Transition to turbulence in a heated non-Newtonian pipe flow

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Résumé

The transition to turbulence is among the most investigated topics in fluid mechanics as it relies on non-trivial phenomena that are not yet fully understood since the experiments of Osborne Reynolds in 1883. Several investigations focused on linear instabilities triggering the most dangerous perturbations that lead to transition in model flows such as the Kolmogorov flow [1] or in paradigmatic setups such as the Taylor–Couette [2] or the Rayleigh–Benard flows [3].

On the other hand, when dealing with pipe flows, nonlinear interactions between finite-amplitude perturbations are essential for transition to turbulence [4,5] as the Hagen–Poiseuille flow is linearly stable. Among the most interesting features of transition to turbulence in pipe flows there is the phenomenon of intermittent turbulence, where small turbulent regions (puffs) grow up to larger turbulent patches (slugs) and then they decay because of a restabilization of the mean velocity profile. This has been recently investigated by [6], who proposed a reduced-order model that retains the essential non-linear effects of the momentum equation required to explain the intermittency, as well as the non-linear interaction between turbulent regions leading to transition.

Building upon the model of Barkley, we generalize the framework of such reduced-order approach by adding the energy equation and the thermal effect on the dynamic viscosity. This has a remarkable impact on the local Reynolds number when the outer wall of the pipe is heated up leading to a significant reduction of the area occupied by the flow dynamics represented in the $q-u$ phase plane, where q is the the turbulent intensity and u is the streamwise velocity at the pipe axis.

As observed by [7], the effect of viscoplasticity on the dynamics of turbulent slugs is significant. Hence, a further generalization of the model of Barkley is proposed including the non-Newtonian effects for a viscoplastic flow. To generalize the constitutive equation of the stress tensor, we consider the Herschel–Bulkley model, i.e. $\tau = \tau_0 + K\dot{\gamma}^n$ for $\tau \geq \tau_0$ and $\dot{\gamma} = 0$ for $\tau < \tau_0$, where τ and $\dot{\gamma}$ are the shear stress and the shear rate, K is the consistency index, n denotes the flow index and τ_0 is the yield stress. Upon a decrease of the flow index n, hence increasing the importance of viscoplasticity, we obtain an effect on the the $q-u$ phase plane that opposes the one of temperature.

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