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THE STATE OF TURBULENCE IN A PIPE FLOW WITH DRAG REDUCTION

E. Gallorini
Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy,
D. Massaro
SimEx/FLOW, Engineering Mechanics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
P. Schlatter
Institute of Fluid Mechanics (LSTM), Friedrich–Alexander–Universität (FAU) Erlangen–Nürnberg, DE-91058 Erlangen, Germany
M. Quadrio
Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy,

INTRODUCTION

Since their introduction [5], streamwise traveling waves of spanwise wall velocity (StTW) have been an efficient approach to reducing drag in wall-bounded flows such as channel flow or pipe flow. The drag-reducing effect of StTW has been confirmed experimentally for the first time by [1], where a discrete counterpart of the continuous sinusoidal wave was used. Drag reduction figures represented in figure 1 were obtained. The figure plots drag reduction in a pipe flow for a wave experimentally discretized by three discrete segments ($s = 3$), with the streamwise wavenumber fixed at $k_x^+ = 0.0082$ (where the superscript $^+$ stands for viscous units of the reference case) and compares them to the original channel flow data obtained by DNS. Here, $R = 1 - \frac{C_f}{C_{f,0}}$ is the drag reduction, and C_f and $C_{f,0}$ are the friction coefficients measured respectively in the actuated and reference cases.

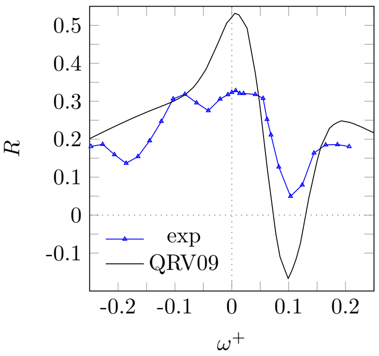

Figure 1: Drag reduction R experimentally measured for StTW in [1] in the pipe flow (blue triangles), compared at the same value of k^+ to available DNS information for StTW from the DNS study of [5] in the planar geometry (continuous black line).

The experimental and the numerical curves are not identical. The experiments show wiggles absent in the simulations and with the maximum drag reduction limited to $R \sim 0.3$. These effects, already noticed in [1], have been recently discussed in [3], which focused on the discrete nature of the control, which explains the wiggles observed in the experiment. The higher drag reduction observed in the simulations has been attributed to a state of partial relaminarization that could not be reached in the experimental facility. The present work intends to explore this last topic further, by studying how StTW affect the flow state. In particular, since flow relaminarization is obtained at (bulk) Reynolds numbers that are much higher than the usual ones around which transition to turbulence in pipes is observed [2], we ask the question whether Re is enough to characterize the transition process in a controlled pipe flow.

METHODOLOGY

Direct numerical simulations (DNS) of a turbulent pipe flow modified by StTW are carried out to study how skin friction modifications alter the flow state. Navier–Stokes equations are written in non-dimensional form and in cylindrical coordinates, for the primitive variables pressure p and velocity $\boldsymbol{u}$, as described in [3]. Temporal discretization is based on a partially implicit scheme with a combination of the implicit Crank-Nicholson scheme for the linear terms and a three-substeps, low-storage Runge–Kutta scheme for the convective terms. Regarding spatial discretization, the homogeneous streamwise and azimuthal directions x and θ call for a spectral discretization, naturally enforcing the required periodic boundary conditions with the computational efficiency of the pseudo-spectral approach. Compact, fourth-order accurate finite differences are used to discretize differential operators in the radial direction. The azimuthal resolution would increase above the required level as the pipe axis is approached, with expensive requirements on the timestep to satisfy the CFL conditions. The present numerical method, as described in [3], works around this issue by gradually truncating the Fourier series in θ direction as the radial coordinate approaches the center of the channel, such that the azimthal resolution remains approximately constant with the radial coordinate. The pipe studied in this set of numerical experiments has a length $L_x = 30D$, being D the pipe diameter. This extended dimension, compared to work on similar topics, has been chosen to make sure that the phenomena are not constrained by the domain length. To duplicate the experiment, the simulations are run at a constant flow rate, with a bulk Reynolds number $Re_b = \frac{U_b D}{\nu} = 4900$ and a reference friction Reynolds number $Re_\tau = \frac{u_\tau R}{\nu} = 169$. StTW are applied by explicitly imposing a Dirichlet condition for the azimuthal velocity of the type

$u_\theta(x,t) = A\sin(k_x x - \omega t)$, being A, k_x and ω the control amplitude, wave-length and frequency. Several simulations in different positions of the $k_x - \omega$ plane are performed, while $A = 0.5$ ($A^+ = 14.5$). As k_x is changed, the length of the domain is slightly enlarged/contracted to always accommodate an integer number of waves.

