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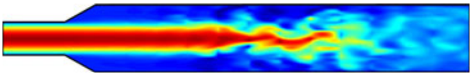
Pipe flow clogged with turbulence



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The flow inside a circular pipe is known to support localised patches of turbulence travelling downstream. When the diameter of the pipe is slowly increasing, seemingly analogous but motionless patches can congest the flow and lead to disastrous energetic performance. Until now, no theory has predicted quantitatively the flow rates at which such a steady turbulent puff could be expected. The recent large-scale numerical study by Selvam *et al.* (*J. Fluid Mech.*, vol. 771, 2015, R2) offers the first realistic simulation of this phenomenon, with a detailed analysis of the bifurcation sequence leading from the laminar flow to the localised turbulence regime. Similarities and differences between straight and divergent cases are also discussed.

Key words: instability, transition to turbulence

1. Introduction

Transition to turbulence in cylindrical pipe flow was pioneered by the work of Reynolds (1883). Two regimes were identified, laminar and turbulent, characterised respectively by high and low flow rate for the same pressure loss. Alternatively, when the flow rate is imposed rather than the pressure gradient, laminar and turbulent regimes correspond to low and high pressure loss, respectively. This implies that more energy should be input into the system to achieve a given flow rate when the flow is turbulent. The Reynolds number, the ratio of viscous to inertial time scales, is a convenient control parameter, and broadly speaking turbulent flows are encountered for high enough *Re*. One of Reynolds' main contributions to the field, today still unexplained, is the discovery that turbulent flow manifests itself only intermittently at low enough Reynolds numbers: turbulence takes the form of localised turbulent puffs with a specific and complex internal structure and dynamics such as spontaneous decay or self-replication (Avila *et al.* 2011).

Pipes are straight only in laboratories, whereas in many industrial applications the flow often consists of fluid passing successively through several pipes, with different diameters. Examples are numerous and include pipeline transport of oil and gas, thrust-vectoring nozzles, diffusers, jet engine exhausts, micropipettes, stenotic pipes mimicking arteries, etc. The junction area between two successive pipes is a typical source of hydrodynamic instability, with a strong contribution to the total drag. For a constant flow rate and a diameter increasing in the direction of the

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J. Fluid Mech. (2015), *vol.* 776, *pp.* 1–4. © Cambridge University Press 2015

doi:10.1017/jfm.2015.285

flow, the Reynolds number decreases with distance downstream. If the flow at the inlet is turbulent, the decrease of *Re* can lead to the well-known phenomenon of flow relaminarisation (Narasimha & Sreenivasan 1979). Now if the flow at the inlet is already laminar, depending on the exact geometry of the junction, different instabilities might trigger a localised turbulent zone – eventually followed further downstream by relaminarisation. Even if it is spatially localised, the local increase in drag is likely to cause significant deterioration in the energetic performance of the global system. In the context of energy saving, carefully designed pipe junctions are needed, requiring detailed knowledge of the conditions favouring localised transition to turbulence past the expansion. In particular, the Reynolds number range where turbulence arises should help in choosing appropriate dimensions for the pipe, or for a given geometry should reveal the range of possible flow rates in which to use the pipe most economically.

Many studies, initially experimental and later numerical, have been performed in the context of sudden expansions, known to favour the emergence of 'dead flow', i.e. recirculation zones with possible asymmetry. The study of Selvam, Peixinho & Willis (2015) considers instead the case of a continuous expansion connecting two straight pipes. Inside the expansion, the diameter increases linearly in a cone-like fashion. This numerical study provides the fluid dynamics research community with the first quantitatively and qualitatively realistic description of the phenomenon.

2. Overview

The literature on the instability of divergent pipe flow remains scarce (Sahu & Govindarajan 2005; Swaminathan *et al.* 2011) and deserves a detailed parametric study. The occurrence of localised turbulent motion in slowly expanding pipes has been demonstrated experimentally by Peixinho & Besnard (2013) for a small expansion angle. That work was complemented by axisymmetric simulations of the flow, with both experiments and simulations showing the presence of a long and thin recirculation bubble inside the expanding part of the set-up, whose length increases with increasing *Re* (here *Re* is based on a constant flow rate and on the diameter of the narrower pipe). Such recirculation flows are also common in sudden expansion flows, which have been more thoroughly investigated in both their planar and axisymmetric versions. In the latter case, recurring quantitative discrepancy was reported between experiments and linear stability theory (predicting an instability only for higher flow rates). Theory, simulations and experiments were reconciled only once it was realised (e.g. in Sanmiguel-Rojas & Mullin 2012) that permanent geometrical defects, such as a small, but finite, asymmetry of the set-up, could be responsible for the appearance of new finite-amplitude solutions for even lower *Re* than predicted by linear theory. Selvam *et al.* (2015) used this idea to perform direct numerical simulation of the flow inside a pipe with gradual expansion, with a half-angle of 26.57° and a diameter ratio of two (see figure 1*a*). They imposed a small and permanent lack of asymmetry to the laminar flow inside the inlet tube, mimicking the effect of an unavoidable defect in the geometry of the cross-section. Numerically speaking, this amounts to a modified inlet boundary condition.

