EXPERIMENTAL STUDY AND LARGE EDDY SIMULATION OF ACCELERATING FLOW FROM AN INITIAL TURBULENT FLOW

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ABSTRACT

In this paper, we report a combined experimental and LES study of transient flow in a rectangular channel accelerating from an initial turbulent flow following the opening of the control valve. We show that this transient flow undergoes a process of laminar-turbulent transition even though the initial flow is turbulent. This is consistent with the findings from the numerical studies of idealised flow transients (He & Seddighi 2013, 2015 and Seddighi et al 2014). The transient flow is characterised by a time developing laminar-like boundary layer, which later becomes unstable and breaks up into turbulence. This process is similar to the bypass transition of spatially developing boundary layer.

INTRODUCTION

Direct numerical simulation (DNS) of a transient channel flow following an increase of flow rate of an initially turbulent flow has previously been conducted by the present authors to investigate the response of turbulence (He & Seddighi 2013, 2015 and Seddighi et al 2014). It has been shown that the transient flow undergoes a process of laminar-turbulent transition even though the initial flow is turbulent. The process resembles boundary layer bypass transition. In response to the rapid increase of flow rate, the flow does not progressively evolve from the initial turbulent structure to a new one, but undergoes a process involving three distinct phases (pre-transition, transition and fully turbulence) that are equivalent to the three regions of the boundary layer bypass transition, namely, the buffeted laminar flow, the intermittent flow and the fully turbulent flow regions. This transient channel flow represents an alternative bypass transition scenario to the free-stream turbulence (FST) induced transition, whereby the initial flow serving as the disturbances is a turbulent wall shear flow with pre-existing streaky structures. A thin boundary layer of high strain rate is formed adjacent to the wall following the rapid increase of flow rate, which grows into the core of the flow with time providing the main reasons for further changes of the flow. The pre-existing turbulent structures act as background perturbations to this boundary layer, much like the role the free stream turbulence plays in a bypass transition. These turbulent structures are modulated by the time-developing boundary layer and stretched to produce elongated streaks of high and low streamwise velocities, which remain stable in the pre-transitional period. At this stage, the axial fluctuating velocity increases steadily but the other two components remain effectively unchanged. In the transitional phase, localised turbulent spots are being generated which are distributed randomly in space. Such turbulent spots grow longitudinally as well as in the spanwise direction, merging with each other and eventually occupying the entire wall surfaces when the transition completes and the flow becomes fully turbulent.

In this paper, we report an experiment of transient flow in a rectangular channel accelerating from an initial turbulent flow following the opening of the control valve of a flow loop to demonstrate the theory that has been established from the numerical studies of idealised flow transients discussed above in a real system. These experiments were then simulated using large eddy simulation (LES).

The transient flow accelerating or decelerating from an initial turbulent flow in a pipe or channel has previously been studied extensively. Interested readers are referred to the literature, including for example, experimental studies of Maruyama et al (1976), He & Jackson (2000), Greenblatt & Moss (2004), He et al (2011) or computational studies of Chung (2005), He et al (2008), Seddighi (2011), Jung & Chung (2012). In addition, much of the concept of boundary layer bypass referenced here can be found from a large body of literature, including for example, Andersson et al (1999), Matsubara & Alfredsson (2001), Jacobs & Durbin (2001), Brandt et al (2004), Fransson et al (2005), Ovchinnikov et al (2008).

EXPERIMENTAL AND COMPUTIONAL METHODS

The experiments were performed in a gravity-driven water flow loop shown in Figure 1. The loop was made of the main test section, a return pipe, an over-flow pipe and a top and a bottom tank. The flow was pump from the bottom tank to the top one through the return pipe which carried a flow rate greater than that through the test section. The excess fluid then flowed through the over flow pipe down to the bottom tank, hence maintaining the water level at the top tank constant. The control of the flow was achieved by a pneumatically actuated, fast response, control valve.

