Pipe Dreams and Pipe Flows: Elastic Routes to Turbulence in Polymer Solutions

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Brief Biographical Sketch

V. Shankar has been a faculty member in the Department of Chemical Engineering, IIT Kanpur since July 2002. He obtained his PhD from IISc Bangalore, and did a post-doc stint at the University of Minnesota before joining IIT Kanpur. His group works in the broad area of hydrodynamic instabilities in rheologically complex fluids, and on the role of wall elasticity on laminar-turbulent transition in flow through deformable tubes. Their work employs a balanced combination of theory, numerics, and experimental observations to uncover novel physical phenomena in these areas.

Abstract

Despite its hoary origins in the Reynolds experiments (1883), and routine mention of the threshold Reynolds number (of around 2000) in fluid mechanics texts, transition from the laminar state in Newtonian pipe flow (and other canonical rectilinear shearing flows such as plane Couette and Poiseuille flows) is a subtle and complex process. This is largely due to the absence (plane Couette and pipe-Poiseuille flows) or irrelevance (plane Poiseuille flow) of an underlying linear instability. Thus, it is only a hundred years after the Reynolds experiments, and with the relatively recent advent of a dynamical systems perspective, that the Newtonian transition has come to be understood as fundamentally nonlinear. In this view, transition is associated with the appearance of three-dimensional invariant solutions of the governing equations—so-called exact coherent states—that coexist with, but remain disconnected from, the laminar solution. The proliferation of such states and their interactions are believed to underlie the complex dynamics leading to turbulence.

Over the past decade, it has been established that flows of dilute polymer solutions can undergo transition at Reynolds numbers far below the Newtonian threshold, giving rise to a distinct flow state known as elasto-inertial turbulence (EIT). This state may be closely related to the maximum drag reduction (MDR) regime known from the drag-reduction literature. For sufficiently elastic polymer solutions, the transition to EIT occurs at an amplitude-independent threshold, and the coherent structures observed in this regime differ markedly from those characteristic of Newtonian turbulence. In contrast to the long-standing disconnect between linear stability theory and experimental observations in Newtonian pipe flow, we have shown that the onset of EIT can in fact be driven by an underlying linear instability.

Linear stability analysis, based on viscoelastic models such as Oldroyd-B and FENEP, reveals the presence of an unstable center-mode whose phase speed is close to the maximum of the base flow. The predicted instability thresholds are in good agreement with experimental observations for moderately elastic polymer solutions. For channel flows, the same instability persists down to zero Reynolds number, indicating that the elasto-inertial center-mode instability continuously connects to a purely elastic one. This finding challenges the conventional view that purely elastic instabilities—leading to elastic turbulence—require streamline curvature and the associated hoop stresses. In this talk, we summarize recent advances in this area, drawing both from our work and from that of other groups. We also discuss the broader implications of the center-mode instability for viscoelastic flows in curvilinear configurations such as Taylor–Dean and Dean flows.