The authors reveal, as *Re* is increased, a sequence of bifurcations from purely laminar flow to a steady recirculation flow, followed by temporal oscillations and eventually by a turbulent puff stuck at the entrance of the larger pipe. The oscillatory regime is found only in a narrow range of values of *Re*. The order of magnitude of the resulting frequency strongly suggests an instability analogous to the classical vortex shedding around circular or spherical obstacles. A turbulent regime is identified for *Re*

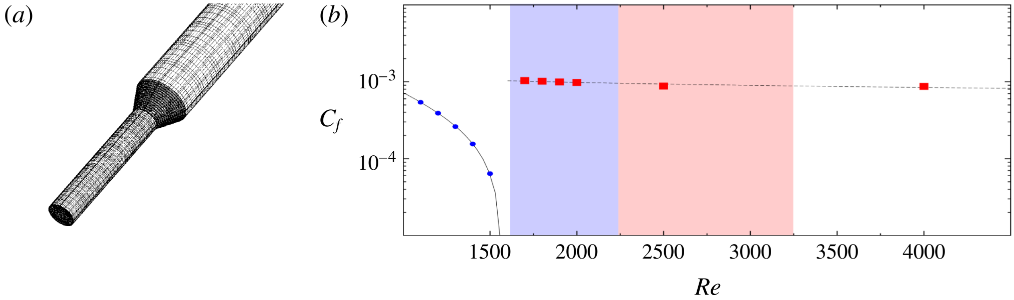

FIGURE 1. (*a*) Three-dimensional view of the mesh used for the simulation zoomed near the expansion. (*b*) Friction factor measured numerically as a function of *Re*. The dark shaded zone indicates hysteresis between turbulent and laminar flow. Based on figures in Selvam *et al.* (2015).

ranging from 1680 to 2200, the upper value reflecting only the finite extent of the numerical domain unable to accommodate longer recirculation bubbles. Importantly, the turbulent regime maintains itself in this range of values of *Re*, even if the asymmetric perturbation at the inlet is removed: the system admits hysteresis, i.e. a multiplicity of solutions coexist in the same parameter range since both axisymmetric laminar flow (with low drag) and turbulence (with high drag) can be found as end states for identical parameters (see figure 1*b*). As far as the present numerical study is concerned, the patch of turbulence stays localised near the entrance of the larger pipe for all values of *Re* until 5000. Yet, as *Re* increases, more and more vortical fluctuations are emitted downstream of the main puff, the similarity in the mechanisms allowing the authors to suggest a new regime analogous to the precursor of puff splitting described in straight pipes (Avila *et al.* 2011; Shimizu *et al.* 2014). The persistence of the localised turbulence patch was tested by reducing directly *Re* (hence the flow rate) from $Re_0 = 2000$ (above the critical value of $Re \approx 1680$) down to a value of Re_f strictly below the threshold. The turbulent patch was reported to decay and to be flushed downstream after a time t_R proportional to Re_f, a result in good agreement with experimental investigations (Peixinho & Besnard 2013).

Eventually, the structure of the puff is claimed to differ from that of puffs in pipes with constant diameter. This discrepancy is evident from the analysis of azimuthal correlations of the velocity field, parametrised by the downstream coordinate: an asymmetric mode seems to dominate the turbulent zone at all times, whereas in straight pipe flow no asymmetric mode was reported from correlation studies (Willis & Kerswell 2008). This dominant mode is accompanied by other higher-order azimuthal wavenumbers representative of high- and low-speed streaks, i.e. coherent structures common to most wall-bounded shear flows.

3. Future

An underlying idea in the paper of Selvam *et al.* (2015) is the recurrent comparison with subcritical transition concepts well identified – though also not always fully understood – in straight pipes. Even though the present study offers only a few insights, it opens the way for further comparison. For example, how does the sequence of bifurcations identified in this study depend on the permanent perturbation imposed at the inlet? Can an optimal defect be identified using a numerical optimisation, such as done in pipe flow by Gavarini, Bottaro & Nieuwstadt (2004), that would reveal the lowest value of *Re* for which turbulence can arise, if not be sustained?

As in straight pipes, the system is shown to admit a multiplicity of solutions for the same parameter range, since both axisymmetric laminar flow (with low drag) and turbulence (with high drag) can coexist. This multiplicity makes flow control strategies interesting, provided a method is found to reduce the basin of attraction of the non-turbulent solutions. Can exact finite-amplitude solutions, potentially unstable, also be identified for a better description of the dynamics inside and at the exit of the turbulent patch (Duguet, Willis & Kerswell 2008; de Lozar *et al.* 2012)? Can one unfold a full bifurcation sequence from a dynamical systems point of view, as in Avila *et al.* (2013)? Turning our attention to the spatiotemporal properties of the turbulent patches, the analogy with straight pipe flow can be pushed further. Can proper puff decay or puff splitting events be identified in the hysteretic regime, or beyond? The novel evidence for an asymmetric mode closer to the centreline of the pipe calls for future investigation, as it suggests a clear difference from usual puffs. How crucial is this difference and how does it affect the dynamics or the potential to control it? Does this mode possess swirl? Other geometric parameters (half-angle, expansion ratio, . . .) as well as other geometries could also be considered and varied. This can be particularly interesting from an industrial perspective, again as a way to control passively or to delay the emergence of the turbulent patches.

Eventually, from a broader perspective, this recent study by Selvam *et al.* (2015) demonstrates how in recent years large-scale numerical simulations have progressively reached maturity, in the sense that they are now able to compete with and complement real laboratory experiments.

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