THE SPEED OF TURBULENT-LAMINAR FRONTS IN PIPE FLOW

Dwight Barkley[1,2], Marc Avila[3] & Björn Hof [4]
[1] *Mathematics Institute, University of Warwick, Coventry CV4 7AL, United Kingdom*
[2] *PMMH, ESPCI, 10 rue Vauquelin, 75231 Paris Cedex 5, France*
[3] *Institute of Fluid Mechanics, Department of Chemical and Biological Engineering*
Friedrich-Alexander-Universität Erlangen-Nürnberg, Cauerstrasse 4, 91058 Erlangen, Germany
[4] *Max Planck Institute for Dynamics and Self-Organization, Bunsenstrasse 10, 37073 Göttingen, Germany*

Abstract The speeds of turbulent-laminar interfaces in pipe flow are studied theoretically, and through numerical simulations of the Navier-Stokes equations and laboratory experiments. A particular focus is the continuous, but non-smooth transition from localized puffs to expanding slugs. Different interfaces within the slug regime are discussed.

INTRODUCTION

Puffs and slugs in pipe flow are demarcated by turbulent-laminar interfaces, i.e. fronts, at their leading and trailing edges. In this work we are concerned with the speed of these fronts for Reynolds numbers from around the critical value for the onset of sustained turbulence, $Re_c = 2040 \pm 10$[1], to well into the slug regime [2, 3, 4, 5, 6]. The approach is to use a simplified model of pipe flow [7, 8]. The model lends itself both to simulations and also to asymptotic analysis of individual front speeds. From this analysis we gain a bifurcation-theoretic understanding of the transition from puffs to slugs.

MODEL

The model has two variables, q and u, corresponding to turbulence intensity and axial center-line velocity. These depend on a single coordinate corresponding to the axis of the pipe. The model captures remarkably well the character of turbulent pipe flow and in particular it captures puffs and slugs as seen in figure 1. Details can be found in [7, 8].

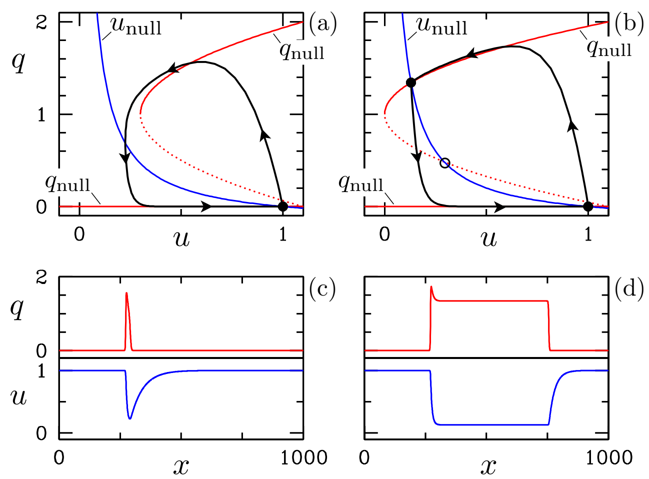

Figure 1. Puffs (left) and slugs (right) in the model system. Upper plots show dynamics in the u-q phase plane while lower plots show spatial profiles at a particular time instant. Structures travel to the left. The puff has a constant width while the slug expands.

RESULTS

Results from an analysis of turbulent-laminar front speeds in the model are summarized in figure 2. Shown is a bifurcation diagram for the leading-edge and trailing-edge turbulent-laminar fronts. The analysis explains why the speed of the trailing-edge front of a slug is smoothly connected with the speed of puffs at lower Reynolds numbers [2, 3] and it explains the continuous, but non-smooth variation in speed of the downstream turbulent-laminar front, the leading edge. The model predicts that there are two types of slugs – something that appears to have gone unnoticed in the literature. These two types of slugs gives rise to the changes in curvature of the leading-edge branch.

The model also provides a comprehensive theoretical picture of how puff speeds are related to the speed of edge states, and in particular, why edge states move faster than the mean flow speed and why puff speed decreases with Reynolds number. An asymptotic analysis of the simplified model agrees remarkably well with real experiments and fully resolved DNS (not shown).

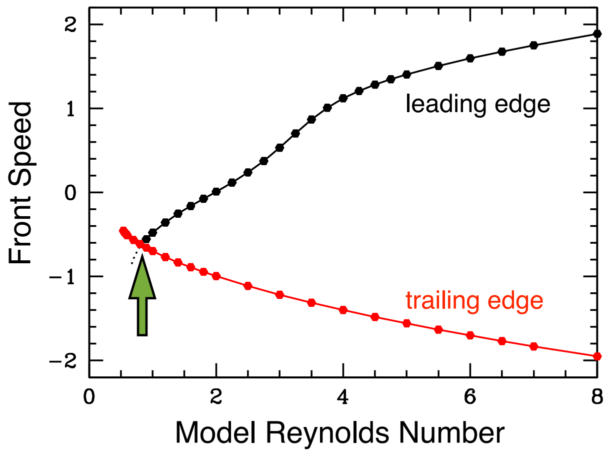

Figure 2. Theoretical prediction of turbulent-laminar front speeds. Shown are the speeds (relative to the mean flow velocity) of the leading and trailing edges as a function of model Reynolds number. The arrow indicates a continuous, but non-smooth transition. Below this point the leading and trailing interfaces move at the same speed and puffs are observed. Above this point the speed of leading and trailing interfaces differ. Hence expanding regions of turbulence, i.e. slugs, are found.

CONCLUSIONS

The model captures the qualitative character of the transition from puffs to slugs and gives new insight as to why slugs emerge continuously from puffs without a critical exponent of 1/2, common in front bifurcations. The current analysis does not take into account puff splitting [1, 3], but work including this important effect is planned for the future.

References

[1] K. Avila, D. Moxey, A. de Lozar, M. Avila, D. Barkley, B. Hof, Science **333**, 192-196 (2011).
[2] I. Wygnanski and H. Champagne, J. Fluid Mech. **59**, 281 (1973);
[3] I. Wygnanski, M. Sokolov, and D. Friedman, J. Fluid Mech. **69**, 283 (1975).
[4] A. Darbyshire and T. Mullin, J. Fluid Mech. **289**, 83 (1995).
[5] M. Nishi, B. Ünsal, F. Durst, and G. Biswas, J. Fluid Mech. **614**, 425 (2008).
[6] Y. Duguet, A. P. Willis, and R. R. Kerswell, J. Fluid Mech. **663**, 180 (2010).
[7] D. Barkley, Phys. Rev. E **84**, 016309 (2011).
[8] D. Barkley, J. Phys.: Conf. Seri. **318**, 032001 (2011).