RESULTS

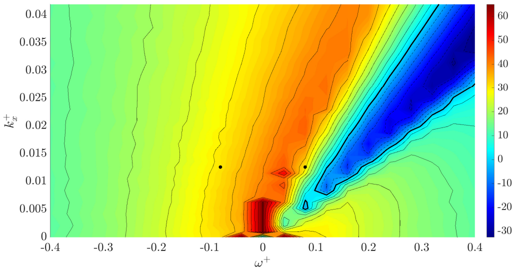

Figure 2: Map of friction drag reduction (percentage) in the $\omega - k_x$ plane for $A = 0.5$ and $Re_b = 4900$. Contours are spaced by 5% intervals, with the zero level indicated by thick lines. The two dots, at the same R, correspond to the two flows considered later in figure 3.

We first explore the $\omega - k_x$ parameter space by performing approximately 700 DNS for different combinations of k_x and ω. The data are organized in a drag reduction map as in [5] and plotted in figure 2. The simulation outcomes in terms of drag reduction resemble those of the plane channel flow, and exhibit, as expected, regions of high drag reduction and drag increase at similar frequencies and wavelengths. In the present case, the maximum drag reduction is obtained at low wavenumbers where a complete relaminarization of the flow is obtained, corresponding to a drag reduction of $\mathcal{R} = 65\%$.

All the cases are at $Re_b = 4900$, and it is known [2] that this is well above the transitional regime in the natural pipe flow. Here, however, the picture is complicated by the presence of the drag-reducing forcing, possibly leading to a state of spatially-localized turbulence observed in [3] and also typical of the natural pipe flow but at much lower Re_b. One might surmise that, since the StTW alter the one-to-one relationship between Re_b and Re_τ of the natural pipe flow, perhaps Re_τ is a better indicator for transition.

To describe the flow state, we compute at any time instant the integral of the cross-stream turbulent kinetic energy q across the cross-section A of the pipe:

$$q(x,t) = \int_A (u_r^2 + u_\theta^2)\, dA, \tag{1}$$

which is an acknowledged indicator of turbulence [4]. In fact q is useful to emphasize where along the pipe axis turbulent puffs develop, and where a nearly laminar flow exists.

We show the spatio-temporal evolution of $q(x,t)$ for two cases, identified with dots in figure 2. These have the same $k_x^+ = 0.0126$; the two frequencies $\omega^+ = \pm 0.08$ yield a similar amount of $\mathcal{R} \sim 31\%$, hence the same value of friction Reynolds number Re_τ.

Figure 3 represents the evolution of $q(x,t)$ over the periodic pipe with time. The two cases have the same friction and bulk Reynolds numbers, yet the flow behavior is different. With the backward-traveling wave (top panel), turbulence reduces compared to the reference case, but the flow is turbulent everywhere during the whole simulation. With the forward-traveling wave (bottom panel), instead, turbulence is localized in highly energetic spots, while the regions inbetween are quiescent and nearly laminar. This is often observed in transitional pipe flows, and closely resembles the puff structures observed in pipe flow experiments [2]. Note that here these transient phenomena appear at $Re_b = 4900$, that is well beyond the critical value (around $Re_b = 2000$) identified in previous work to sustain turbulence [2]. Hence, the global bulk and friction Reynolds numbers are insufficient to identify the flow regime in a pipe under the action of drag-reducing control. Further research is ongoing to clarify if and how local friction affects the localized state of turbulence.

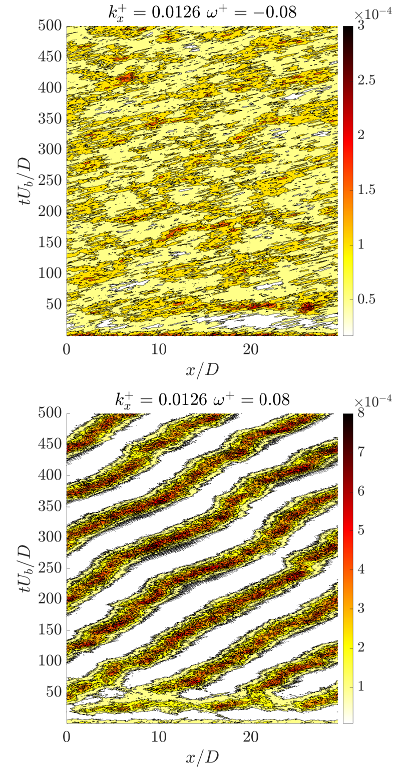

Figure 3: Space-time contour plot of $q/(AU_b^2)$ in a reference frame moving with a convection velocity $U_c = U_b$, for the two cases with $k_x^+ = 0.0126$ and $\omega^+ = \pm 0.08$. Flow is from left to right.

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