydraulic diameter $D_H = 46\ mm$). Reynolds numbers are defined as $Re{=}\rho D_H U_B/\mu_W$ where for CMC and XG μ_W, was determined from τ_W and the flow curves and U_B is the bulk velocity. For water Re = 18900, CMC Re = 13500, XG Re = 13000. A perspex test section, length $100mm$, is located $6m$ (130 D_H) from the inlet. We used a 2D LDA system (measuring volume length 200 μm, diameter 20 μm) to measure the transverse variation of the mean and fluctuating velocities. In the test section we use a unique open-slot technique, inspired by Poggi et al [6], which allows unimpeded access of the laser beams to the flow, simultaneous and coincident measurement of u, u' and v', and hence the determination of the Reynolds shear stress $\overline{uv}$, without the need for a complex optical arrangement. w' was measured separately.

3 Results and discussion

Mean velocity profiles. The excellent quality of the data is apparent from Figure 1(a) which shows the mean velocity distributions plotted in u^+ vs log y^+ form. For CMC and XG, $y^+ = \rho u_\tau y / \mu_W$. For water the data closely follow the standard log law for $y^+ > 30$ and extend down to $y^+ \approx 10$. For CMC there is an upshift $\Delta u^+ \approx 3$ corresponding to the modest drag reduction (DR = 28%). For the high DR (67%) XG the data follow $u^+ = y^+$ from $y^+ \approx 1.5$ to ca 15 and then lie close to Virk's ultimate profile, $u^+ = 11.7 \ln y^+ - 17$. The sub-layer data for XG confirm that the surface slit has no discernible influence on the flow. In each case, the smallest y-value is $0.5mm$

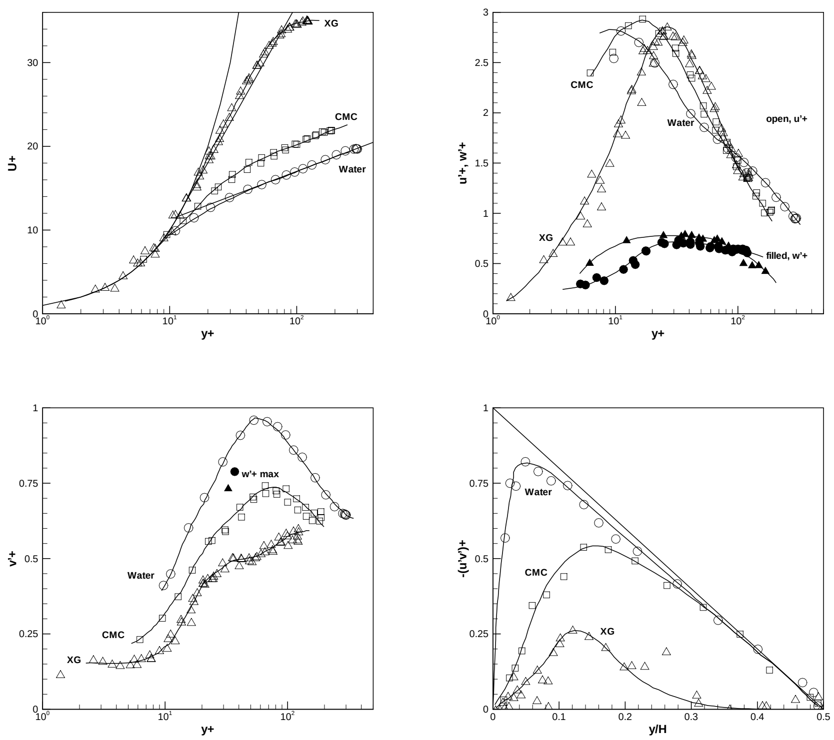

Fig. 1. Normalised mean velocity, Reynolds normal and shear stresses in wall units (a) u^+, (b) u'^+ and w'^+, (c) v'^+ and (d) $\overline{uv}^+$

Normal-stress profiles. The u'^+ vs y^+ data in Figure 1(b) (open symbols) show that the peak values in all three cases are roughly the same but the peak moves to higher y^+ values with increasing drag reduction and at the same time the distribution narrows. The lateral (z-direction) fluctuation data

w'^+ in Figure 1(b) again show little difference in the peak values which are about 25% of those for u'^+. The v'^+ data (Figure 1(c)) show slightly more complex behaviour with a much greater spread of peak values, from 0.95 for water to about 0.55 for XG. What the data also reveal is that the degree of anisotropy increases with drag reduction. All fluctuations are reduced (normalised with bulk velocity) with the greatest reduction in u': for water, u'/v' $\approx$ 3.1, for CMC 4.2 and for XG 4.8 (for peak values) while $u'/w' \approx 4$ for all fluids.

Reynolds shear stress. For any fully developed flow, the variation of total shear stress τ_T must follow the diagonal straight line in Figure 1(d). For water, the difference $\tau_T + \rho\overline{uv}$ must equal the viscous contribution $\mu\partial u/\partial y$. For polymers, as u' and, even more, v' are suppressed, the difference $\tau_T +$ $\rho\overline{uv}$ - $\mu\partial u/\partial y$ has to be made up by the so-called polymer stress. In the case of CMC the polymer contribution is negligible except in the near-wall region (y/H $<$ 0.2) but for XG it is clear that the polymer stress dominates over the entire cross section. Only in the near-wall region (y/H $\approx$ 0.15) is there any contribution to τ_T from -$\rho\overline{uv}$, but even this is small.

4 Conclusions

Selected measurements have been reported for turbulent flow of water and two shear-thinning, drag-reducing polymer solutions through a rectangular duct. The novel experimental approach involves a slit cut into the duct surface to allow easy access for LDA measurements of u, u', v' and, above all, $\overline{uv}$. The measurements demonstrate that the slit has negligible effect on the near-wall flow (to $y^+ \approx 2$). The measurements also include w' and so permit the determination of turbulent kinetic energy k in addition to the Reynolds and polymer stresses.

References

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