The test section was a rectangular cross section of 50 mm x 350 mm (height x width) to facilitate flow visualisation. It was 8 m long and made of transparent Perspex with a glass window for optical measurements. The latter as about 7 m downstream of the inlet, making the length prior measurement to be about 140 channel heights. Particle Image Velocimetry (PIV) was used to measure the instantaneous velocity and a flush-mount hot film sensor was used to measure the wall friction. Further details of the test rig and the validation of the measurement can be found in Gorji (2015) and Mathur (2016).

In the experiment, a transient test begins with the control valve partially open and the flow running through the test facility for a long time until a statistically steady turbulent flow is established; then a further opening of the control valve is initiated and the valve reaches the prescribed position within a fraction of a second. Accordingly, the flow is accelerated rapidly due to the newly imposed additional pressure force, reaching its final value within a few seconds. Several test cases are performed, having similar starting Reynolds numbers but various final Reynolds numbers (Table 1). In each case, the test is repeated at least 60 times to facilitate ensemble averaging to obtain turbulence statistics and wall shear stress.

Case	Re_b	U_b (m/s)	Δt (sec)	Measurements
E1	2800 – 7400	0.11 – 0.28	1.8	v-PIV, h-PIV
E2	2800 – 15500	0.11 – 0.64	1.9	v-PIV, h-PIV
E3	2400 – 22500	0.10 – 0.91	2.1	v-PIV

Table 1. Experimental test cases. Re_b is based on the bulk velocity (U_b) and channel half height; Δt is the transient time period; v- & h-PIV arrangements measuring velcoity field on a vertical or horizontal plane, respectively.

Case	Domain	Grid	Δx^{+1}	Δz^{+1}	Δy_c^{+1}
E1DNS	18δ×2δ×5δ	1024×240×480	7	4	7
E1LES	18δ×2δ×5δ	300×150×180	26	12	9
E2LES	18δ×2δ×5δ	648×300×450	22	9	11
E3LES	24δ×2δ×5δ	1200×360×540	22	10	12

Table 2. Simulation parameters used to reproduce the experimental flow cases.

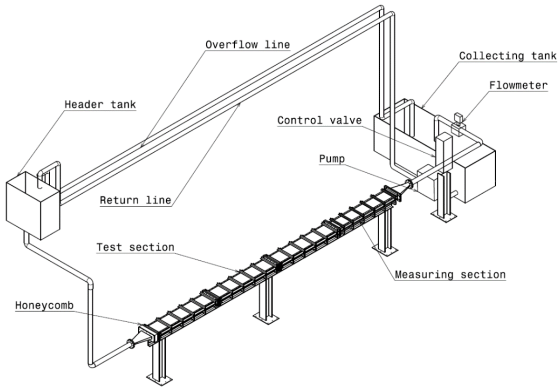

Figure 1 Schematic of the experimental facility (Gorji 2015)

Direct numerical simulation (DNS) and Large Eddy Simulations (LES) were carried out directly simulating the transient flow experiments (Table 2). An in-house computer code CHAMSim was used (Seddighi 2011, He & Seddighi 2013, Mathur 2016). The filetered governing

