TURBULENT SPOTS IN CHANNEL FLOW: FROM TRANSIENT GROWTH TO SELF-SUSTAINABILITY

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Abstract We present an experimental investigation of the development of turbulent spots in channel flow. The internal structure of a turbulent spot is analyzed. We show the importance of transient growth of the perturbation in the early stage of a spot and the appearance of a self-sustained process that allows the perturbation to survive and eventually grow.

INTRODUCTION

It is well established that shear flows, such as pipe or channel flows, present different regimes increasing the Reynolds number. Between the laminar flow at low Reynolds number and the turbulent regime at high Reynolds number, there is coexistence of laminar and turbulent regions, the latter being commonly called turbulent spots. The linear stability theory failed to predict the transition process in Poiseuille flow. Indeed, the critical Reynolds number predicted by the linear stability theory for the plane Poiseuille flow is Re_c = 5772, where the Reynolds number is $Re = u_c h/\nu$ with u_c the center line velocity, h the half channel height and ν the kinematic viscosity of the fluid. This is to be compared to the experimentally observed critical Reynolds numbers ranging between 1000 and 2000 [4, 1]. The transition process in wall bounded flows remain one of the most fundamental and practical problem still unsolved in fluid dynamics.

EXPERIMENTAL SET-UP AND METHODOLOGY

In the present work, we are studying this transition process in a dedicated water channel [3] (figure 1) which is three meters long with a 20×150 mm cross section. The walls are located in $y = \pm h$. The x and z axis are respectively the streamwise and spanwise coordinates. The design of the inlet section, together with the smooth connections between all parts of the channel, minimize the upstream perturbations leading to a laminar flow at least up to $Re = 5000$. It is then possible to study the influence of a well controlled perturbation on the transition process. The perturbation is induced by short injection of water, $\Delta t = 150$ ms, through a round hole of diameter $d = 0.1h$, drilled in the upper plate. The velocity field is studied using time-resolved Particle Image Velocimetry (LaVision ®) in the $y = 0$ and $y = 0.5h$ plane. We use three synchronized high speed cameras in order to measure the flow field in a 0.8 m long section of the channel.

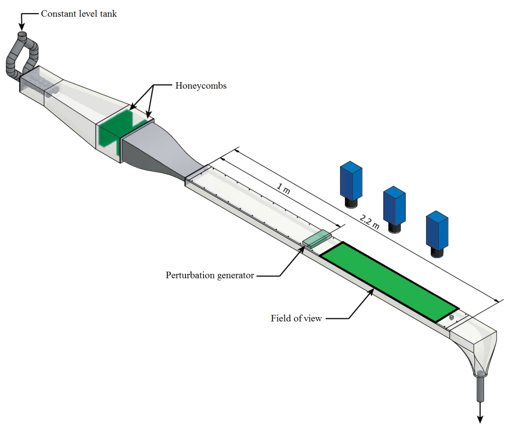

Figure 1. Sketch of the experimental setup. The channel's cross section is 20×150 mm and the test section's length is 2.2 m. The PIV measurement area (green) is 150 mm wide and 900 mm long.

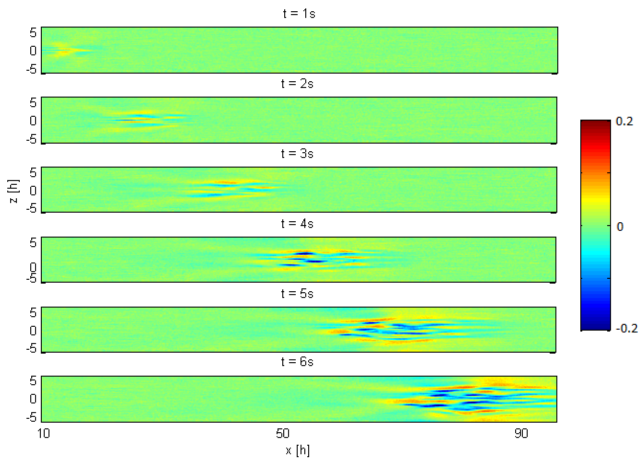

Figure 2. Time evolution of the streamwise velocity $u - u_{laminar}$ in the $y = 0.5h$ plane for $Re = 2000$. The perturbation has been generated in $(x, z, t) = (0, 0, 0)$.

