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High Reynolds Number Measurements of Vorticity Generation and Annihilation with Rapidly Changing Boundary Conditions

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ABSTRACT

The project aims at understanding how rapid vorticity annihilation takes place across a sharp vortical interface over a wide range of Reynolds numbers. In order to exclude any influences of (convective) length scales from the flow scenarios under consideration, all investigations center around boundary layer development at the outer wall of rotating facilities. In continuation of the original thought experiment by Kriegseis et al. [1] on the impact of initial conditions, two distinct yet similar cases are contrasted to characterize the formation process. Particularly, development and annihilation of vorticity is directly compared between one case with an irrotational core and its corollary with opposite-signed vorticity across this interface. As such, the possible impact of initial conditions on the effect of rapidly changing boundary conditions can be uncovered.

Previous studies [2] already stated that the spin-up case is immediately comparable to an inverse Oseen vortex. For spin-down motions of the rotating tank, in contrast, this diffusion process is perturbed early on due to instabilities during boundary layer development. The onset of Görtler vortices (GV) causes a rapid exchange of high and low momentum fluid, which in turn leads to an expedited annihilation of vorticity. Subsequently, secondary shear instabilities ultimately destroy the coherence of the GVs [3]. Multiple distinct regions have been identified in the resulting azimuthal velocity profile: A core region with persistent solid body rotation (SBR) and a vorticity-dominated near wall layer and a buffer zone containing both decaying secondary instabilities and GVs. Most interestingly, spatially averaged, the latter area turned out to reveal zero axial vorticity ω_z and the corresponding velocity profile $u_\varphi(r)$accordingly mimics the potential vortex [2]. This phenomenon was then hypothesized to be the result of the Rayleigh criterion [4], where zero vorticity is the minimum criterion for stability in a rotating flow.

The present study considers the investigation of the high Reynolds number range. The experiments are presently performed in the Coriolis tank at LEGI, Grenoble [5], as indicated in Figure 1. The diameter of $2R = 13$m and rotational speeds of the water tank up to $\Omega = 1/60$Hz allow investigations of a parameter range up to $Re = \Omega R^2/\nu = 4.4 \times 10^6$. The experiments take advantage of planar and stereo PIV measurement capabilities in the rotating frame of reference of the test facility. In order to provide best possible comparability with the moderate Re-range as investigated at KIT [2], the slowest angular velocity of the present study is chosen as $\Omega = 1/470$Hz to match the highest investigated Reynolds number $Re = 2.8 \times 10^5$ of the earlier experiments in the smaller tank [2]. Additional complementary DNS calculations cover the low-Re-range ($Re < 30.000$), such that the findings can be analyzed over several orders of magnitude in the range $3 \times 10^3 < Re < 4.4 \times 10^6$. The boundary layer growth for low and moderate Reynolds numbers is already compared in Figure 2.

However, based on the above-reported insights the objectives addressed with the present experiments are twofold. First, it remains yet to be verified that the findings revealed from the low-Re simulations and experiments at moderate Reynolds numbers hold for very high Reynolds numbers $Re > 10^6$. Therefore, three cameras (2 PCO.edge 5.5; 1 Dalsa Falcon2 4M) are aligned in radial direction to record planar PIV data in the $r - \varphi$ plane such that the boundary layer growth is tracked and the three distinct regions can be analyzed; see Figure 1(a). A 25W continuous wave laser (Spectra Physics Millennia eV 255) generates the horizontal light sheet. Occurrence and spatial distribution of the afore-mentioned instabilities and co-occurring radial jets are recorded with a stereo PIV setup (2 Vision Miro M310), which records the particle images in back

scatter mode from the outer window as shown in Figure 1(b). Second, all experiments are inevitably influenced by the development of Ekman layers, which according to Benton and Clark [6] form within the first revolution of the test facility. Even though this process has been studied at the bottom wall of the used Coriolis platform by Sous et al. [7], no experience is available for the outer boundary. Therefore, additional stereo experiments (2 PCO PixelFly, 1 Quantel Evergreen) are conducted in the $r-z$ plane to explicitly uncover, whether Ekman or Görtler effects are the predominating mechanism to perturb the initially quasi two-dimensional boundary layer formation; see Figure 1(c). This experiment is furthermore complemented with an additional planar PIV experiment (PCO 1200hs) in the $r-\varphi$ plane (see left camera in Figure 1(a)), where the SBR condition might be manipulated by Ekman effects independent from the inboard motions of the outer boundary layer.

As recommended by Nordsiek et al. [8], selected experiments will be repeated with a salty sub layer in the tank, which already turned out to be beneficial for Ekman layer suppression at moderate Reynolds numbers (see Figure 2). The ISPIV presentation will revolve around a detailed elaboration of the new high-Re data and the comparison with earlier results and insights.

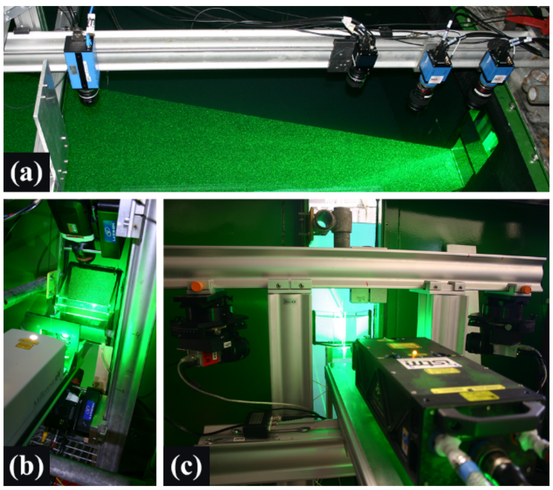

Figure 1 Experimental setup of all PIV experiments as conducted simultaneously in the rotating Coriolis tank.

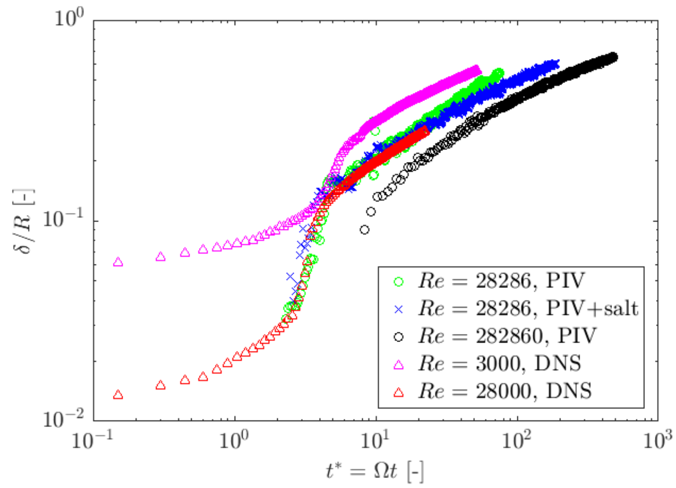

Figure 2 Boundary-layer development of the spin down case for various Reynolds numbers.

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