DIRECT NUMERICAL SIMULATION OF TURBULENT PIPE FLOW AT HIGH REYNOLDS NUMBERS.

Bendiks Jan Boersma
Chair of Energy Technology
Delft University of Technology
Delft The Netherlands
email:b.j.boersma@tudelft.nl

Abstract With todays supercomputers we are able to simulate flows with moderate to high Reynolds numbers. These flows show features that are not present in simulations with lower Reynolds numbers. Recently we have finished a fully resolved direct numerical simulation of a turbulent pipe flow with a bulk Reynolds number of 76,000 on a computational domain which is 18 pipe diameters long. During the conference we will present results from this simulation, such as velocity statistics, pre-multiplied energy spectra and auto correlations.

NUMERICAL MODEL

The flow in the pipe is considered to be incompressible. The incompressible Navier-Stokes equations written in cylindrical coordinates, with u_r, u_θ and u_z as velocity components in the radial, circumferential and axial direction, are discretized with a pseudo spectral (FFT based) method in the periodic circumferential and axial directions. In the radial direction we use the 6th order staggered compact finite difference method. The staggered arrangement in the radial direction has as advantage that boundary conditions at the centerline of the system do not have to be specified, except for the diffusion of the radial velocity for which a simple Neumann condition is used. Due to the staggered arrangement boundary conditions for the pressure have not to be specified. The computational grid in the radial direction is non uniform, with the grid points slightly clustered towards the wall. The equations are advanced in time with a 3rd order Adams-Bashforth method. The model is parallelized with the library 2decomp&fft [2] which is implemented on top of MPI.

RESULTS

The velocity in the simulations is normalized with the friction velocity u_* which is by definition equal to $\sqrt{\tau_w/\rho}$ where τ_w is the wall friction and ρ the fluids mass density. The flow is driven by a constant pressure gradient $dp/dz = 4D^2/u_*$ in which D is the pipe diameter. There is some evidence in the literature [1] that above a certain Reynolds number structures with a length scale longer than the pipe diameter exist. To capture these structures we have decided to use a long computational domain with a length of 18D. This more or less the upper limit of what can be handled on the computer systems which are available to us. The gird consists of $7200 \times 2400 \times 420$ points in the streamwize, spanwize and radial direction. With a frictional Reynolds number $Re_* = u_8 D/\nu = 3685$ this corresponds to a non-dimensional grid spacing $\Delta z u_*/\nu = 9.2$, $r_{max}\Delta\theta u_*/\nu = 4.82$ and $\Delta r_{wall} = 0.5 u_*/\nu$. Computations are carried out on 12,000 CPUs of a Cray-XE6. A time step on the grid of $7200 \times 2400 \times 420$ takes typically 25 seconds (wall clock time).

In Figure 1 (left) we show the axial velocity normalized with the friction velocity. In Figure 1 (right) the root mean square profiles of the radial, circumferential and axial velocity are plotted.

In Figure 2. we show the pre-multiplied 1D energy spectrum (z-direction) as a function of the radial coordinate for a pipe flow with a bulk Reynolds number of $34,000$ (left) and a pipe flow with a Reynolds number of $76,000$ (right). In both cases the maximum in kinetic energy is observed for a radial position $r = 15\nu/u_*$ and a wavelength $\lambda^+ = 1000$.. For the high Reynolds number, Re=76,000 a second local maximum is observed for $r^+ \approx 500$. Which is in agreement with the experimental results of [3].

References

[1] Kim, K.C., & R.J. Adrian, 1999, Very large-scale motion in the outer layer, *Phys. of Fluids*, **11**, 417.
[2] Library for 2D parallelization, freely available from: http://www.2decomp.org
[3] Hutchins, N. & I. Marusic, 2007, Evidence of very long meandering features in the logarithmic region of turbulent boundary layers, *J. of Fluid Mech*, **579**, 1-28.

