Near-Wall Turbulence in a Localized Puff in a Pipe

Alexander Yakhot, Yuri Feldman, David Moxey, Spencer Sherwin and George Em Karniadakis

Abstract We have performed direct numerical simulations of a transitional flow in a pipe for $Re_m = 2250$ when turbulence manifests in the form of fleshes (puffs). From experiments and simulations, $Re_m \approx 2250$ has been estimated as a threshold when the average speeds of upstream and downstream fronts of a puff are identical (Song et al. in J Fluid Mech 813:283–304, 2017, [1]). The flow regime upstream of its trailing edge and downstream of its leading edge is almost laminar. To collect the velocity data, at each time instance, we followed a turbulent puff by a three-dimensional moving window centered at the location of the maximum energy of the transverse (turbulent) motion. In the near-wall region, despite the low Reynolds number, the turbulence statistics, in particular, the distribution of turbulence intensities and Reynolds shear stress becomes similar to a fully-developed turbulent pipe flow.

1 Introduction

More than forty years ago, experiments conducted in a pipe for mixed laminar-turbulent flows at the range of Reynolds numbers of $2000 < Re_m < 2700$ revealed turbulent self-sustained confined regions, surrounded by a laminar flow and convected downstream [2]. The authors referred to these regions as puffs and slugs. It was found that with an increase in the Reynolds number, puffs increase in size,

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turn into slugs, split and even recombine. For reviews on the transition to turbulence in a pipe together with a thorough analysis of the flow structure and dynamics of a puff, see [3].

Direct numerical simulations (DNS) of turbulent-laminar states in pipe flows at transitional Reynolds numbers have been carried out for axially periodic pipes of length L and diameter D in [4, 5] and recently in [6]. The moving window approach applied in [6] allows computing long-time statistical and average properties of the velocity field inside a localized turbulent puff. The conclusions derived from DNS results are that localized puffs indeed exist in long pipes at $Re_m = 2200 \div 2350$. Recently, a summary of extensive experimental and numerical studies led to the conclusion that for Reynolds numbers $Re_m \simeq 2250$, turbulent puffs are localized, in the sense that their upstream and downstream front speeds are identical, and, therefore, their size does not change for reasonably long but finite times [1].

2 Results

2.1 Moving Window Approach

We have performed DNS of a turbulent puff in pipe flow for $Re_m = 2250$. Here, $Re_m = U_m D/\nu$ is the Reynolds number, $U_m = 1$ is the bulk velocity, $D = 1$ is the pipe diameter and $L = 25D$ is the pipe length. In this paper, the corresponding velocities are denoted by $\mathbf{u} = [u_r(\mathbf{x}, t), u_\theta(\mathbf{x}, t), u_z(\mathbf{x}, t)]$. For details regarding the code and numerical resolution parameters, we refer to [6]. In [6], we assimilated a *snapshot-ensemble* of 10,000 snapshots to analyze the flow field inside a narrow moving window shown in Fig. 1. In this paper, we present also the results obtained up- and downstream of the moving window.

The location with $e_\perp^{(\max)}$ is the indication of the locally turbulent regime. The streamwise fluctuating velocity component is defined as $w = u_z - \overline{u}_z$, where (and hereafter) a bar-sign denotes the snapshot-ensemble averaging. Figure 1 shows the distributions of the snapshot-ensemble averaged kinetic energy of the radial motion in the (r, z)-plane. Upstream of the moving window trailing edge ($z = -2D$), the energy is extracted from the high-speed almost laminar flow by the low-speed fluid ejected outward from the wall.

Figure 2 shows the time trace of the centerline velocity measured at a fixed point in the laboratory reference frame in which the pipe is stationary. The laminar (Poiseuille) centerline velocity normalized by U_m is 2. The deficit in the streamwise velocity is visible, that is, the flow behind the puff is not completely relaminarized. This results from the fact that the periodic computational domain is of insufficient length. The time trace in Fig. 2 replicates that obtained in [4] for $Re = 2350$ and $L = 90D$ after several puff splits, indicating that the flow dynamics is not fully isolated, but rather corresponds to a chain of weakly interacting puffs. Evidently, we should consider the results of our study as the characteristics of a single, but not a completely isolated puff. A steep pattern of the time-trace indicates a sharp interface between the almost laminar and turbulent regions at the puff upstream edge vicinity. Note that with

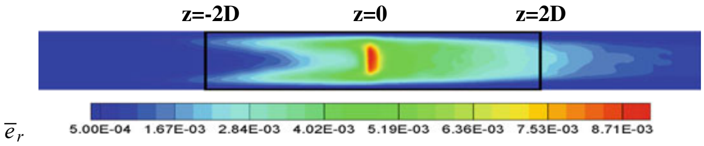

Fig. 1 Contours of the snapshot-ensemble averaged energy of radial velocity ($\overline{e}_r$). At each time step, a moving window ($-2D \leq z \leq 2D$) is centered around $z = 0$ where the kinetic energy of the transverse motion $e_\perp = \sum_{CS}(u_r{}^2 + u_\theta{}^2)$ is maximal; $\sum_{CS}$ denotes the summation over all cross-sectional points

