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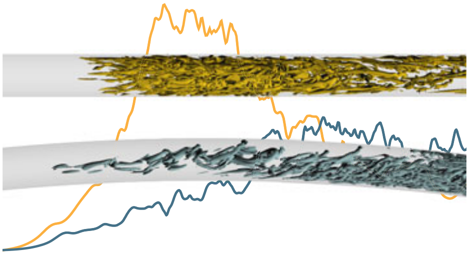
Taming turbulent fronts by bending pipes



D. Barkley†

Mathematics Institute, University of Warwick,
Coventry CV4 7AL, UK

The flow of fluid through a pipe has been instrumental in illuminating the subcritical route to turbulence typical of many wall-bounded shear flows. Especially important in this process are the turbulent–laminar fronts that separate the turbulent and laminar flow. Four years ago Michael Graham (*Nature*, vol. 526, 2015, p. 508) wrote a commentary entitled 'Turbulence spreads like wildfire', which is a picturesque but also accurate characterisation of the way turbulence spreads through laminar flow in a straight pipe. In this spirit, the recent article by Rinaldi *et al.* (*J. Fluid Mech.*, vol. 866, 2019, pp. 487–502) shows that turbulent wildfires are substantially tamed in bent pipes. These authors find that even at modest pipe curvature, the characteristic strong turbulent–laminar fronts of straight pipe flow vanish. As a result, the propagation of turbulent structures is modified and there are hints that the route to turbulence is fundamentally altered.

Key words: pipe flow boundary layer, transition to turbulence

1. Introduction

The route to turbulence in pipe flow is subcritical, meaning that turbulence can be initiated and sustained even though laminar flow remains linearly stable. At the lowest flow rates for which it can be successfully triggered (Reynolds numbers of approximately 2000), turbulence takes the form of localised patches known as puffs. A typical puff is illustrated in figure 1(*a*). Try as one might, it is simply impossible to produce extended regions of sustained turbulence in pipe flow at these 'low' Reynolds numbers. The situation changes at higher Reynolds numbers, as illustrated in figure 1(*b*). Localised patches of turbulence expand and now it is impossible to have a flow that is eventually anything other than fully turbulent. Expanding turbulent patches are known as slugs. Puffs and slugs are the key players in transitional pipe flow and have been the subject of numerous experimental and numerical studies, (Lindgren 1969; Wygnanski & Champagne 1973; Darbyshire & Mullin 1995; Nishi *et al.* 2008; Shimizu & Kida 2009; Duguet, Willis & Kerswell 2010; Hof *et al.* 2010; Barkley *et al.* 2015; Song *et al.* 2017), to cite just a few.

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† Email address for correspondence: D.Barkley@warwick.ac.uk

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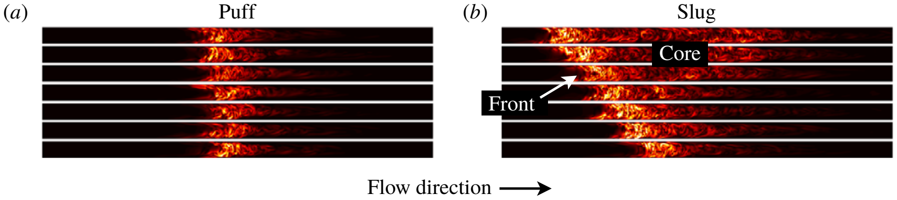

FIGURE 1. Evolution of (*a*) a localised puff at $Re = 2000$ and (*b*) a slug at $Re = 2600$. Time evolves in the upward direction. Dark areas correspond to laminar flow and bright areas correspond to turbulent fluctuations. The flow is from left to right and visualisations are in a co-moving reference frame to keep the turbulent structures centred. Reproduced from Song *et al.* (2017).

As a consequence of the strongly subcritical character of pipe flow, fluid motion is in one of two distinct states, turbulent or laminar, and these are separated by turbulent–laminar fronts where the flow switches between the two. The significance of these fronts was recognised as far back as Coles (1962). Of particular importance here is the intense upstream front (left-hand front) seen in figure 1(*b*). Essentially, the kinetic energy contained within the laminar upstream flow is fuel for this front. The front 'burns this fuel', converting laminar kinetic energy into turbulent kinetic energy (TKE). Dissipation increases downstream from the front and after a short distance dissipation and production of TKE come into balance and form the core of the slug – or what is just called turbulent pipe flow once it fully occupies the pipe. The intense upstream front is call a strong front.

To understand the puff, consider what happens to the slug as the Reynolds number is decreased, that is viscosity increased. There comes a point where TKE production in the core can no longer balance the increased dissipation due to the increase in viscosity. The core collapses. However, at the strong front production is still large and so it survives the increase in viscosity. The strong front becomes the puff – an isolated front continually 'burning' upstream laminar kinetic energy but leaving no persistent downstream turbulent wake. (The transition from slug to puff can be viewed as a transition from bistability to excitability (Barkley 2011, 2016; Barkley *et al.* 2015; Graham 2015).)

