THE REORGANISATION OF TURBULENT PIPE FLOW BY A DRAG-REDUCING POLYMER ADDITIVE

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Abstract The effect of a drag-reducing polymer additive on the organisational states of turbulent pipe flow is investigated by performing stereoscopic particle image velocimetry measurements in a large-scale pipe flow experiment at $Re_D = 10000$ using both water and a visco-elastic, shear-thinning, semi-dilute aqueous polymer solution. The effect of the polymer is to decrease the drag (by 62%) whilst significantly increasing the probability that the flow exists in a flow state with a low azimuthal wavenumber ($k_\theta = 2$). This result indicates that the $k_\theta = 2$ state is potentially a favourable (i.e. low drag) flow state.

INTRODUCTION

Recently, the presence of a set of distinct organisational states has been identified in Newtonian turbulent pipe flow at Reynolds number, $Re_D = U_b D/\nu = 35000$ (where U_b = bulk velocity, $D = 2R$ = pipe diameter and ν = kinematic viscosity), through the decomposition of the two-point spatial correlation of the streamwise velocity fluctuations (R_{uu}) by azimuthal wavenumber (k_θ) [2]. States with dominant azimuthal wavenumbers corresponding to k_θ = 2,3,4,5,6 were discovered and each state was characterised by the frequency and longevity of its occurrence. The state corresponding to $k_\theta = 3$ was found to be the most common and coherent. Each of the states were characterised by alternating positive and negative fluctuations of the streamwise velocity (u) around the pipe azimuth, which were related to a series of alternately-rotating quasi-streamwise vortices. The overall picture was reminiscent of a set of non-linear travelling wave solutions previously identified at Reynolds numbers an order of magnitude lower [6, 13]. Since Toms [10] first observed that a small amount of polymer added to the pipe flow of a Newtonian fluid leads to a significant decrease in skin friction, the phenomenon of drag reduction by additives has been extensively researched. The effect of the polymer on the mean velocity profile, the turbulence structure and the large-scale turbulent motions have been investigated, both experimentally and numerically, in a variety of wall-bounded flows [12, 1, 14, 7, and many others]. In this work we examine the effect of the polymer on the organisational state of the flow, which is found to be dramatic, significantly changing the probability of certain states occurring and increasing the coherence of the favoured states.

EXPERIMENT

The experiments were performed in the Very Large Scale Pipe Flow (VLSPF) facility at the University of Liverpool. This facility consists of a 23.3m long pipe constructed of a series of borosilicate glass sections with an internal diameter of 100mm. The turbulent flow at $Re_D = 10000$, is investigated using a high-speed, stereoscopic particle image velocimetry technique similar to [11, 5, 4] in which the measurement plane (located 22m from the pipe inlet, corresponding to $220D$) is perpendicular to the streamwise velocity, providing all three components of velocity across the entire pipe cross section with good temporal resolution. The VLSPF is filled with approximately 750 litres of ordinary tap water for the Newtonian flow case and a semi-dilute (225ppm), visco-elastic, shear-thinning, aqueous solution of polyacrylamide (PAA) for the non-Newtonian (drag reduced) case. PAA has a high molecular weight and presents a non-rigid structure ideal for high drag reduction. Indeed, the drag-reduction achieved by the addition of the polymer is 62%. Throughout the experiments, measurements of the pressure drop over a length of 7.2m are recorded, and are used to calculate the shear stress at the wall (by a force balance) and hence the drag reduction. This allows monitoring of the degradation of the polymer and assures that the data have all been taken at similar flow conditions. The viscosity as a function of the shear stress is obtained from the rheological analysis of the solution measured with a controlled-stress rheometer using a rotating conical geometry of 2.2° and 60mm in diameter. The value of the viscosity used to calculate Reynolds number is that which corresponds to the average value of the shear stress at the wall (obtained from pressure-drop measurements) according to the relationship between shear stress and viscosity determined from the rheometer measurements.