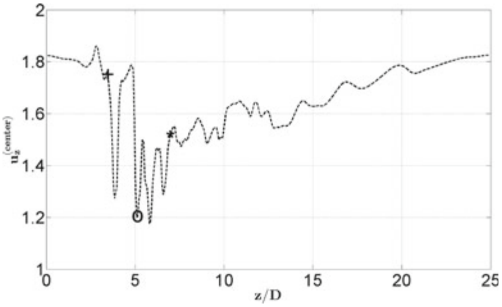

Fig. 2 Typical time trace of the centerline velocity. The symbols are an example of a single snapshot in the moving window reference frame: an asterisk (*) for the leading edge ($z = 2D$), an open circle (○) for the middle section ($z = 0$) and a plus sign (+) for the trailing edge ($z = -2D$) of the moving window

respect to the moving window, the upstream edge of the puff is slightly upstream. Indeed, from Fig. 2, at the trailing edge of the moving window, corresponding to $z = -2D$ in the moving window reference frame, the flow regime is in the onset of turbulence.

2.2 *Cross-Plane Flow and Turbulence Sustaining*

The cross-plane motion plays an important role in turbulence production. In the framework of the Reynolds decomposition turbulence modeling approach, the leading terms of the Reynolds-stress budget equations are [6]:

$$P_{r,z} \simeq -\overline{u_r^2}\frac{\partial \overline{u_z}}{\partial r}, \quad P_{z,z} \simeq -2\overline{wu_r}\frac{\partial \overline{u_z}}{\partial r}, \tag{1}$$

where $P_{r,z}$ and $P_{z,z}$ denote the production of the Reynolds stress $\overline{wu_r}$ and the kinetic energy of the streamwise fluctuations $\overline{w^2}$, respectively. The important consequence of the Reynolds stresses budget equations is that the production of turbulent kinetic energy directly from the mean flow occurs in the equation for $\overline{w^2}$. In order to start this process, the radial component u_r must be generated and from the point of view

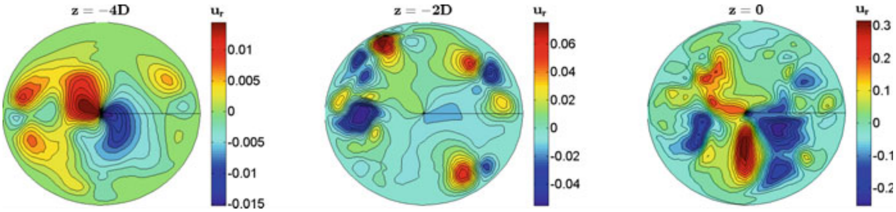

Fig. 3 At the moving window trailing edge ($z = -2D$), in the pipe core there is still no strong movement in the radial direction to generate turbulent kinetic energy (1). This is because the low-speed fluid, that lifted up from the near-wall region, did not reach the center. Further downstream, between $-2D \leq z \leq 0$, the intense turbulent motion in the core associates with the penetration of the fluid that lifted-up from the wall and entrained by a high-speed flow (**c**)

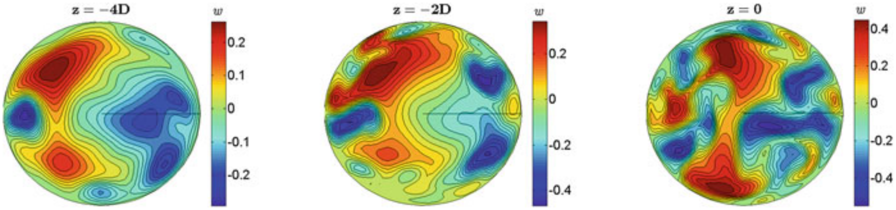

Fig. 4 At the moving window trailing edge ($z = -2d$), there are three footprints of $w < 0$ indicating the radial motion of low-speed fluid from the wall; their locations are marked as 1, 2 and 3 in Fig. 5 (left). Such strong negative fluctuations of the streamwise velocity lead to a significant momentum deficit, and high speed fluid sweeps toward the wall to compensate this deficit. As a result, near the wall, alternating regions of high- and low-speed streaks appear (Fig. 5)

of sustaining the turbulence, the cross-plane radial motion indicates the onset of turbulence energy production.

Figures 3 and 4 show typical contours of the instantaneous radial (u_r, c) and fluctuating streamwise (w, b) velocity components along the pipe. From Fig. 3, the radial movement intensity and pattern change very rapidly along the pipe. In particular, upstream of the puff's trailing edge, at $z = -4D$, u_r is negligibly small. Here, within a short pipe section of 2 diameters, $-2D \leq z \leq 0$, the strong radial motion and, apparently, high mean shear, led to a rapid conversion of kinetic energy from the fast, almost laminar upstream flow into turbulence.