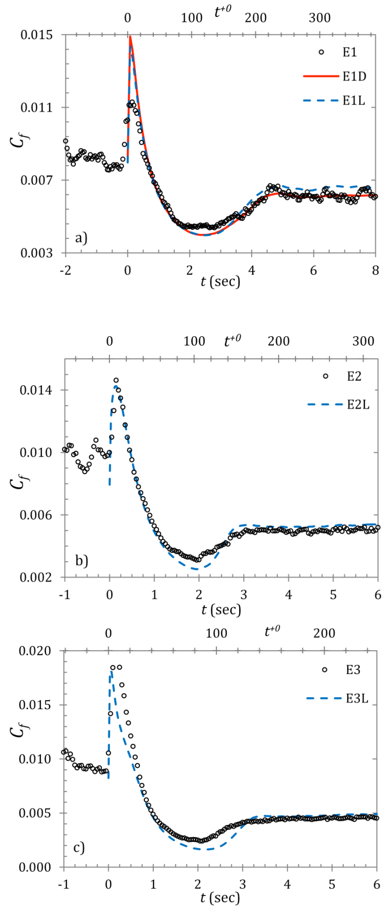

Figure 2 Response of the friction coefficient from experiments (markers) and LES (lines). (a) E1, (b) E2, (c) E3The friction coefficient is defined as $C_f = \tau_w/(0.5\rho U_b^2)$, where $\tau_w$is wall shear stress, ρ the density of the fluid and $U_b$the bulk velocity at time *t*.

equations are spatially discretized using a second-order, central finite-difference scheme. An explicit third-order Runge-Kutta scheme is used for temporal discretization of the non-linear terms, and an implicit second-order Crank-Nicholson scheme is used for the viscous terms. In addition, the continuity equation is enforced using the fractional-step method. The Poisson equation for the pressure is solved by an efficient 2-D FFT solver. Periodic boundary conditions are applied in the streamwise and spanwise directions and a no-slip boundary condition is imposed on the top and bottom walls. The code is parallelized using the message-passing interface (MPI) for use on a distributed-memory computer cluster. Detailed information on the numerical methods and discretization schemes used in the code, and its validation can be found in Seddighi (2011), He & Seddighi (2013) and Mathur (2016). The subgrid-scale stress is modelled using the Wall-Adapting Local Eddy-viscosity (WALE) model of Nicoud & Ducros (1999).

Below, it will be shown that the LES results agree closely with the experimental data. They always show the same trend, and hence the discussion herein does not distinguish between the two sets of data. The LES results are used to illustrate detailed flow features which are not available from experiments.

RESULTS AND DISCUSSION

The responses of the friction coefficient in the three test cases obtained from the experiments and DNS/LES are shown in Figure 2. As indicated earlier, the two sets of data agree very well. The main trend is discussed below with respect to E2, with a starting and final Reynolds number of 2800 and 15500, and a transient period of 1.9 s. In response to the flow acceleration, the friction on the wall increases sharply to a peak value in a fraction of a second as the viscous force on the wall restricts the acceleration of the fluid adjacent to it, resulting in a boundary layer of a high strain rate over the wall (Figure 1). As the boundary layer develops into the flow due to diffusion, the wall friction reduces. This trend continues until around 2 s after the opening of the valve, when the friction starts to turn around increasing with time, reaching its final value at about t= 3 s. Conventionally, the variation of friction factor is associated with the observation of a ‘frozen’ turbulence during the first period of the flow transient (up to 2 s) and then a ‘delayed’ but rapid response of turbulence to follow, which causes the friction on the wall to increase accordingly (Greenblatt & Moss 2004, He et al 2011).

Our new theory is that the overturn of the wall friction at t=2 s is actually caused by the transition of the boundary layer formed adjacent to the wall. This boundary layer is initially laminar but later reaches a stage when it is unstable and transition to turbulence occurs. The transient-flow transition undergoes three phases: pre-transitional, transitional and fully turbulent. Various criteria may be used to define the transitions between the phases. Here we define the lowest point of the fraction factor c_f as the onset of turbulence (t=2 s) and the first peak of c_f after the onset of transition to be the completion of the transition (t=3 s).

