THE TIME-VARYING NATURE OF THE ASYMMETRICAL FLOW OF A SHEAR-THINNING POLYMER SOLUTION IN TRANSITIONAL PIPE FLOW

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Abstract Previous studies of shear-thinning fluids in pipe flow discovered that, although the time-averaged velocity profile was axisymmetric when the flow was laminar or fully turbulent, contrary to expectations it was asymmetric in the laminar-turbulent transition regime. The general consensus of these previous experiments was that the location of the peak velocity remained at a fixed point in space. We present new experimental data which demonstrates that this is in fact not the case. Our results confirm the significant departures from axisymmetry in transitional flows of shear-thinning fluids, in addition to the observation that the asymmetric flow pattern is not stationary, the peak velocity is seen to preferentially arise at certain azimuthal locations.

INTRODUCTION

Despite the considerable progress in understanding the physics of the transition process in pipe flow of Newtonian fluids, for non-Newtonian fluids, due to the inherent additional complexities involved, very little literature is available. Intriguingly, existing studies of shear-thinning polymer solutions reveal a yet unexplained phenomenon: when the flow is transitional, significant flow *asymmetry* appears while in purely laminar and fully turbulent flow of same fluids, the flow is axis-symmetric. This asymmetry has been found experimentally in independent research programmes in U.K. [2, 3], France [7, 4, 5], and Australia [8], subsequently and also independently in Canada [6]. A jointly published paper [1] was produced to highlight this effect utilizing a wide range of polymer solutions. This phenomenon was repeatable and many possible causes have been ruled out, such as the rotation of the earth, curvature of the pipe axis, significant imperfection of flow geometry, upstream and downstream disturbances or temperature gradients [3]. Therefore, this asymmetry is thought to be attributed to some, as yet unknown, fluid mechanism. The previous research largely concentrates on the description of the asymmetric distortion of the time-averaged streamwise velocity profile using Laser Doppler Velocimetry (LDV). We present stereoscopic particle image velocity (SPIV) data over the entire circular cross-section of the pipe to characterize the time-varying nature of this asymmetry in transitional pipe flow of shear-thinning fluids.

EXPERIMENTAL FACILITY

The experiments were implemented in the Very Large Scale Pipe Flow (VLSPF) facility at University of Liverpool. The facility comprises a 23m long pipe constructed of a set of borosilicate glass tubes with 100 $\pm$ 0.1 mm internal diameter. A SPIV system is located at 220 pipe diameters downstream of the inlet. A laser sheet produces a measurement plane positioned perpendicular to the streamwise flow direction thus the flow is advected through the laser sheet and recorded by two CMOS cameras. To analyze the asymmetric flow pattern over a long time scale, the minimum SPIV data acquisition frequency is 5Hz and the corresponding experimental duration is 330 seconds. A LDV system is located at 200 pipe diameters downstream of the inlet, upstream to the SPIV system to detect the onset of transition. The experiment was performed using an aqueous solution of xanthan gum (0.15wt %), which is shear-thinning and essentially inelastic. In consideration of the inhomogeneity of the viscosity, the Reynolds number is defined as $Re_w = U_b D/\nu_w$, where U_b is the bulk velocity, D is the diameter of pipe, ν_w is the kinematic viscosity that corresponds to the shear stress at the wall (measured through pressure drop over $7.2m$ in conjunction with measurements from a controlled stress rheometer).

RESULTS & DISCUSSIONS

To quantitively describe the degree of azimuthal flow asymmetry and reveal the evolution of asymmetrical flow pattern, a parameter, named the asymmetry factor α (similar to that in reference [3], but applied three-dimensionally) is introduced. Figure 1 shows time-averaged streamwise velocity from the SPIV measurements. The flow patterns from the SPIV data presents axisymmetric velocity profiles for both laminar and turbulent flow and significant asymmetry in transition, which is consistent with observations from previous LDV measurements [1].

