Experimental investigation of torque scaling and coherent structures in turbulent Taylor–Couette flow

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Abstract. The effect of flow structures to the torque values of fully turbulent Taylor-Couette flow was experimentally studied using tomographic PIV. The measurements were performed for various relative cylinder rotation speeds and Reynolds numbers, based on a study of Ravelet et al. (2010). We confirmed that the flow structures are strongly influenced by the rotation number. Our analyses using time-averaged mean flow showed the presence of Taylor vortices for the two smallest rotation numbers that were studied. Increasing the rotation number initially resulted in the shape deformation of the Taylor vortices. Further increment towards only outer cylinder rotation, showed transition to the dominance of the small scale vortices and absence of Taylor vortex-like structures. We compared the transition of the flow structures with the curves of dimensionless torque. Sudden changes of the flow structures confirmed the presence of transition points on the torque curve, where the dominance of small and large scale vortical structures on the mean flow interchanges.

1. Introduction

Following the pioneering paper of Taylor (1923), the flow between two coaxial rotating cylinders has attracted a lot of attention. Slight changes in the relative rotation speeds of two coaxial cylinders gave scientists lots of parameters to study for many years. The detailed work of Andereck et al. (1986) showed richness of the Taylor-Couette geometry in the terms of flow patterns. Capability of performing torque (Cole, 1976; Lewis & Swinney, 1999; Paoletti & Lathrop, 2011; van Gils et al., 2011), hot wire (Smith & Townsend, 1982; Townsend, 1984) and optical measurements like laser Doppler velocimetry (LDV) (Wereley & Lueptow, 1994) and particle image velocimetry (PIV) (Wereley & Lueptow, 1998), helped to determine the characteristics of the different flow regimes.

Even though other flow patterns were studied relatively more in detail, the fully turbulent regime has not revealed all of its secrets so far. Studies using instantaneous data of the fully turbulent flow regime showed the presence of small scale vortices (Dong, 2007, 2008; Ravelet et al., 2010). Additionally, the appearance of Taylor vortices has been reported in the literature for time-averaged fully turbulent flow (Townsend, 1984; Dong, 2008; Ravelet et al., 2010).

The measured torque values are strongly related to the flow regimes. In their recent work, Ravelet et al. (2007, 2010) used the torque scaling approach (Eckhardt et al., 2007) to study the effect of the rotation number, $Ro$, to the torque characteristics. They studied the role
of the rotation number on the mean flow pattern using both torque and Stereoscopic PIV measurements. Recently Paoletti & Lathrop (2011) and van Gils et al. (2011) confirmed the dependency of the torque to the rotation number at high Reynolds numbers. Both papers showed the presence of a peak in the dimensionless torque. In their paper, van Gils et al. (2011) explained that peak as a point, where optimum angular momentum transportation takes place.

Ravelet et al. (2010) plotted the friction factor, $c_f$, as a function of $Ro$. They observed almost constant torque values for $Ro \leq -0.035$ at high Reynolds numbers. After $Ro \approx 0$, the torque values decrease for increasing rotation numbers. They explained this change in the scaling as the change of the role of the large scale structures and turbulent fluctuations on torque characteristics. Dominance of the large scale structures might be effecting the dynamics of the flow especially for high Reynolds numbers.

Moreover, Ravelet et al. (2010) showed the presence of the counter-rotating vortices in the time-averaged data with only inner cylinder rotation. They showed that the coherent structures in the time-averaged flow are the mechanism that is responsible for the angular momentum transportation. However, in case of counter rotation and of only outer cylinder rotation, they reported the absence of any coherent structures. They explained the reason as the negligible amplitude of secondary flow when the outer cylinder rotates faster than the inner one.

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Dong (2007) numerically studied the relation between coherent structures and the torque values using only the inner cylinder rotation and showed the presence of Taylor vortices in the time-averaged flow. Similarly, Dong (2008) confirmed Taylor vortices for the exact counter rotation of the cylinders. Both studies were performed for relatively low Reynolds numbers ($Re = 1000 - 8000$), and lower cylinder gap ratio ($\eta = 0.5$).