The instantaneous flows of cases E1 and E2 are visualised in Figures 3 and 4 using contours of the streamwise fluctuating velocity of the PIV measurements and DNS/LES results over a horizontal plane close to the wall (y=2mm, or $y^{+0} = 15$, where $y^{+0} = yu_{\tau 0}/\nu$ and y is the distance from the wall, $u_{\tau 0}$ the friction velocity of the initial flow). The view field of the LES is much greater than that of the PIV measurement, and the former is cropped to the same size as that of the latter for ease of comparison. The results are clearly in excellent agreement. Consider case E2. At t=0 s, the flow shows random fluctuations with some light streaky structures, which is a typical feature of turbulent flow at a low Reynolds number. During the first stage of the transient process (up to 2 s), high- and low-speed steaks are formed and strengthened with time. This is a typical feature of the early stage of boundary layer bypass transition (Matsubara & Alfredsson 2001, Jacobs & Durbin 2001), explained using the transient growth theory associated with lift up (Andersson et al 1999). At t=2 s, isolated turbulent spots are generated locally (more clearly shown in the LES results due to the larger domain size), which grow with time during the transition period (2 s-3 s), and eventually the entire plane is filled with newly generated turbulence and the transition is seen to have completed. The results show that the flow does not progressively evolve from the initial turbulent state to a new one, but instead, undergoes a process that is typical of bypass transition: the formation of strong streaks followed by the generation of localised turbulent spots, which spread and merge with each other, eventually leading to a new turbulent state.

Figure 5 illustrates the responses of the fluctuating velocities and the abrupt transition of the flow from a different angle. Here the time histories of the streamwise and wall-normal fluctuating velocities along a line across the span of the flow channel are presented. During the pre-transitional period, the wall-normal and the spanwise (not shown) fluctuating velocities remain completely calm and un-responding. Following the onset of transition, they begin to respond spontaneously and abruptly, at slightly different times across the span of the channel. The flow clearly switches from one state to another without gradual evolutions in between. In addition, there are occasionally isolated turbulent spots passing the monitoring line. By contrast, the streamwise fluctuating velocity (u') grows significantly with time during pre-transition, but the characteristics of the fluctuations during this period and those after the transition are categorically different. The pre-transition growth is a reflection of the streaks passing through the monitoring line, which evidently grows in strength with time until onset of transition. The statistics of the fluctuating velocities (see below) shows that the energy of the streamwise velocity fluctuations grows monotonically and significantly during the pre-transition period, consistent with those exhibited in a boundary layer transition (Matsubara & Alfredsson 2001, Jacobs & Durbin 2001, Fransson et al 2005), but the energy of the other two velocity fluctuations remain unchanged.

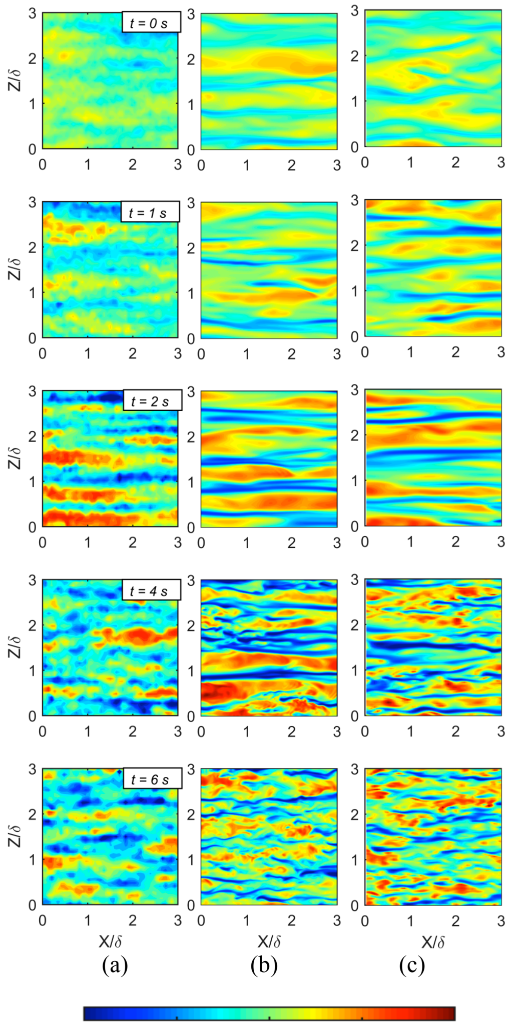

Figure 3 Contour plots of streamwise velocity fluctuations, *u'* (*m/s*), at several instants during the transient at wall distance of *y* = 2 mm for cases a) E1, b) E1DNS, and c) E1LES.

