MANIPULATING TURBULENCE IN PIPE FLOW

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Summary Turbulence causes higher friction in shear flows and much larger pumping costs (e.g. in oil pipelines) than laminar flow. Consequently, developing control techniques to eliminate turbulence in pipe flow is of great interest. Insights into turbulence sustaining mechanisms, in particular the redistribution of the mean shear by streamwise vortices may help to identify techniques to suppress turbulence. In one of our earlier works the elimination of localized turbulent puffs was achieved by a modification of the velocity profile at the trailing edge of the puff. In this paper, we investigate consequences of profile modifications of fully turbulent flows. Relaminarisation is observed for flows with mean profiles which are forced to be more plug shaped (i.e. flatter) than the averaged turbulent profile. The numerical studies are carried out with a hybrid spectral-finite-difference method.

MOTIVATION

In the past decades, various studies have dealt with the self-sustaining mechanism of near-wall turbulence, where the important role of the vortex streak interaction including non-normal growth has been emphasized[1, 2, 3]. Streamwise vortices create streaks which undergo an inflectional instability that gives rise to new vortices. The efficiency of this cycle relies on the mean shear, which supplies the necessary energy. If this energy extraction can be reduced sufficiently, turbulence will not be able to sustain itself and finally the flow relaminarises. A recent work of Hof, *et al.*[4] shows that localized turbulence, so called puffs, can be eliminated by modifying the velocity profile at the trailing edge of the puff. There it was argued that the majority vorticies were created at an inflectional instability at the rear of the puff and that the modification of the profile subdued the inflection point and hence the vorticity production. This could be achieved by replacing the parabolic velocity profile directly behind the puff by a more plug-like profile. Then the question emerges as to what can be done to relaminarise fully turbulent flow? Here a technique to eliminate full turbulence in a pipe is proposed and studied numerically.

DIRECT NUMERICAL SIMULATION

The incompressible Navier-Stokes equations reformulated in terms of toroidal and poloidal potentials are solved with a hybrid spectral-finite-difference method in a $2\pi D$-long pipe, with D being the diameter of the pipe [5]. All unknowns are represented by complex Fourier series in axial and azimuthal directions,

$$A(r,\theta,z) = \sum_{k,m} A_{km}(r) exp(i\alpha kz + im\theta).$$

where $\frac{2\pi}{\alpha}$ gives the pipe length and αk and m are wave numbers in axial and azimuthal directions. In the radial direction finite difference method with a stencil of 9 points is used to calculate all derivatives with respect to radial coordinate r. Details about the formulation of the N-S equations and boundary conditions can be found in Ref. [5]

RESULTS

For a fully turbulent flow a local profile modification is insufficient to enforce relaminarisation. However, applying a global forcing which decreases shear at the pipe centre and increases it at the wall, hence producing a more plug-like profile, leads to relaminarisation. The flattening of the profile is accompanied by a strong reduction of transient growth, which shows that the generation of streaks due to streamwise vortices is subdued. An alternative method to obtain a plug-like flow, which does not require an additional forcing, is to expose the fluid to a high level of turbulence. To achieve this situation we initiate a turbulent flow at high Reynolds number. As shown in Figure 1 the mean turbulent velocity profile at Re=10000 is substantially more plug-like than that at Re=3000. Starting from Re=10000 we suddenly reduce the Reynolds number to 3000 to study how the flow adjusts to the new velocity profile. Relaminarisation is indeed found (see blue line in Figure 2), confirming that given a flattened velocity profile, which cuts down the energy that streamwise vortices extract from the mean flow, the turbulent flow can relaminarise. Hence the velocity field at high Reynolds number is not inside the basin of attraction of turbulence at lower Re.

Our simulations show that the outcome of the Reynolds number reduction does not only depend on the Reynolds number change but also on the specific initial conditions. While some velocity fields lead to relaminarisation others obtained at the same Reynolds number survive (see Figure 2). We hence carried out a statistical investigation for 40-50 cases for several

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Reynolds numbers. Besides Re=10000 we also carried out reduction experiments starting from Re=5000. For all runs Re was suddenly quenched to Re=3000. Figure 3 shows the statistics, where we can see that for reduction from Re=5000, turbulence survives in almost all cases and the Re=10000 case gives a considerable percentage of relaminarisation. Our study confirms that distorted, sufficiently plug shaped velocity profile can not support turbulence. Future work is aimed at testing more Reynolds numbers and finding perturbation methods which result in plug-like flows and can be applied in experiments to relaminarise turbulence.

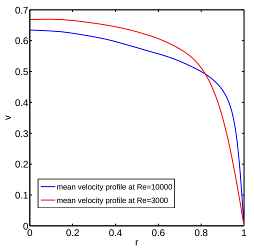

Figure 1. *Comparision of mean velocity profiles at Re=10000 and Re=3000*

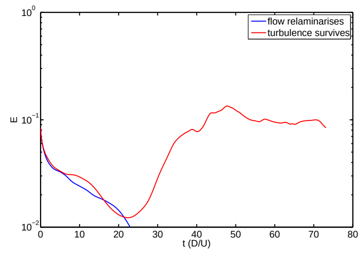

Figure 2. *History of fluctuation energy of two cases for Reduction from Re=10000 to Re=3000*

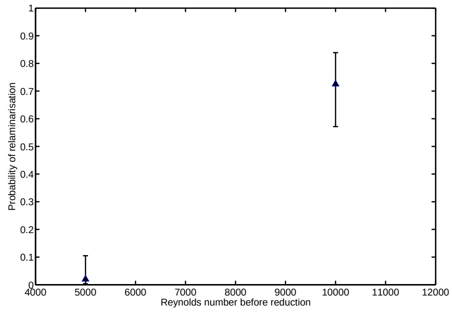

Figure 3. *Probability of relaminarisation for Re reduction from 10000 and 5000 to 3000*

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