Hydrodynamic stability of non-Newtonian fluid-porous channel flows

Abstract

The flow of fluid over a porous medium is widely observable across a diverse range of geophysical, industrial, and biological applications. A majority of the fluids involved in such a scenario do not obey the simplistic Newtonian rheology. A proper understanding of the flow transition characteristics involving such non-Newtonian fluids can be of immense help in either triggering flow transition (for achieving enhanced mixing) or delaying the transition (for example, in applications where mixing is highly undesirable). Despite the importance of non-Newtonian fluids in practical applications, the literature on hydrodynamic stability of fluid-porous channel flows was mostly confined to Newtonian fluids. Therefore, an attempt has been made to address this major shortcoming in this thesis by working on "Hydrodynamic stability of non-Newtonian fluid-porous channel flows". The overarching motivation has been to develop a fundamental understanding of the flow transition characteristics for a fluid-porous dual-layer configuration in channel flows, where the fluid follows non-Newtonian rheology.

Within the domain of linear hydrodynamic stability, while the traditional modal analysis technique is proficient at dealing with problems involving thermal instability (for example, the onset of thermal convection), it often fails to predict the experimental findings for transition in channel flows. This is because channel flows are known to demonstrate short-time transient growth that cannot be captured within the purview of modal analysis (modal analysis is mainly good at predicting long-time characteristics only). The non-modal analysis is an indispensable tool in this regard. It can predict transient growth that often leads to secondary instability and earlier flow transition than that predicted by modal theory. However, the existing literature in the hydrodynamic stability of fluid-porous channel flows was primarily restricted to modal analysis, even for Newtonian fluids. In this context, a major highlight of this thesis is the employment of non-modal analysis in the hydrodynamic stability of fluid-porous systems. In fact, both modal and non-modal stability analyses have been carried out to compare and contrast the long-time and short-time flow transition characteristics.

In this thesis, the following classes of non-Newtonian fluids have been considered: (i) yield stress fluids, (ii) shear-thinning fluids, (iii) shear-thickening fluids. A detailed investigation of the effects of both shear-driven (Couette) and pressure-driven (Poiseuille) channel flows has been undertaken. A combination of analytical and numerical methodologies has been employed for various studies.

Another critical aspect involved in fluid-porous systems is the quantification of the flow behaviour near the fluid-porous interface. In particular, the effect of viscous diffusion could be prominent at the interface. Even though many investigations aim to unravel "accurate" interface conditions and velocity profiles near the interface, there is a dearth of studies that connect the interface characteristics to flow transition. This gap has been addressed by undertaking a comprehensive study assessing the role of the transition layer (existing in between the fluid and the porous layers) on flow stability. An interdependence has been unveiled between the velocity discontinuity (existing at the interface) and the thickness of the transition layer towards dictating the final characteristics of flow transition.

Overall, an intricate interplay between the non-Newtonian rheology of the fluid and the various characterizing parameters of the porous layer is found to influence the flow transition characteristics significantly. The possible fundamental mechanisms involved in such flow transition have also been explored in detail in this thesis. The novel findings emerging out of the research would possibly aid better designing and control of flow in fluid-porous systems involving real-life (non-Newtonian) fluids.

Keywords: *Hydrodynamic stability*; *linear stability*; *non-modal analysis*; *Bingham fluid*; *power-law fluid*; *porous media*.