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Turbulent flow of a viscoelastic liquid through an axisymmetric sudden expansion

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1 Introduction

The turbulent flow of fluids through sudden expansions has both fundamental scientific interest and numerous practical applications: such flows occur, for example, in pipe-flow systems in the chemical, pharmaceutical and petroleum industries, in air-conditioning ducts, in dump combusters and in fluidic devices. Although many naturally occurring fluids, and the majority of synthetic fluids such as those encountered in the food, processing and chemical industries, are non-Newtonian in character, the existing literature is almost devoid of both experimental and computational studies of the turbulent flow of non-Newtonian fluids in any situation other than fully-developed pipe or duct flow. Most research into the turbulent flow of non-Newtonian liquids has been concerned with the important, but still not completely understood, phenomenon of drag reduction in pipe or duct flow.

Pak et al[1] used flow visualisation to investigate the flow of two non-Newtonian liquids through an axisymmetric sudden expansion (as in the current study the expansion was preceded immediately by a smooth contraction): a purely viscous shear-thinning liquid, Carbopol , and viscoelastic polyacrylamide solutions. The reattachment lengths for Carbopol were found to be essentially the same as for water whereas for the polyacrylamide solutions they were two to three times longer than those for water, increasing with concentration.

2 Experimental rig and instrumentation

Apart from a different expansion module, the key dimensions of which are shown in Figure 1, the flow loop used for the present experiments was identical to that used by Escudier and Smith[2].

A Dantec Fibreflow laser Doppler anemometer (LDA) system was used for the velocity and turbulence measurements and comprised a Dantec 60X10 probe and a Dantec 55X12 beam expander in conjunction with two Dantec Burst Spectrum Analyzer signal processors (one model 57N10, the other model 57N20).

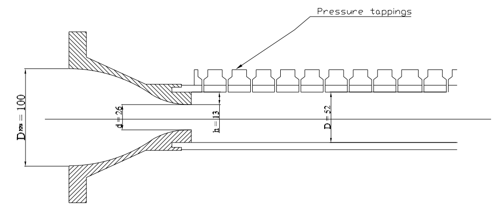

Figure 1: Axisymmetric sudden expansion dimensions in mm

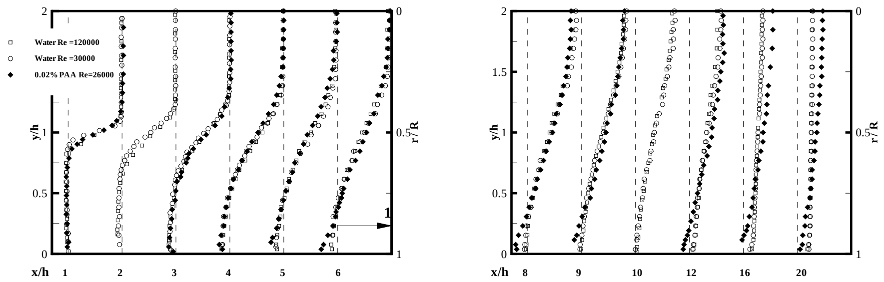

Figure 2: Mean velocity profiles (U/U$_B$)

3 Rheology

The working fluid used in this investigation was a 200 p.p.m w/w aqueous solutions of a polyacrylamide (PAA), Separan AP273 E supplied by SNF UK limited. PAA was chosen as the working fluid as it is highly viscoelastic, is optically transparent (thereby permitting LDA measurements) and has been used extensively in previous investigations in our laboratory and elsewhere. PAA is very flexible in its molecular structure and this gives rise to its increased elastic properties compared to other water-soluble polymers such as xanthan gum and carboxymethylcellulose. The flow curve (i.e. viscosity versus shear rate) is well fit by the Carreau-Yasuda model fit with $\mu_0 = 0.0220$ Pa.s, $\mu_i = 0.00262$ Pa.s, $\lambda = 0.551, n = 0.623, a = 0.623$.

