

DIRECT NUMERICAL SIMULATION OF TURBULENT TAYLOR-COUPETTE FLOW WITH GROOVED WALLS

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Abstract We present direct numerical simulations of Taylor-Couette flow with grooved walls up to inner cylinder Reynolds number of $Re_i = 3.76 \times 10^4$, corresponding to Taylor number of $Ta = 2.15 \times 10^9$. The simulations are performed at a fixed radius ratio $\eta = r_i/r_o = 0.714$. The grooves are axisymmetric V-shaped obstacles attached to the wall with a tip angle of 90° . Results are compared with the smooth wall case in order to investigate the effects of the grooved walls. In particular, we focus on the effective scaling laws for torque, boundary layers and flow structures. With increasing Ta , the boundary layer thickness finally becomes smaller than the groove height. When this happens, the plumes are ejected from tips of the grooves and a secondary circulation between the grooves is formed. This is associated with a sharp increase of the torque and thus the effective scaling law for the torque becomes much steeper. Further increasing Ta does not result in an additional slope increases. Instead, the effective scaling law saturates to the same "ultimate" regime effective exponents seen for smooth walls.

The Taylor-Couette (TC) flow, in which a fluid is confined between two independently rotating coaxial cylinders, has been investigated for more than a century. At low Reynolds numbers, TC has been well analysed and shows rich flow patterns (see [2, 7] for a comprehensive review). For the turbulence regime, the focus is on the global transport property, i.e. torque T . Eckhardt, Grossmann & Lohse [6] have derived a mathematically exact analogy between TC and Rayleigh-Bénard (RB) flow, in which a fluid is driven by the temperature difference between the hot bottom plate and the cold top plate. Under this framework, the temperature difference between top and bottom plate in RB can be analogous to different rotation rate of the inner and outer cylinder. And TC can also be regarded as one kind of convection. Based on the analogy, the torque is non-dimensionalized as Nusselt number Nu_ω . Because of the similarities, better understanding of TC can surely leads to more profound insight in RB and vice versa.

To better understand the relationship between the global transport properties and the driving forces, it is important and natural to alter the boundary conditions and find out how the flow responds to the changing of boundary layer (BL). Also new insights of convective flows can be gained considering the fact that non-smooth surfaces exist everywhere in geophysics and meteorology.

In RB flow, the study of thermal convection over rough surfaces has been addressed in a lot of works. There have been many different results concerning the changing of the scaling law $Nu = ARa^\beta$. When the height of roughness (δ) is larger than the thermal BL thickness ($\lambda_\theta \simeq h/(2Nu)$), Du & Tong [5] measured the increase of A to be as much as 76% but the exponent β also stayed the same. Based on the visualisation, they concluded that the enhancement of heat transport is due to the plume ejection from the tip of pyramids. In contrast, Stringano et al. [12] numerically investigated thermal over grooved plates, and they showed that the secondary vortex inside the grooves would lift up the BL and help the plumes detach from the tip, which is consistent with the result in [5]. Also A and β increased and β changed to 0.37. However, by implementing V-shaped axis-symmetrical roughness both on the side walls and horizontal plates, Roche et al. [11] obtained an increase of β to 0.51, which was interpreted as triggering the ultimate region 1/2 law proposed in [8], after λ_θ is below the roughness height. Nevertheless, the 1/2 scaling they saw might possibly be due to a crossover between rough surfaces with a groove depth less than the BL thickness to a regime where the groove depth is larger than the BL thickness[1].

In contrast, for TC flow, the studies concerning the rough wall is rare. Cadot et al. [4] made a experiment by gluing equidistance ribs on both the inner and outer surface and these ribs were straight and parallel to the axis of the cylinders. They concluded that with the smooth boundary, the dissipation in the boundary is dominant and then drag coefficient decreases with Reynolds number. However, with rough walls, the boundary drag coefficient will no longer be dominant. Inspired by this work, in another experiment by van den Berg et al. [13] with the same style of roughness, they have reported results for the four cases of two smooth walls, smooth-inner/rough-outer, rough-outer/smooth-inner, and two rough walls. The flow was found to have changed from the BL dominant to bulk dominant.

In the present study, we perform a systematical direct numerical simulation (DNS) of the TC flow with grooved walls. Because the grooves are quite large, we tend to call it in this name not roughness as the same way in [12]. The grooves implemented here are axis symmetry V-shaped obstacles attached to the wall with a tip angle of 90° and perpendicular to the axis of cylinder. A schematic view of the structure is in Figure 1.

