RELAMINARISING FULLY TURBULENT PIPE FLOW

Baofang Song[1], Marc Avila [2] & Björn Hof [1]

[1]*Group of Complex Dynamics and Turbulence, Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany*

[2]*Institute of Fluid Mechanics, Friedrich-Alexander-Universität Erlangen-Nürenberg, Erlangen, Germany*

Abstract We locally applied a control technique to relaminarise fully turbulent pipe flow at Reynolds numbers of up to 20,000. Downstream of the control point the flow remains laminar because of the linear stability of the basic flow and consequentely the drag is reduced substantially. At Re=20000 the pressure drop is reduced by an order of magnitude. We also applied a closely related control mechanism in experiments and managed to relmainarise turbulence at Reynolds number 6000 and the drag dropped by a factor of more than 3. The principal underlying the control scheme in experiments and simulations is closely connected to the self sustaining mechnism of wall bouned turbulence.

MOTIVATION

Turbulence is ubiquitous in nature and applications. In certain situations such as combustion and mixing it has favourable effects but not in some others. It is far more energy consuming to pump fluids through pipes, ducts, and channels when the flow is turbulent compared to smooth laminar flow. Therefore, preventing turbulence from forming or relaminarising turbulence is of great practical interest. Up to now, there is no general theory on the mechanism of the onset of turbulence, nevertheless, the extensive studies on the self-sustaining process of the near-wall turbulence[1, 2, 3] have shown the dominant role of the streaks-streamwise vortices interaction in this process and given some interesting insights for turbulence control. General turbulent motion requires a constant energy supply otherwise it will decay. In pipe and duct flows, the shear in the mean flow is the main energy source for the turbulence self-sustaining process. This implies that modification of the velocity profile and redistribution of the mean shear will affect the self sustaining process and a reduction of shear in areas where vortices arise can lead to a reduction in turbulence levels and may even lead to relaminarisation. Following this thought, [3] succeeded in experimentally relaminarising localized turbulence in pipe flow, the so-called turbulent puff, however, they also pointed out that their control technique failed to work for fully turbulent flow at high Reynolds numbers. We are seeking to relaminarise fully turbulent flow at high Reynolds numbers by mean shear modifications.

NUMERICAL FORMULATION

To apply our control numerically, we developed a primitive-variable Navier-Stokes solver with a hybrid spectral and finite-difference scheme for the spacial discretization. We solve the nondimensional incompressible N-S equations

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u} = -\boldsymbol{\nabla} p + \frac{1}{Re} \Delta \boldsymbol{u}, \ \boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \tag{1}$$

in cylindrical coordinates (r, θ, z) in a circular pipe where r, θ, z denote radial, azimuthal and streamwise coordinates respectively. The mass flux is kept constant (that of the Hagen-Poiseuille flow) by adjusting the streamwise pressure gradient accordingly. The Reynolds number is defined as $Re = UD/\nu$ with U being the mean velocity, D the diameter of the pipe, and ν the kinematic viscosity of the fluid. The periodicity imposed in the streamwise direction and that in the azimuthal direction allow us to use the Fourier expansion of the velocity field as following

$$\boldsymbol{u}(r, \theta, z, t) = \sum_{k=-K}^{K} \sum_{m=-M}^{M} \hat{\boldsymbol{u}}_{k,m}(r, t) \exp\left(i\alpha k z + i m \theta\right) \tag{2}$$

where $\alpha = 2\pi/L_z$ gives the length of the pipe and $2K, 2M$ give the total number of Fourier modes in streamwise and azimuthal directions. To remove the aliasing, the $\frac{3}{2}$-rule is used for the evaluation of the nonlinear term with pseudo-spectral method. In radial direction the finite-difference method with a 9-point stencil is employed for the discretization. A 2^{nd} order of accuracy semi-implicit scheme, which is a combination of Adams-Bashforth and backward differentiation (AB/BD) schemes, is used for time integration. A time-splitting scheme, refered to by the authors as improved projection scheme (see [**?**] for details), allows us to deal with the pressure field and impose the incompressibility condition. The code was tested by calculating the friction coefficient of fully turbulent flow at various Reynolds numbers with a direct comparison with Blasius law.

RESULTS

In the simulations we explored different methods to modify the mean shear of the turbulent flow. One method was localised forcing mimicking an injection mechanism and in another case a change in boundary conditions was used (again in a streamwise localised segment of the pipe). Both resulted in full relaminarisation downstream (see Fig. 1). Based on our insights from the simulations an experimental control scheme was developed and successfully applied. In first tests fully turbulent flow at Re up to 6000 could be relaminarised (Fig.2) and remained laminar downstream of the control point.

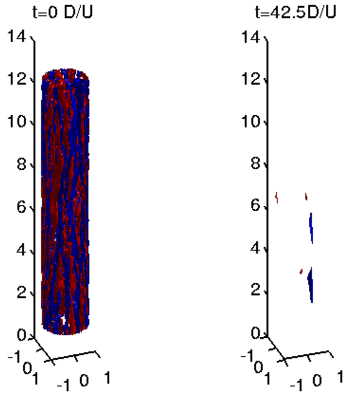

Figure 1. *Isosurfaces of $u_z = \pm 0.05$ at two time instants for a slimulation at Re=10000. Flow is from bottom to top and the control was turned on at t=0 D/U.*

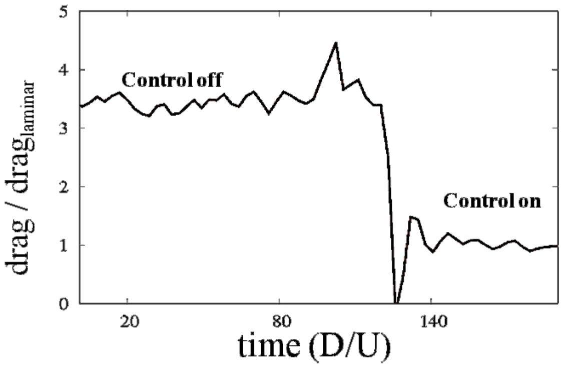

Figure 2. *Drag reduction of the control in an experiment at Re=6000.*

References

[1] J. M. Hamilton and J. Kim. Regeneration mechanisms of near-wall turbulence structures. *Journal of Fluid Mechanics* **287**: 317–348, 1995.
[2] J. Jiménez and A. Pinelli. The autonomous cycle of near-wall turbulence. *Journal of Fluid Mechanics* **389**: 335–359, 1999.
[3] B. Hof and A. D. Lozar and M. Avila and X. T and T. M. Schneider. Eliminating Turbulence in Spatially Intermittent Flows. *Science* **327**: 1491–1494, 2010