2.3 Turbulence Flow Intensities, High-Order Statistics

In this section, we present the long-time statistical and average properties of the velocity field inside the moving window. Figure 6 shows the streamwise velocity. An observer sitting in the middle section ($z = 0$) of the moving window, will see a sharp upstream interface between the almost laminar and turbulent states when the velocity profile rapidly flattens (Fig. 6, $z = -2D$ versus $z = 0$ curves). For comparison, we

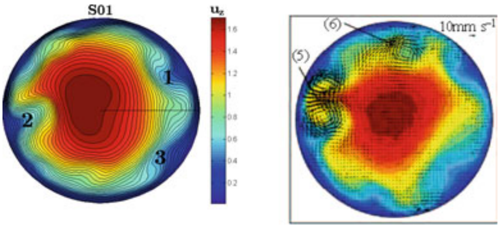

Fig. 5 Contours of the streamwise velocity u_z at $z = -2D$ (left). The wavy form near the wall indicates ejection of a low-speed fluid toward the center; five near-wall streaks can be recognized. On the right, the pattern from [7]

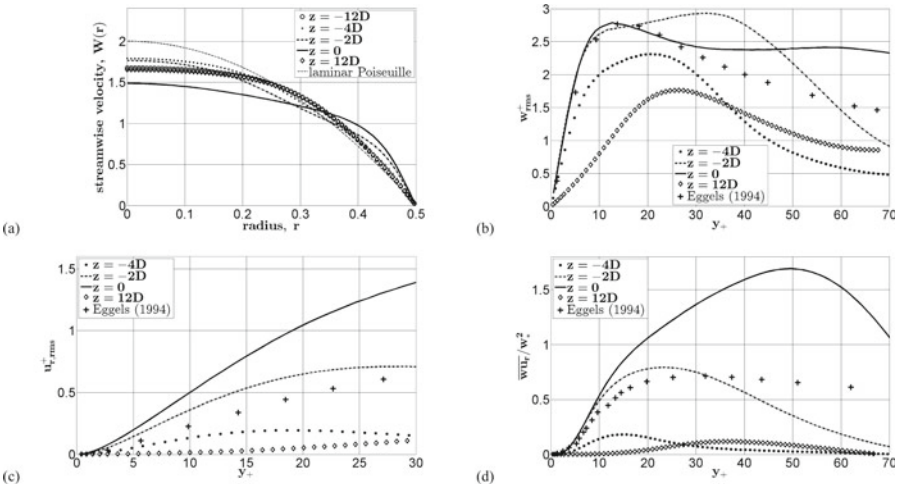

Fig. 6 **a** Streamwise velocity $W(r)$ normalized by the mean velocity; **b** The root-mean-square streamwise fluctuating velocity $w^+_{\rm rms}$ and **c** radial velocity u_r, rms$^+$; **d** Reynolds shear stress $\overline{wu_r}$ normalized by a shear velocity, in wall units. The profiles are averaged over 10,000 snapshots and 78 azimuthal points for each radius

present in Fig. 6 the DNS results obtained for a fully-developed turbulent flow in a pipe at $Re_m = 5300$ [8] (hereinafter referred to as Eggels94). Near the wall, for $y_+ < 14$, we found that the streamwise fluctuating velocity r.m.s. distributions $w^+_{\rm rms}$ are virtually unchanged right after the puff's upstream interface along several diameters downstream (Fig. 6b, $z = -2D$ and $z = 0$ curves, the curve $z = 2D$ not shown). The maximum value of 2.8 is reached at $y_+ = 13.8$, which is in remarkable agreement with Eggels94. This is an evidence that the near-wall streamwise turbulence is formed (locked) in close proximity to the puff interface without being influenced by the energy generation in the core.

In the moving frame of reference, the location $z = 0$ corresponds to the maximum energy of the transverse turbulent motion, while downstream the turbulence decays. At $z = 12D$ (and at $z = -12D$ due to periodicity), near the wall, the radial motion intensity (u_r, rms$^+$) is negligibly small, slightly and gradually increasing towards the center (Fig. 6c). The radial motion decays very quickly, because the velocity profile flattens and it is no longer possible to extract energy from the mean flow. The streamwise fluctuations ($w^+_{\rm rms}$) decay insignificantly upstream from the puff (Fig. 6b, $z = -4D$ and $z = 12D$ curves). On the other hand, the Reynolds stress practically absent near the wall (Fig. 6d, $z = -4D$ and $z = 12D$ curves) and very small far from the wall. Possible interpretation of this is that at the final stage of laminarization, streamwise fluctuations and radial motion weakly correlate.

3 Summary

The purpose of this study is to analyze turbulence in a localized puff for a threshold Reynolds number of $Re_m = 2250$ before it expands in the streamwise direction into a slug. To obtain long-time statistical and average properties of the velocity field inside a localized turbulent puff travelling through a pipe, we collected a velocity database over the time interval of $T = 2000D/U_m$ in a moving window (co-moving reference frame) linked with a puff. In the near-wall region, despite a low Reynolds number, the r.m.s. of streamwise fluctuating velocity distributions $w^+_{\rm rms}$ is virtually unchanged right in the vicinity of the puff upstream interface along several diameters downstream. Moreover, for $0 < y_+ < 15$, it is similar to a fully-developed turbulent pipe flow. On the other hand, near the wall, the intensity of the radial motion decays much faster than the intensity of the streamwise fluctuations.

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