Finally, the issue that has captured much attention in recent years is the fate of puffs on long time scales. Puffs are metastable structures that ultimately either decay (revert to laminar flow) or split (initiate a second puff downstream). Collectively these two processes determine a critical point for a percolation transition (Avila *et al.* 2011). Below the critical point, puff decay is more frequent than puff splitting and eventually the flow is entirely laminar. Above the critical point, puff splitting is the more frequent process and turbulence is sustained in a highly intermittent form.

2. Overview

In their recent paper, Rinaldi, Canton & Schlatter (2019) address how the classical puffs and slugs of straight pipe flow are transformed in the case of bent pipes, and more broadly how the subcritical route to turbulence is potentially affected by the presence of pipe curvature. Specifically, the authors perform direct numerical simulations of flow in toroidal pipe with pipe-to-torus-diameter ratio of $\delta = 0.01$. The immediate, striking observation is that the strong turbulent–laminar fronts, so dominant in straight pipes, vanish even for such a moderately curved pipe. Visually the fronts in straight and curved pipes are unmistakably different. See the lead image of this commentary as well as the movies attached to the original article. In a straight pipe, an intense concentration of vortices abruptly forms at the upstream front, while in the curved pipe vortices emerge gradually from laminar flow. Quantitatively, in the curved pipe the TKE production at the upstream front is barely larger than its value in the slug core, while for the straight pipe the production at a strong front is about five times that of the core. Velocity fluctuations at the upstream front are also greatly curtailed in the curved pipe, even though fluctuations in the slug core attain similar values for straight and curved pipes. As could then be expected from the connection between puffs and fronts, puffs exhibit a dramatic reduction in intensity in bents pipes. Interestingly though, their streamwise extent is about twice that of puffs in a straight pipe.

Through an examination of the energy budget in the pipe cross-section, Rinaldi *et al.* show that there is a significant localisation of TKE production toward the outer bend of the pipe, consistent with early experimental observations by Sreenivasan & Strykowski (1983). The authors argue, convincingly, that the secondary flow (Dean 1927) generated in the curved pipe is responsible for this localisation, and moreover, that due to this localisation, turbulence in the front can be sustained at smaller energies than is the case for a straight pipe, thereby explaining why and how strong fronts vanish in a bent pipe. To be clear, owing in part to the numerous applications of curved pipe flow, there is a substantial literature on instabilities and turbulence in helical and toroidal pipes (see the discussion and citations in Kühnen *et al.* (2015) and Rinaldi *et al.* (2019)), and the secondary Dean flow is well known to play an important role in bent pipes. However, Rinaldi *et al.* are the first to demonstrate its important role in the energy budget, not only at turbulent–laminar fronts and also in the turbulent core within toroidal pipe flow.

Potentially the most interesting observations in Rinaldi *et al.* (2019) concern the way pipe curvature affects the route to turbulence. It is known from Kühnen *et al.* (2015) that in toroidal pipes with pipe-to-torus-diameter ratio greater than about $\delta = 0.028$, the transition scenario switches from subcritical to supercritical. At $\delta = 0.01$, still considerably away from the supercritical scenario, Rinaldi *et al.* observe that, in comparison with straight pipes, there is a substantial reduction in the range of Reynolds numbers over which a potential percolation transition could take place. Most significantly, the authors failed to detect any puff splitting events in the range of parameters considered. This could be due to a mundane increase in timescales for splitting, caused for some as yet unknown reason. However, Rinaldi *et al.* have shown that puff lengths and intensities are substantially affected by pipe curvature, so this observation (or rather lack of observation of puff splitting), could also be indicative of a modification of the subcritical scenario by which turbulence first becomes sustained.

3. Future

We know from work by Kühnen *et al.* (2015) that there is a cross-over from a subcritical to a supercritical transition in toroidal pipes as the pipe curvature increases. Moreover, we know from Canton, Schlatter & Örlü (2016) precisely where toroidal pipe flow becomes linearly unstable as a function of curvature. What we do not know is what happens to the established subcritical scenario in straight pipes as the curvature is increased, and how this eventually gives way to a supercritical scenario commencing with a linear instability. The present paper takes a step towards answering this, but it also provides as many questions as answers on this fundamental issue. Fortunately, toroidal pipe flow has a well-defined ‘knob’, pipe curvature, that can and should be turned in whatever steps are needed to address this.

On a more general note, we now understand what to simulate and what to analyse in order to quantify turbulent–laminar fronts in wall-bounded shear flows. This applies not only to straight and bent pipes, but to a great many other shear flows where intermittency precedes fully turbulent flow. From simulation data we can compute energy budgets and we can obtain front speeds, critical Reynolds numbers and many other facts. What we cannot do at present is obtain any of these from the governing Navier–Stokes equations, other than by performing large-scale direct numerical simulations. The most important long-term goal in this area then is the derivation, through some properly justified approximations, of expressions for front dynamics directly from the Navier–Stokes equations. This is perhaps too much to hope for, but we know that on a qualitative, and even semi-quantitative level the dynamics of turbulent–laminar fronts is relatively simple (Barkley *et al.* 2015) and this gives some hope. There are many practical reasons to pursue such a theory, but independently of those reasons, fronts between different states are always interesting, and when one of the two states is turbulent flow, they are especially fascinating.

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