TURBULENT-SPOT DEVELOPMENT IN CONSTANT-MASS-FLUX CHANNEL FLOW

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Abstract The development process of a turbulent spot in plane Poiseuille flow, as well as the related turbulence characteristics, are investigated using direct numerical simulation at transitional Reynolds numbers. We compare the results obtained under two different conditions of either constant mass flux or constant driving force. The results clearly indicate the turbulent spot grows rapidly but stays compact when driven by a constant-mass-flux, the turbulence intensity in its core getting more intense with time, while the spot subjected to constant-driving-force develops turbulent stripes.

INTRODUCTION

A structure similar to an equilibrium turbulent puff in a transitional pipe flow was found in a transitional plane Poiseuille flow by Tsukahara *et al.* [1] through direct numerical simulation (DNS). Its unique structure is called 'turbulent stripe pattern', consisting of quasi-laminar and turbulent regions in a periodic arrangement oblique with respect to the streamwise direction. Recent studies by several groups have reported that the turbulent stripe pattern would occur spontaneously from a turbulent flow field and be an equilibrium state, once the Reynolds number was decreased down to a value in the transitional regime [2, 3]. In these previous studies, the emergence of the turbulent stripe pattern has been confirmed only in the process of "turbulent → transitional regime". One of the well-known observations made in studies of the transition process from laminar to turbulence has been that turbulence first appears in localized regions with a characteristic shape, so-called 'turbulent spots'. The initial stage of its development has been widely investigated by flow visualizations and simulations for more than half a century. Recently, Aida *et al.* [4] reported the development of a spot into a striped pattern in a plane Poiseuille flow. Their DNS was performed under the condition that the magnitude of the driving force, i.e., the pressure gradient, was fixed during the spot evolving. Hence, the velocity in the background laminar region, as well as the flow rate, decreases gradually as the turbulent region spreads out over the computational domain. It is interesting to observe somewhat altered behavior of an evolving spot under the constant flow rate in the channel flow at a transitional Reynolds number. In this work, we have performed large-scale DNS on growth of a turbulent spot in the constant-mass-flux channel flow and examined its growth process by comparison with results found under a constant driving force.

NUMERICAL METHOD AND INITIAL CONDITION

The present DNS to be analysed here used the channel-flow code, which was originally developed for simulation of fully-developed turbulence [1] and is based on a finite differences scheme. The fundamental equations are the continuity and the Navier-Stokes equations for incompressible Newtonian fluids. We used a large computational domain of $731.4\delta \times 2\delta \times 365.7\delta$ in the streamwise (x), wall-normal (y), and spanwise (z) directions, respectively, with a grid of $4096 \times 64 \times 2048$. The periodic boundary conditions are imposed in the horizontal directions.
The mean flow is driven by a uniform pressure gradient described as $-\partial P/\partial x = \rho u_\tau^2/\delta$, where P is the cross-section averaged pressure field, ρ the density, and u_τ the spatially-averaged friction velocity. A laminar flow field is used as the initial condition. A turbulent spot to be tracked is triggered at initial time by a vortex pair with a size of O(δ). It is known from experimental investigations of spots in various types of flows that the spot characteristics become essentially independent of the initial disturbance if its magnitude is strong enough to develop. In this paper, we compare the temporal development of spots under two different kinds of driving force: (i) temporally-constant pressure gradient as $\mathrm{Re}_\tau = u_{\tau 0}\delta/\nu$ (here, $u_{\tau 0}$ is the initial value of u_τ) is fixed to 56; (ii) temporally-constant mass-flux as $\mathrm{Re}_\mathrm{m} = 2U_\mathrm{m}\delta/\nu$ (here, U_m is the bulk mean velocity) is fixed to 2090. Note that in the case of a fully laminar flow $\mathrm{Re}_\tau = 56$ implies $\mathrm{Re}_\mathrm{m} = 2090$.

RESULTS AND DISCUSSION

Figure 1(a) and (b) show developing spots in both cases i) and ii), respectively. The comparison reveals clear differences in the shape of the front and in the interior structures. In the early stage of development, the initial disturbance breaks down and develops into a well-known arrowhead-shaped turbulent spot as it propagates downstream. The spot for the fixed-Re_τ (constant driving force) flow is found to change its form into a V-shape around $tu_{\tau 0}/\nu = 800$, and several turbulent branches grow from the downstream tips of the deformed spot, as previously reported in [4]. Moreover, quasi-laminar regions emerge within the V-shaped turbulent region, so that quasi-laminar and turbulent regions form multiple V-shapes.