RESULTS AND DISCUSSION

We present on figure 2 the time evolution in the $y = 0.5h$ plane of the streamwise velocity of a small perturbation induced at $(x, z, t) = (0, 0, 0)$ for $Re = 2000$. Thanks to the very long PIV field, we are able to follow the perturbation for a relatively long time. Time series obtained from this measurements allow us to construct a precise image of the structure of a turbulent spot in a channel flow.

Figure 3 shows the vorticity transport $\langle|\omega_y|.(u - u_{bulk})\rangle$ (with u_{bulk} the streamwise velocity averaged on the entire channel's section) inside a spot averaged in time in a frame moving at u_{mean}. At the leading edge of a spot, some elongated structures (figure 2) are moving downstream ($\langle|\omega_y|.(u - u_{bulk})\rangle > 0$) and are slowly damped whereas at the trailing edge, highly active structures (figure 2) are moving upstream ($\langle|\omega_y|.(u - u_{bulk})\rangle < 0$). These coherent structures are mainly high and low velocity streaks which are destabilized and exhibit sinuous modes.

Figure 4a shows the temporal evolution of the energy associated to the spot for different Re. For sufficiently small Re ($Re = 1000$) we observe a transient growth followed by a decay of the energy. On the other hand, for higher Re ($Re = 2000$ and $Re = 3000$), the transient growth is followed by an important increase of the energy [5]. Duriez *et al.* [2] have demonstrated the existence of a self-sustained process for the turbulence in a flat plate boundary layer, comparing the ratio between the streamwise and spanwise energy. Using the same approach, we present in figure 4b the time evolution of this ratio for different Re. For $Re = 2000$ and 3000, this ratio reaches a plateau after a first growth. This constant ratio shows that the energy transfer between the two components has reached an equilibrium. This can be interpreted as a proof of the existence of a self-sustained process [6].

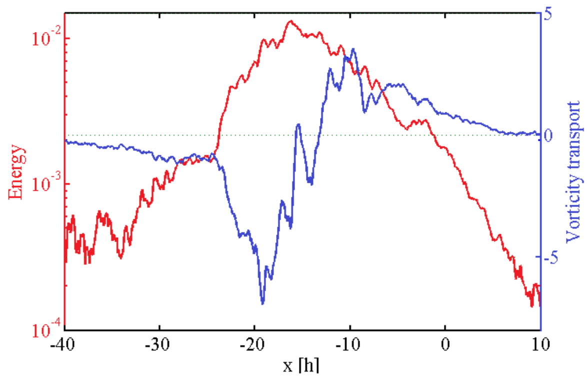

Figure 3. The turbulent kinetic energy, integrated along the spanwise direction, z, and averaged in time in a moving frame at u_{mean} is shown in red. The vorticity transport $\langle|\omega_y|.(u - u_{bulk})\rangle$ is shown in blue. Vortices at the leading edge are moving downstream and vortices at the trailing edge are moving upstream.

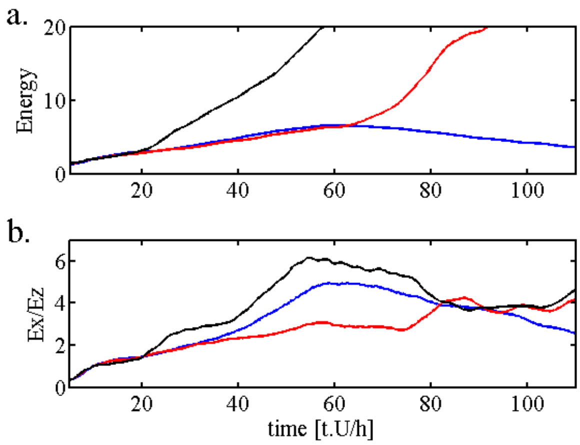

Figure 4. Blue: $Re = 1000$, red: $Re = 2000$, black: $Re = 3000$. **a.** Time evolution of the spot's energy. **b.** Time evolution of the ratio between streamwise and spanwise energy showing a plateau for $Re = 2000$ and 3000.

In summary, the spatio-temporal structure of a turbulent spot in channel flow has been investigated for more than 100 advection time units. After a first linear stage of transient growth, for sufficiently large Re, a nonlinear self-sustained process is triggered, refraining the turbulent spot from decaying.

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