PHASE DIAGRAM OF TURBULENT TAYLOR-COUETTE FLOW

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Abstract We will present the results of our recent numerical work on the nature of the phase diagram of turbulent Taylor-Couette (TC) flow, both with co- and counterrotating cylinder [3]. The work can be seen as the extension of the famous experimental Andereck *et al.* [1] phase diagram for Taylor-Couette flow just above the onset of instabilities, towards the ultimate turbulence regime, and now obtained numerically. In particular, we will understand when and why optimal transport of angular velocity from the inner to the outer cylinder is achieved and how this is connected to the angular velocity profile and the structures in the flow.

MOTIVATION AND EXTENDED SUMMARY OF THE RESULTS, AND OUTLOOK

Taylor-Couette flow (TC), i.e. the flow between two independently rotating concentric cylinders, has for long been used as a model system in fluid dynamics. Taylor [4] found that the system was linearly unstable, unlike pipe-flow and other studied systems to the date. Wendt [5] expanded the study of the turbulent regime, measuring torques and velocities in the system. Since then, and due to its simplicity, TC has been used as a model system for studying shear flows.
Here direct numerical simulations of Taylor-Couette flow were performed. Shear Reynolds numbers of up to $3 \cdot 10^5$, corresponding to Taylor numbers of $Ta = 4.6 \cdot 10^{10}$, were reached. Effective scaling laws for the torque are presented. The transition to the ultimate regime, in which asymptotic scaling laws (with logarithmic corrections) for the torque are expected to hold up to arbitrarily high driving, is analysed for different radius-ratios η, different aspect-ratios and different rotation-ratios. It is shown that the transition is approximately independent of the aspect- and rotation-ratios, but depends significantly on the radius-ratio. We furthermore calculate the local angular velocity profiles and visualize different flow regimes that depend both on the shearing of the flow, and the Coriolis force originating from the outer cylinder rotation. Two main regimes are distinguished, based on the magnitude of the Coriolis force, namely the co-rotating and weakly counter-rotating regime dominated by Rayleigh-unstable regions, and the strongly counter-rotating regime where a mixture of Rayleigh-stable and Rayleigh-unstable regions exist. Furthermore, an analogy between radius-ratio and outer-cylinder rotation is revealed, namely that smaller gaps behave like a wider gap with co-rotating cylinders, and that wider gaps behave like smaller gaps with weakly counter-rotating cylinders. Finally, the effect of the aspect-ratio on the effective torque versus Taylor number scaling is analysed and it is shown that different branches of the torque-versus-Taylor relationships associated to different aspect-ratios are found to cross within 15% of the Reynolds number associated to the transition to the ultimate regime. The work culminates in phase diagrams in the inner vs outer Reynolds number parameter space (Figure 1b,c) and in the Taylor vs inverse Rossby number (Ro) parameter space (Figure 11), which can be seen as the extension of the Andereck *et al.* [1] phase diagram towards the ultimate regime. We also provide the (η, Ta) parameter space (figure 2), from which we find that the transition towards the ultimate regime is delayed for small $\eta = 0.5$.
Our ambition also is to further understand why this transition is delayed at the small η, but also the curvature effects on the ω-profiles in the boundary layers along the ideas of [2]. Curvature effects at $\eta = 0.714$ and $\eta = 0.909$ are too small to be appreciated, and the flow for $\eta = 0.5$ is still in the transition to the "ultimate" regime. Thus, higher Ta simulations for $\eta = 0.5$ will provide further understanding on how curvature makes the boundary layers of TC flow different from those of channel and pipe flow.