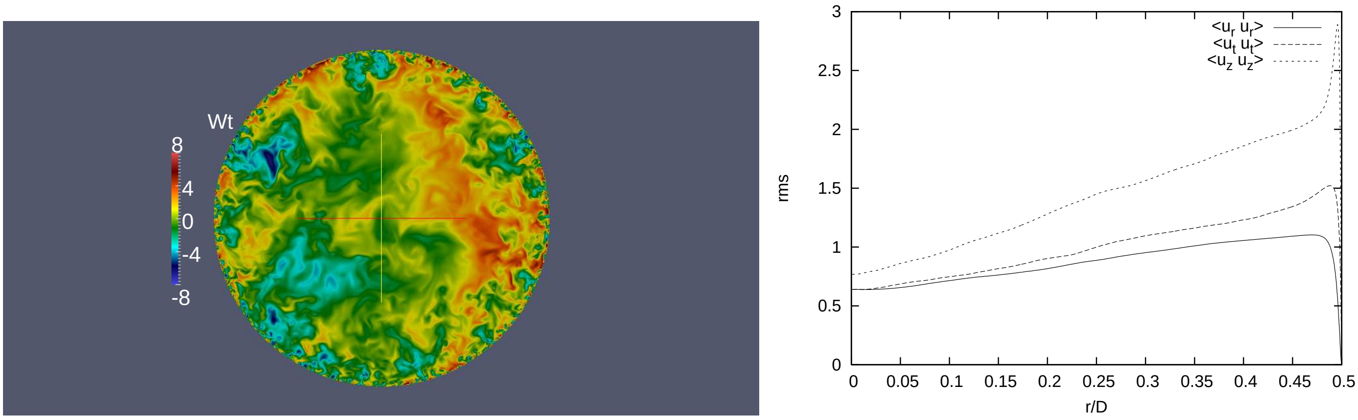

Figure 1. Left: The instantaneous axial velocity in the pipe, normalized with the friction velocity u'_z/u_*. Right the rms profiles normalized with the friction velocity, u_*.

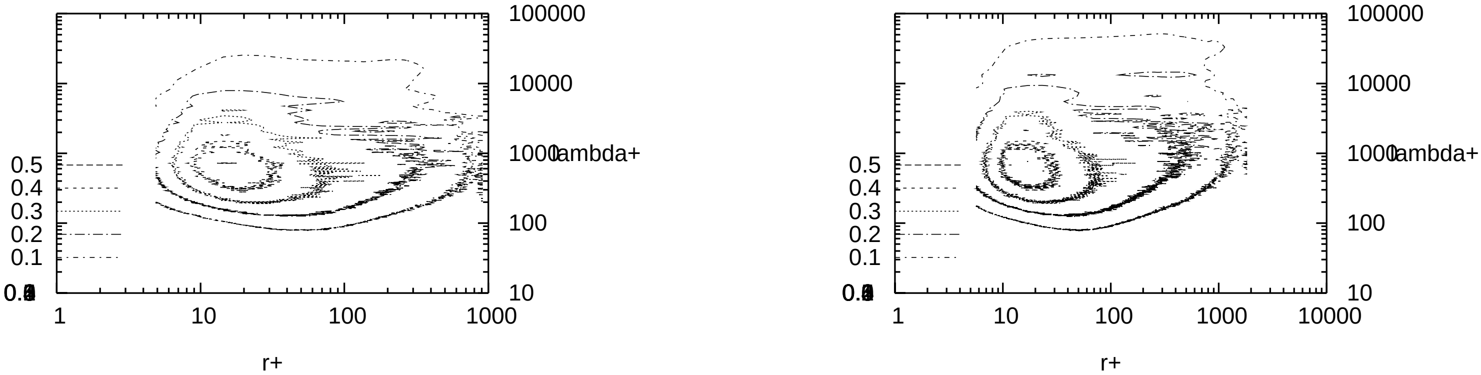

Figure 2. The pre-multiplied energy spectra. Left a pipe flow with a bulk Reynolds number of 34,000. Right a bulk Reynolds number of 76,000.