International Journal of Heat and Fluid Flow 67 (2017) 13–26

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Transient behaviors of wall turbulence in temporally accelerating channel flows

Seo Yoon Jung[a], Kyoungyoun Kim[b,*]

[a] Korea Atomic Energy Research Institute, Daejeon 34057, Republic of Korea
[b] Department of Mechanical Engineering, Hanbat National University, Daejeon 34158, Republic of Korea

ARTICLE INFO

Article history:
Received 13 October 2016
Revised 26 June 2017
Accepted 27 June 2017

Keywords:
Transient channel flow
Direct numerical simulation
Bypass-like transition

ABSTRACT

The effects of mean flow acceleration on near-wall turbulent structures were investigated by performing direct numerical simulations of transient turbulent flows in a channel. The simulations were initiated with a fully developed turbulent channel flow and then temporal accelerations were applied. During the acceleration, almost linearly increasing excursions of the flow rate were imposed between the steady initial and final values. The initial Reynolds number (based on the friction velocity) was fixed to $Re_{\tau,i} = 180$, and four different final Reynolds numbers ($Re_{\tau,f} = 250$, 300, 350, and 395) were selected to show the effects of the Reynolds number ratio ($Re_{\tau,f}/Re_{\tau,i}$) on the transient channel flows. To elucidate the effects of the flow acceleration rates on the near-wall turbulence, a wide range of acceleration durations has been examined. Various turbulent statistics and instantaneous flow fields revealed that the rapid increase in the flow rate invokes bypass-transition-like phenomena in the transient flow. In contrast, the flow evolves progressively and the transition does not occur clearly for the mild flow acceleration. When the increase in the Reynolds number is small during the acceleration, distinct bypass-like transition phenomena do not appear in the transient flows, regardless of the acceleration rate. The present study proposed new criteria based on the impulse of the acceleration in order to explain the transition to the new turbulence in the transient channel flow. The bypass-like transition is primarily due to the larger contribution of the impulse to the increase in the flow rate compared with that in viscous friction.

1. Introduction

1.1. Transient turbulent channel flow

Transient turbulent flow inside a channel is an unsteady flow generated by temporal changes of the pressure gradient or the flow rate. The transient turbulent channel flows can be encountered in many engineering problems, such as the intake of an engine, heat exchangers, valves, or the starting and stopping operations of power plants. Numerous experimental and numerical studies on the transient turbulent channel flows have been conducted; however, intriguing characteristics of transient flows still remain not fully understood. For instance, the response mechanism of the near-wall turbulence to temporal acceleration is still an open question in fundamental turbulence research. In addition, the conventional turbulence models that are widely applied in engineering cannot yet accurately predict the transient flow in a turbulent channel.

Kataoka et al. (1975) used an electrochemical method to measure the changes in the flow when the flow rate changes inside a pipe. They found that the time for the transition from laminar to turbulent state decreases with increasing Reynolds number. Mizushina et al. (1975) observed a time delay in the response of turbulence, i.e., which reacts to an abrupt change of flow rate slower than the mean flow field, in the transient flow inside a pipe when triggered by a sudden increase of flow rate in the steady state. The delay is more prominent in the center of the pipe than close to the wall. He and Jackson (2000) examined the temporal changes in transient flows, when the flow is either accelerated or decelerated, utilizing the laser Doppler velocimetry (LDV). They observed three delays in the turbulence: a delay in the turbulence production, a delay in turbulence energy redistribution, and a delay in the propagation of turbulence toward the radial direction. Greenblatt and Moss (2004) conducted experiments of transient pipe flows to examine the effects of flow rate which was higher than those considered in the previous studies (Mizushina et al., 1975; He and Jackson, 2000). The authors identified the regimes of the transient flow as the steady, initial, and final states. They also identified the reconstitution of the wake in the final phase.

* Corresponding author.
E-mail addresses: syjung77@kaeri.re.kr (S.Y. Jung), kkim@hanbat.ac.kr (K. Kim).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.06.012
0142-727X/

Due to the rapid development of supercomputers, numerical studies regarding the transient flow are becoming more popular. Jung and Chung (2012) examined the temporally accelerated flow in the pipe using large-eddy simulation (LES). They numerically confirmed the three delays in the propagation of turbulence in the radial direction, the turbulence production and the redistribution of the turbulence energy, as pointed out in the experiment (He and Jackson, 2000). In addition, Jung and Chung (2012) analyzed the conditionally averaged flow fields associated with Reynolds shear stress producing events. They showed that sweeps and ejections were closely linked to the delays of the turbulence production and of turbulence propagation away from the wall. He and Seddighi (2013) claimed, through the direct numerical simulation (DNS) study on the transient turbulent channel flow, that the abrupt increase of the flow rate causes similar phenomena to the bypass transitions observed in the laminar boundary layer even though the initial flow is turbulent. They explained that the initial turbulence prior to the acceleration acts as a disturbance to create elongated streaks close to the wall, and then these streaky structures are exposed to secondary instabilities which generate a bundle of turbulence vortices, i.e., turbulent spots. In their subsequent study (He and Seddighi, 2015), it was found that, as the difference between the initial and final Reynolds number increases, the bypass-like transition phenomena becomes more prominent while they becomes uncertain as the Reynolds number difference decreases. It has also been reported that a pipe flow following a step increase in flow rate exhibits the transition which is effectively a laminar-turbulent transition, similar to channel flow (He et al., 2016).