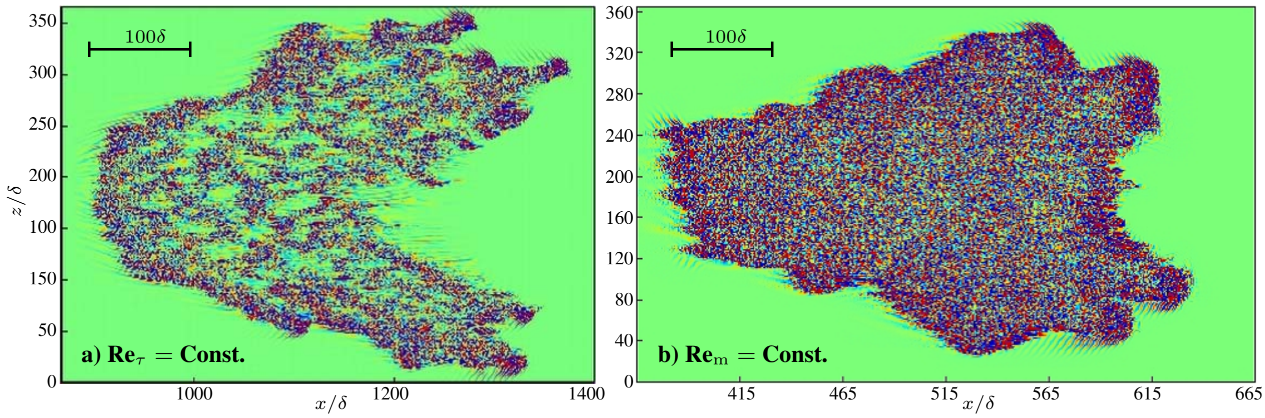

Figure 1. Contours of instantaneous wall-normal velocity in the channel central plane, showing the spot shape and inside structures during the spot evolving at $tu_{\tau 0}/\nu = 3360$ for the constant driving force (a) and at 1790 for the constant mass flux (b). Red and blue colors indicate positive and negative values, respectively, while green represents zero. The mean flow direction is from left to right. The horizontal axis denotes the distance from the trigger point of the spot.

As shown in Fig. 1(a), the stripe arrangement of turbulent regions occurs spontaneously in the spot. On the other hand, for the fixed-$\mathrm{Re_m}$ (constant mass-flux) flow, both the (multiple) V-shaped structure and the branching turbulent region are less remarkable and there does not exist any calm region inside the spot: see Fig. 1(b). The spot expands rapidly and reaches a size comparable to that of the numerical domain: the growth rates in x and z directions are much larger than those for the fixed-Re_τ flow. This difference might be caused by the time-evolving energy input (through the pressure gradient) for the fixed-$\mathrm{Re_m}$ flow, in which the given energy should be dissipated by the increased fully turbulent regions, while the intermittent turbulent state might be essential to compensate for the constant energy input in the case of the fixed-Re_τ flow.

The friction Reynolds number is estimated also in the fixed-$\mathrm{Re_m}$ flow, as shown in Fig. 2(a). Its value is found to increase linearly with time until the spot has reached a size comparable to size of the numerical domain. According to the DNS results on equilibrium states [1, 3], $\mathrm{Re_m} = 2090$ would be equivalent to $\mathrm{Re}_\tau \approx 70$ once the disturbance fully develops in the computational domain and attains a statistically steady state. Therefore, the spot observed in the fixed-$\mathrm{Re_m}$ flow corresponds to a transient characterized by intensifying turbulence and increasing mean wall shear. Streamwise and spanwise front propagation speeds are reported in Fig. 2(b). It can be clearly seen that the respective spot edges propagate at constant speeds for the fixed-Re_τ flow, but depend on time for the fixed-$\mathrm{Re_m}$ flow. It implies that the propagation velocities are determined by Re_τ. In the full paper, additional DNS at lower Reynolds numbers will be reported to examine the presence/absence of turbulent stripe pattern for the fixed-$\mathrm{Re_m}$ flow.

References

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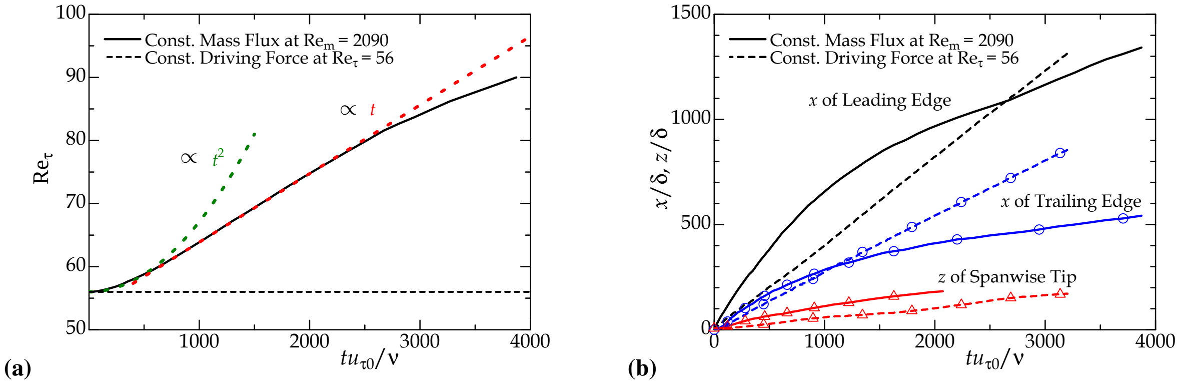

Figure 2. Temporal variations of friction Reynolds number (a) and positions of stream- and spanwise edges of spot (b).