The major findings are as follows: When the groove height is smaller than the boundary layer thickness, the torque is the same or even less than that of the smooth cases, as the grooves impede the movement of Taylor vortices. With increasing Ta , the boundary layer thickness becomes smaller than the groove height. Plumes are ejected from tips of the grooves and a secondary circulation between the grooves is formed. This is associated to a sharp increase of the torque and

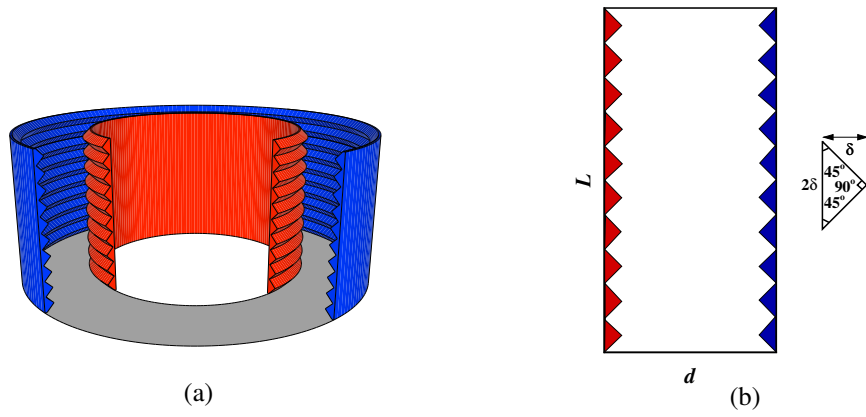


Figure 1. Schematic view of the Taylor-Couette system and the groove geometry. (a) Three dimensional view; (b) Cross-section view.

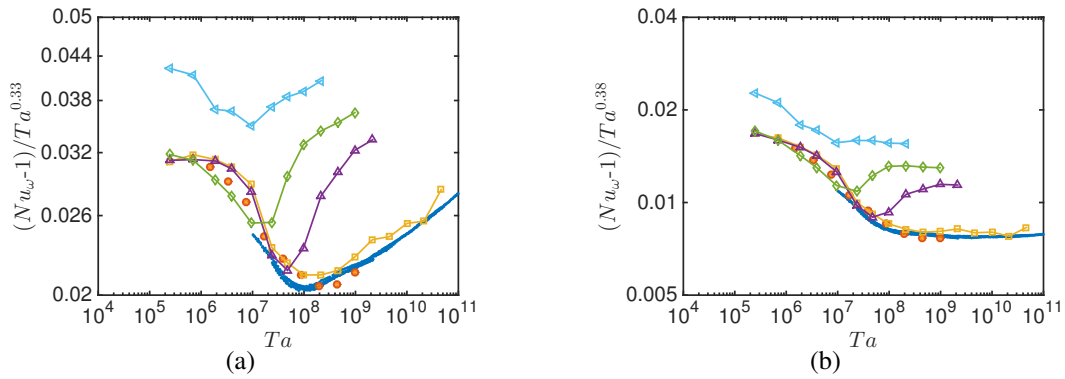


Figure 2. (a) Nusselt number as a function of the Taylor number for $\eta = 0.714$ compensated with $Ta^{-0.33}$. The datas are from experiments and numerical simulations: \dots , smooth walls experiments by [9]; \circ , smooth walls simulations by [3]; \square , smooth walls simulations by [10]; \triangle , grooved walls simulations with $\delta = 0.052d$ in the present study; \diamond , grooved walls simulations with $\delta = 0.105d$ in the present study; ∇ , grooved walls simulations with $\delta = 0.209d$ in the present study. (b) The same as (a) for the Nusselt number compensated with $Ta^{-0.38}$.

thus to a much steeper effective scaling law for the torque. Further increasing Ta does not result in an additional slope increases. Instead, the effective scaling law saturates to the “ultimate” regime effective exponents seen for smooth walls. The magnitude of the torque, however, increases by about 60% for the largest Ta number simulation. It is found that even if after saturation the slope is the same as the smooth case, the absolute value of Nu_{ω} is increased beyond the ratios of the wet areas between grooved and smooth wall. The compensated scalings between Ta and Nu_{ω} are shown in Figure 2.

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