References

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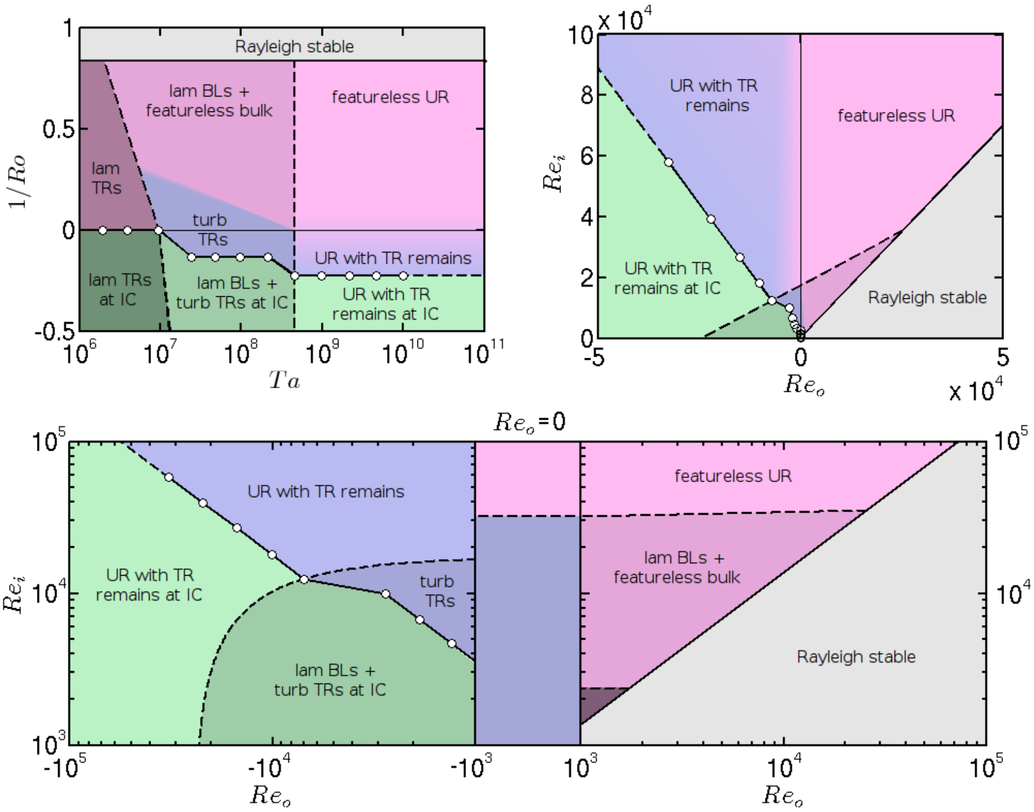

Figure 1. Transitions between different regimes in the (Ta, Ro^{-1}) (top-left) and (Re_i, Re_o) (top-right and bottom) parameter spaces for $\eta = 0.714$. The hollow circles indicate the location of optimal transport, and serve as an indication of the movement of the division between co-rotating or weakly counter-rotating regime (CWCR, blueish and reddish) and the strongly counter-rotating regime (SCR, greenish) with Ta. In both DNS and experiments, Ro_{opt}^{-1} reaches an asymptotic value for $Ta > 5 \cdot 10^8$. For larger η (smaller gap), this separation line moves towards smaller Ro^{-1}. For $Ta \leq 10^7$, we have the rich variety of different states of [1], not detailed in this diagram. Abbreviations: boundary layer (BL), Taylor rolls (TR), ultimate regime (UR), and inner cylinder (IC).

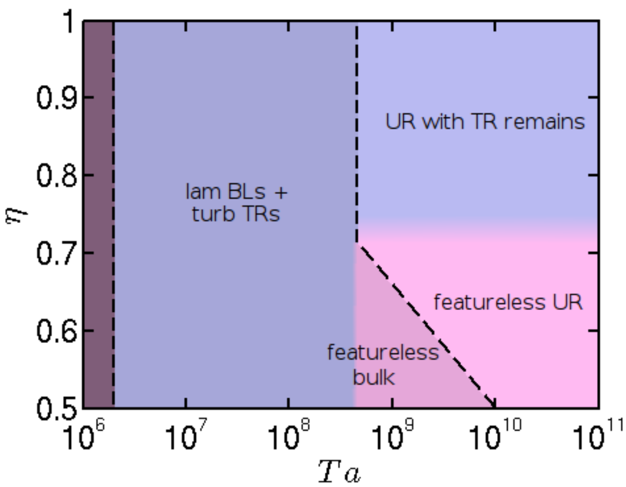

Figure 2. Transitions between different regimes in the (Ta, η) parameter space for pure inner cylinder rotation $Ro^{-1} = 0$. The transition to the ultimate regime occurs at a higher Ta for smaller η (wider gap), while the vanishing of the large scale structures occurs at around the same Ta for $0.5 < \eta < 0.714$. Remains of the Taylor rolls can only be seen for large η, i.e. smaller gap.