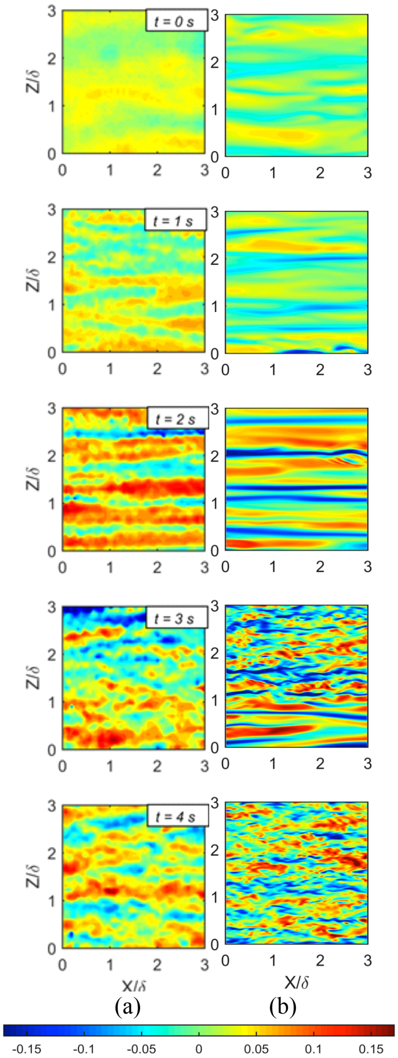

Figure 4 Contour plots of streamwise velocity fluctuations, u' (m/s), at several instants during the transient at wall distance of y = 2 mm for cases a) E2, and b) E2LES.

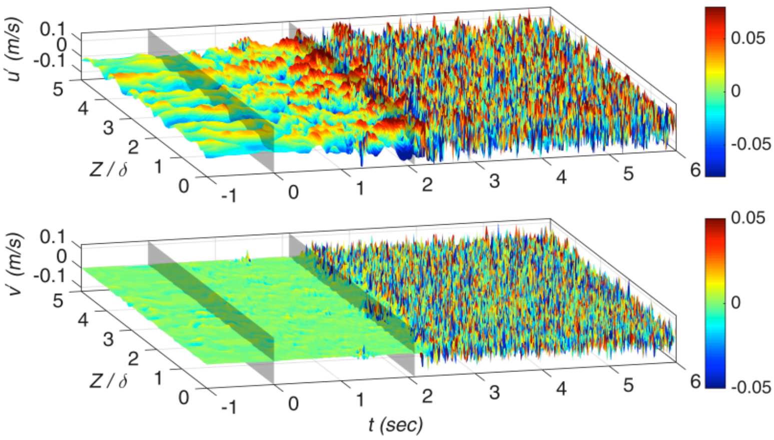

Figure 5. Time histories of the streamwise (top) and wall-normal (bottom) fluctuating velocities along a horizontal line across the span of the channel at y=2mm in E2LES.

Figure 6 shows that the streamwise turbulence near the wall (y/δ=0.07) starts to increase shortly after the commencement of the transient, which continues throughout the pre-transition period and most part of the transition period. This can be linked to the generation and strengthening of the streaks observed above in figures 3 to 5. In contrast, the wall normal turbulence and the turbulent shear stress remain unchanged during the pre-transition period. At the time of transition observed in the flow visualisation, they start to increase spontaneously in the wall region (e.g. y/δ=0.07 and 0.2) and reach to their respective steady values within a short period of time. This period corresponds to the transition period observed in flow visualisation. In the core of the flow, the responses of the various turbulence components are similar, all starting to respond after the completion of the transition near the wall. The delay is longer further away from the wall.

