Turbulence control in a diverging pipe flow: Stabilizing Edge States and Reducing Energy Dissipation

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Date de la soutenance

06/11/2024 à 14:00

Lieu de la soutenance

LOMC

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Abstract

When driving fluids through pipes, the increased friction losses associated with turbulence are responsible for the majority of the energy used, corresponding to nearly 10 % of the global electric energy consumption. If one wants to succeed in reducing our energy footprint, discovering innovative ways to efficiently pump fluids is crucial. It is now understood that turbulence is organized around a set of unstable invariant solutions. By implementing bespoke control schemes, it is possible to force the flow into a more energetically favorable region of the phase space. This thesis focuses on the subcritical transition to turbulence in various divergent pipe configurations through detailed numerical simulations. It was found that larger divergence angles generally reduce the critical Reynolds numbers required for the onset of turbulence, though this effect varies with specific pipe configurations such as sudden expansion pipe. The influence of divergence angle and Reynolds number on the positioning of stationary turbulent puffs and the reattachment points of recirculation zones was also investigated. Notably, larger angles and higher Reynolds numbers cause both puffs and reattachment points to stabilize closer to the expansion point in contrast to the linear growth of the recirculation zones observed in laminar flow conditions. Adopting a dynamical system perspective, the thesis also examines the stabilization of the least dissipative state, known as the edge state, through feedback controls schemes. While complete stabilization was not achieved, significant reductions in viscous drag and enhanced energy efficiency were observed. In a divergent pipe configuration with mirror symmetry, these strategies resulted in substantial energy savings across a broad range of Reynolds numbers. Conversely, in full divergent pipe configurations without symmetry, the effectiveness of these strategies was more limited and restricted to a narrow range around of Reynolds number around the onset of turbulence. Moreover, the robustness and efficiency of these feedback strategies were evaluated under conditions simulating practical operational scenarios, demonstrating their potential applicability in experimental settings. This thesis also analyses the dynamics of edge states in divergent pipe flows, using classical bisection method within the DNS framework Nek5000. We applied these techniques in straight pipes, validating previous research findings and establishing a baseline for further comparative analysis in more complex geometries. Subsequently, the method was applied to a sudden expansion pipe configuration where edge tracking revealed significant challenges due to the flow’s tendency to quickly revert to turbulence due to a potential linear instability. Finally, the algorithm was applied to a gradual expansion pipe, where quasi-periodic bursting events were observed, initiating a self-sustaining cycle of turbulence driven by convective mechanisms and shear layer instability.