1.2. Bypass transition

Before proceeding further, it would be advantageous to review the bypass transition to turbulence in boundary layers. Transition to turbulence in boundary layers is often categorized by natural or bypass transition. When the background perturbation levels are inappreciable, the transition is governed by the amplification of two-dimensional Tollmien–Schlichting (TS) waves (Kleiser and Zang, 1991). However, in the presence of moderate free-stream disturbances, a shorter path termed 'bypass transition' leads to boundary layer turbulence at lower Reynolds numbers [for a recent review, see Zaki (2013)].

The initial stage of bypass transition concerns the penetration of free-stream vortical disturbances into the boundary layer. In the inviscid limit, convected free-stream disturbances are not allowed to penetrate into the boundary layer due to the filtering effect of the mean shear, and this phenomenon is known as *shear sheltering* (Hunt and Durbin, 1999). At finite Reynolds number, however, the sheltering mechanism is less effective, and low-frequency disturbances from the free stream can cause a finite distortion within the boundary layer (Jacobs and Durbin, 1998; Zaki and Saha, 2009).

Forcing due to the low-frequency perturbations generates an energetic response inside the boundary layer in the form of streamwise-elongated streaks. These distortions are termed Klebanoff modes (Klebanoff, 1971) and have been studied using linear theory (Butler and Farrell, 1992; Andersson et al., 1999; Luchini, 2000), experiments (Westin et al., 1994; Matsubara and Alfredsson, 2001) and direct numerical simulations (Andersson et al., 2001; Zaki and Durbin, 2005; 2006). The amplification of streaks is due to an inviscid *lift up* mechanism whereby quasi-streamwise vortices lift up low-velocity fluid away from the wall and sweep high-velocity fluid towards the wall (Landahl, 1980). This inviscid amplification mechanism is curtailed by viscous damping, and the outcome is only a transient growth followed by viscous decay (Butler and Farrell, 1992).

The amplification of streaks can make the flow susceptible to secondary instability which precedes the breakdown to turbulence. Jacobs and Durbin (2001) showed that breakdown occurs when the lifted low-speed streaks are buffeted by the high-frequency free-stream disturbances. Their observations using DNS were confirmed experimentally (e.g. Hernon et al., 2007; Mandal et al., 2010) and complemented by computational studies (e.g. Brandt et al., 2004; Zaki and Durbin, 2005; Schlatter et al., 2008). In addition to the streak breakdown scenario that originates near the edge of the boundary layer, Nagarajan et al. (2007) identified another mechanism that originates near the wall and is initiated by the amplification of an instability wavepacket. To elucidate the numerical and experimental observations of breakdown, a number of studies evaluated the secondary instability of the streaky boundary-layer flow. Andersson et al. (2001) performed inviscid analysis of the linearly-optimal streaks, and could only predict the instability near the edge of the boundary layer. Vaughan and Zaki (2011) applied Floquet analysis to examine the secondary instability of unsteady streaks. They identified two types of instabilities: an outer mode similar to the observations in Jacobs and Durbin (2001) and an inner instability near the wall which bears a close resemblance to the wavepackets reported by Nagarajan et al. (2007). Nolan and Zaki (2013) showed that the onset of breakdown is due to high-amplitude streaks, with streamwise perturbation exceeding 20% of the free-stream velocity. Recently, Hack and Zaki (2014) demonstrated that zero-pressure gradient (ZPG) boundary layers favor the amplification of outer instabilities, and the inner mode is promoted if an adverse pressure gradient (APG) is applied.

1.3. Motivations

Several parameters have been proposed to characterize the transient turbulent flows. He and Jackson (2000) suggested that factors such as the initial Reynolds number, final Reynolds number, and various dimensionless ramp rate parameters define the transient flows inside pipes. The initial and final Reynolds numbers determine the initial and later states of the transient flows, respectively, while the flow increase rate is associated with the difference in the transient flow from the steady flow corresponding to the same Reynolds number. He and Seddighi (2015) examined the effects of the ratio of the final to initial Reynolds number on the bypass-like transition. They showed that in the case of rapid acceleration, a laminar flow similar to Stokes' first problem appears at the early stage of transient flow and then develops into a final turbulent state. When the final Reynolds number is high, the development of the flow is similar to a bypass-like transition, which accompanies the presence of strong streak during pre-transition and the generation of turbulent spots. On the other hand, if the final Reynolds number is low, the transient process is qualitatively different, and the streak formation and breakdown are not dominant. Despite the significant difference in flow visualizations, He and Seddighi (2015) claimed that the transient flows with low Reynolds-number-ratio case can be characterized as the bypass-like transition because they exhibit strong similarity in various turbulence statistics (e.g., critical Reynolds number, energy growth, development of friction factor). Seddighi et al. (2014) have investigated effects of a mild acceleration and compared the results with those of rapid acceleration of He and Seddighi (2013). However, it should be noted that the test cases of Seddighi et al. (2014) are limited to the range of rapid acceleration rates that cause bypass-like transitions.

In this work, we have performed a series of spectral DNS of the turbulent channel flow with temporal acceleration by the prescribed time-dependent mean pressure gradient to examine the flow parameters relevant to the transition behavior. Fig. 1(a) shows the schematic diagram of the accelerated flow in a channel. The initial Reynolds number based on the friction velocity was fixed to $Re_{\tau,i} = 180$ and four different final Reynolds numbers ($Re_{\tau,f} =$