RESULTS AND DISCUSSION

Figure 1 shows an example of the variation of the wavenumber states in the streamwise direction for both the water and polymer solution through the use of Taylor's hypothesis [9, 3]. The axial coherence of each of the states is demonstrated by this figure. All of the wavenumber states found previously at $Re_D = 35000$ (k_θ = 2,3,4,5,6) [2] are also found at $Re_D = 10000$ with and without the polymer. However, in the case of the polymer solution there is a significant change. The $k_\theta = 2$ shows a very strong coherence and the higher wavenumber states are rarely observed. Although this is just one example it is highly representative of the trend throughout the entire dataset (which consists of the equivalent of $240R$ of fluid passing the measurement plane for the polymer and $280R$ for the water). The percentage of instances of $k_\theta = 2$ increases from 19% for the water to 33% for the polymer and is the most common state of the flow. (For water $k_\theta = 3$ is the most common state.) The middle panel of figure 1 is the correlation (R_{uu}) corresponding to the flow state for each streamwise location. This clearly shows several examples of transitions between states, which are far more common in the water than in the polymer solution. It is also notable that the strength of the correlation is increased when it has a greater extent in the azimuthal direction, which corresponds to the lower wavenumbers. The bottom panel is the corresponding instantaneous streamwise velocity fluctuation, which enables the visualisation of the large-scale structures that are responsible for the pattern in R_{uu} shown in the middle panel, and are therefore key in determining the wavenumber state of the flow. The increased azimuthal extent (width) of the coherent structures in the flow with the polymer is particularly clear in this plot, but the improved axial coherence of these structures is also evident.

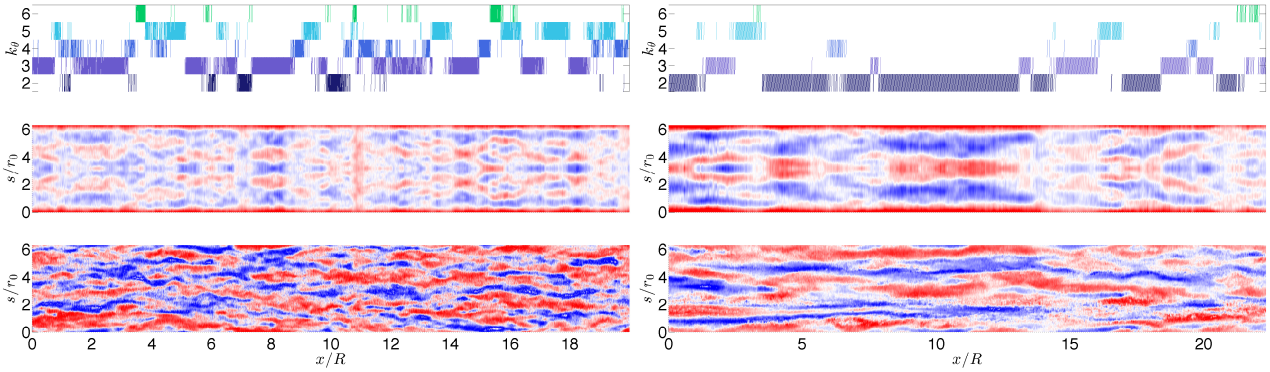

Figure 1. An example of the axial coherence of the wavenumber states for water *(left)* and aqueous polymer solution *(right)*. Top: Variation of azimuthal wavenumber (k_θ) with axial distance (x), showing significant axial coherence of the wavenumber states. Middle: The corresponding correlation map at $r_0/R = 0.75$ showing the correlations that lead to the state allocation and also the transitions between wavenumber states (red indicates $R_{uu} > 0$, blue $R_{uu} < 0$, white $R_{uu} \approx 0$ and s is arclength, i.e. $s = r_0\theta$). Bottom: The corresponding instantaneous velocity fluctuations, where red indicates $u > 0$, blue $u < 0$ and white $u \approx 0$.

It is interesting to note that the "edge-state" (the invariant state embedded in the edge of chaos that neither decays or becomes fully turbulent) identified in numerical simulations at Reynolds numbers near transition [8], would be classified as $k_\theta = 2$ in our system and the conditional average of all $k_\theta = 2$ instances (not shown) does resemble the edge state [2, 8]. Thus, it appears that the polymer is increasing the proportion of time the turbulent flow spends in states similar to this edge-state. Given that the addition of the polymer also corresponds to a large decrease in drag, these could potentially be low-drag states, which would present an interesting target for flow control strategies.

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