4 Discussion

4.1 Mean flow

Included within Figure 2 are the mean axial velocity profiles for 200 p.p.m PAA at a Reynolds number of 26000 together with two water flows (Re=30000 and 120000).The reattachment length is approximately 20 step heights compared to

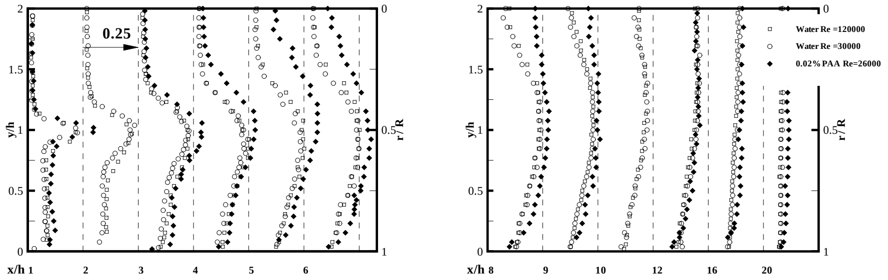

Figure 3: Axial turbulence intensity profiles(u'/U$_B$)

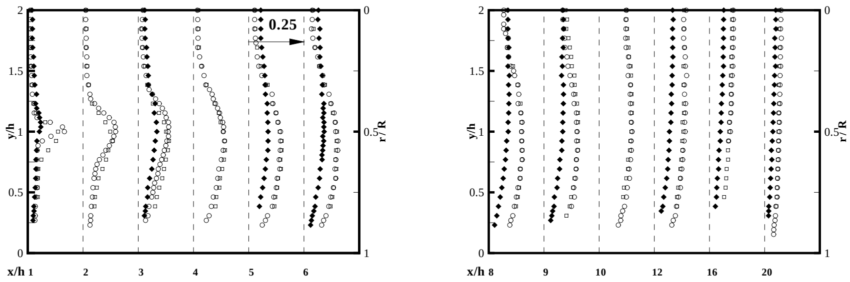

Figure 4: Radial turbulence intensity profiles(v'/U$_B$)

about 9.6-10 h in the Newtonian case. This reattachment length is consistent with the value found by Pak et al in their flow-visualisation study. Coupled with this increase in reattachment length is an increase in the magnitude of the recirculating velocities, especially in the range 5 to 12 step heights: the maximum negative recirculating velocity is almost double the water value at 0.305U$_B$.

4.2 Turbulent flow

Profiles of the axial and radial r.m.s levels (tangential profiles were also measured but are very similar in shape to the radial profiles and are excluded here for brevity) for PAA are shown in Figures 3 and 4 with the water-flow data included for comparison.

The maximum level for the axial turbulence intensity (Figure 3) at x/h=1 is increased by about 35% (from about 0.22 to 0.31 U$_B$) compared to the water flow. This increase, if the tangential and radial turbulence intensities were unaltered, would be expected to have the effect of decreasing the reattachment length. However, the radial (Figure 4) and tangential(see [3]) turbulence intensities at inlet are greatly reduced compared to the water flow (maximum values of v' by over 50% from 0.14 to 0.06 U$_B$ and w' by over 30% from 0.16 to 0.1 U$_B$). This large reduction of v' both at inlet and elsewhere reduces the radial transfer of momentum and so must be the significant factor in increasing the reattachment length for this flow.

5 Conclusion

The flow field for PAA at a Reynolds number of 26000 was significantly different than for the water flows. In agreement with the only previous study (Pak et al [1]) the reattachment length was approximately doubled. The axial turbulence intensity was amplified both at inlet and downstream of the expansion, compared to the water flows, and the maximum value was almost 25% greater. A very high level of turbulence anisotropy was present both at inlet (where v' and w' were both less than 0.3 u') and further downstream (where v' and w' were again significantly reduced compared to the water values). This high level of anisotropy, with the bulk of the turbulent kinetic energy being contributed by the axial component and significantly reduced radial turbulence intensity, must play a significant role in decreasing the radial transfer of momentum and hence the increasing reattachment length.

References

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