The time history of the asymmetry factor and selected instantaneous velocity profiles are presented in figure 2. Although the asymmetry preferentially appears in certain azimuthal positions, it is not stationary. When the asymmetry is very pronounced (indicated by a higher asymmetry factor $\alpha \approx 0.2$), the instantaneous flow pattern (figure 2(a)) is similar to the time-averaged flow pattern (the time scale for this preferred pattern is in the order of one minute). The fluctuation of the asymmetry factor indicates the oscillation of the flow pattern around the preferred position. The time variation of the asymmetry factor clearly shows the "breakdown" process of this asymmetry (figure 2(c)). The time scale of the

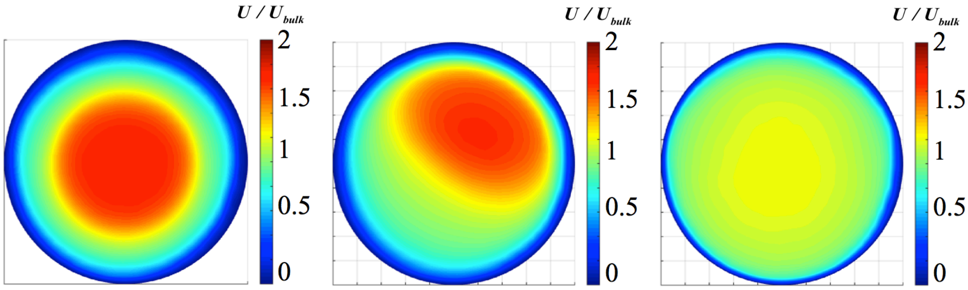

Figure 1. Time-averaged streamwise velocity profile for laminar ($Re_w = 300, \alpha = 0.07$), transitional ($Re_w = 4016, \alpha = 0.21$) and turbulent ($Re_w = 14960, \alpha = 0.08$) flow, from left to right respectively.

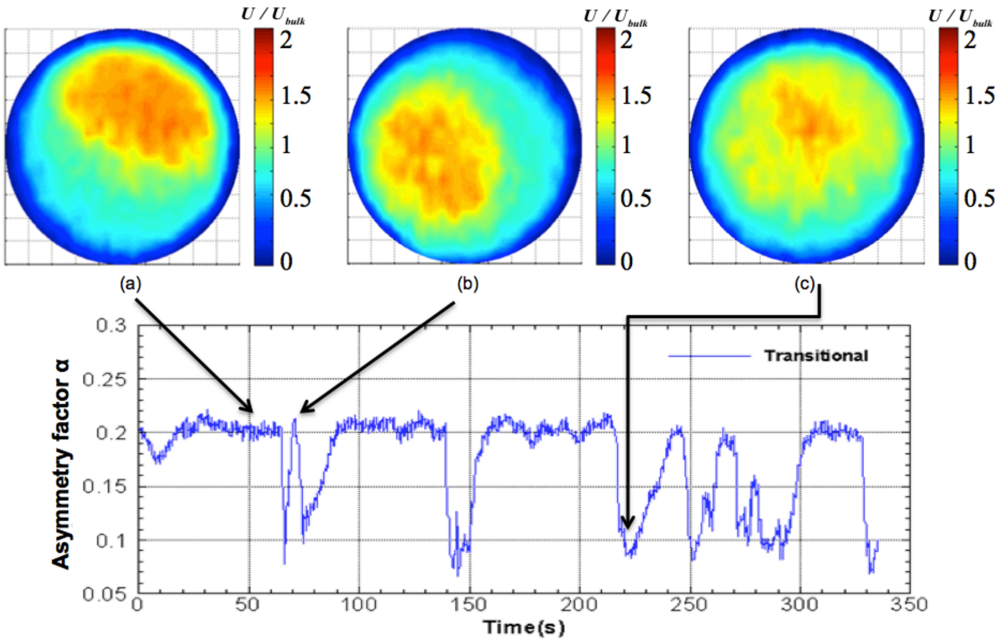

Figure 2. Variations of asymmetric flow patterns in transitional regime. The experimental duration is approximately 340s when the SPIV acquisition rate is 5Hz. The time-varying nature of the asymmetry is indicated by the asymmetry factor. The selected velocity profiles present the distinct asymmetry pattern instantaneously.

breakdown is usually about a few seconds and the flow pattern when breakdown occurs is more axisymmetric. Following the breakdown process, a brief visit to an alternative asymmetric location can be observed, as shown in figure 2(*b*). This process is also very quick, typically about a few seconds. These results provide new insight in this poorly understood phenomenon. In particular, it is clear that the flow is strongly time-varying and the peak velocity has a preferred but not permanent location. Therefore the previous experiments of time-averaged point-wise measurements do not provide a complete picture of this unusual flow behaviour.

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