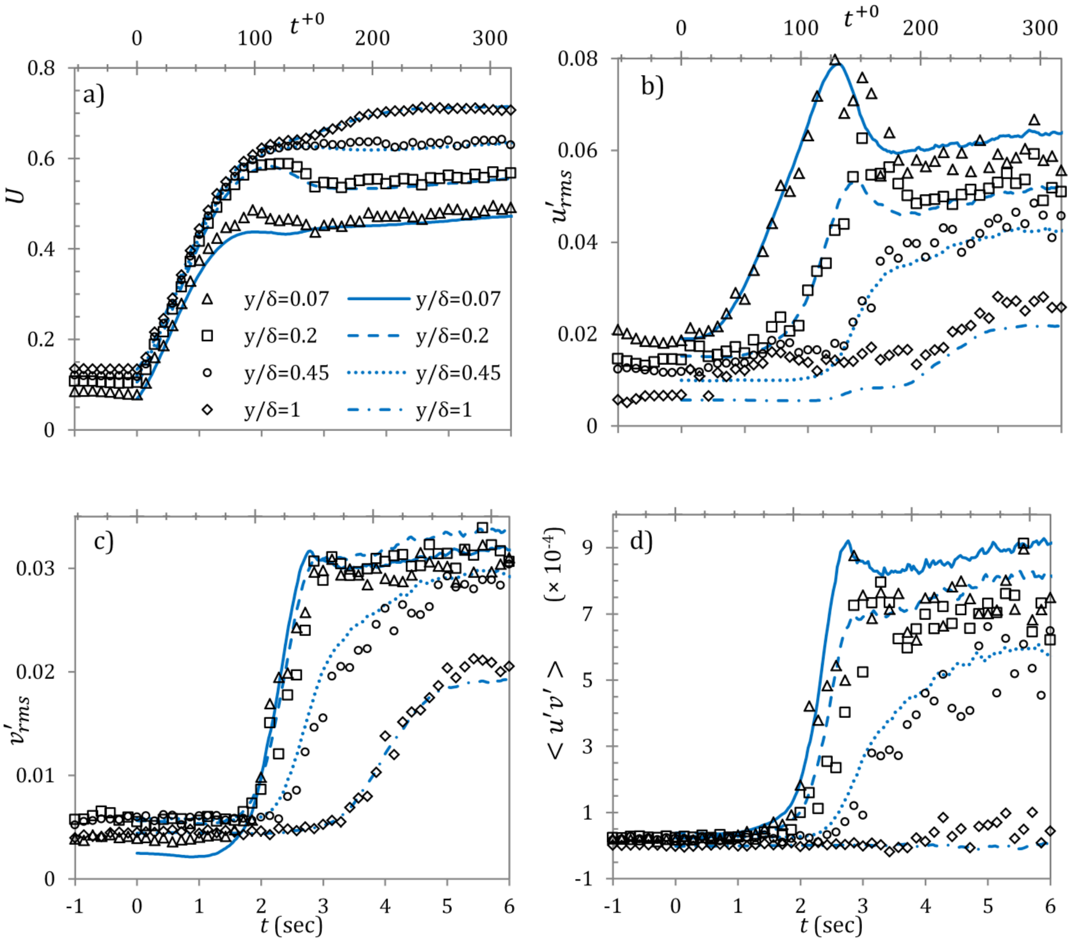

Figure 6. Transient development of mean velocity and the Reynolds stresses in experiment (E2) and LES (E2LES). Symbols denote the experimental data; blue lines represent the LES results of E2L. All quantities are in absolute units: *m/s* for (a)-(c); and m^2/s^2 for (d). All subplots share the same legend.

CONCLUSIONS

A combined experimental and computational (LES) study of an accelerating flow starting from a turbulent state by further opening the control valve has been carried out. The experimental and the LES results agree very well. It has then been shown that this transient flow is characterised by the a laminar-like boundary layer formed on the wall due to the increase of the flow rate, which later becomes unstable and breaks up into turbulence. This process is similar to boundary layer bypass transient. This work hence shows that this real transient flow of a practical system generated from a valve opening behaves in a similar way to those following a sudden increase in flow rate observed in DNS studies.

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