In this research, we implemented tomographic particle image velocimetry (tomographic PIV; Elsinga et al. (2006)) to the Taylor-Couette geometry. Tomographic PIV offers a measurement of all three velocity components of an instantaneous volumetric domain. We aimed to investigate the flow structures that are responsible for the change of the torque scaling in fully turbulent Taylor-Couette flow. We qualitatively studied the change of the flow topology and the role of the large scale structures associated to the observed transition of torque scaling at two Reynolds numbers for different rotation numbers.

2. Experimental setup

Experiments were performed in the Taylor-Couette setup of the Laboratory for Aero & Hydrodynamics in Delft University of Technology. The facility is identical to the setup used by Ravelet et al. (2007, 2010). A sketch of the experimental setup is given in Figure 1. The system basically consists of two independently controllable coaxial cylinders. Inner and outer cylinder radii are $r_i = 110 \pm 0.05$ mm and $r_o = 120 \pm 0.05$ mm, respectively. The gap between the two cylinders is $d = r_o - r_i = 10$ mm, which corresponds to a gap ratio of $\eta = r_i/r_o = 0.917$. The inner cylinder has a height of $L = 220$ mm. This results in an aspect ratio of $\Gamma = L/d = 22$. The top and the bottom covers rotate with the outer cylinder. The torque of the inner cylinder can be measured by a torque-meter that co-rotates with the inner cylinder shaft.

The temperature of the working fluid can not be controlled in our Taylor-Couette system. However, we measured the ambient and the fluid temperatures between the recordings of each data set. The Reynolds numbers were arranged according to the temperature dependent fluid viscosity before each set of recording. Additionally, if the temperature difference between the beginning and the end of each set of the recordings exceed $0.5 \degree$K, the data were considered invalid and were not used. In case of a further change in the temperature, the rotation frequency was adjusted accordingly, in order to match the aimed Reynolds number. Hence, the variations of the temperature of the fluid were less than $\pm 0.5 \degree$K for the results presented here. The $\pm 0.5 \degree$K change in the temperature results in maximum of 1.2% uncertainty in the kinematic viscosity.
of the fluid, which is water in the current study.

The cylinders are transparent, which allows performing tomographic PIV measurements. The tomographic implementation of PIV allows the fully volumetric measurement of all three velocity components of the instantaneous flow field. The recording and the image analysis were done by using commercial software (DAVIS by LaVision GmbH). Four cameras (Imager Pro X 4M) were used in double frame mode for the recording of the particle images. Only about $1000 \times 600$ pixels were enough to capture the whole measurement volume. Objectives with a 105 mm focal length were used. They were mounted on Scheimpflug adapters. The images were recorded at the mid-height of the Taylor-Couette setup, in favour of minimising the effect of the end gaps of the Taylor-Couette facility on the measurements (see Figure 1). The dimensions of the volume recorded by all cameras are roughly $40 \times 20 \times 10.5$ mm$^3$ in axial, azimuthal and radial directions, respectively. One pixel in the recorded image corresponds to 37 $\mu$m in flow field. Velocity vectors were computed using a final interrogation window size of $40 \times 40 \times 40$ voxel, with 75% overlap.

Even though it is more convenient to use the cylindrical coordinate system for the Taylor-Couette geometry, the tomographic PIV measures and represents the data in Cartesian coordinate system. In order to avoid any interpolation errors in the process of the coordinate system conversions, the Cartesian representation is followed through this study. The, $x$, $y$ and $z$ components of the measured velocity data corresponds to axial, azimuthal and radial components of the velocities at the cylindrical coordinate system. See Figure 1 for the difference between cylindrical and Cartesian coordinate systems.

A double-pulsed Nd:YAG laser with 50 mJ/pulse energy, at a wavelength of 532 nm was used as a light source for the volume illumination. Due to the reflections caused by the illumination, the quality of the recorded images was considerably low. Hence, we used fluorescent tracer particles and 570 nm lowpass filters for rejecting the non-fluorescent illumination during the image acquisition. The tracer particles have a mean diameter of 15 $\mu$m and a density of 1.1 g/cm$^3$. Considering the high tomographic reconstruction quality (Elsinga et al., 2006), the seeding density was kept low: 0.025 ppp, with a corresponding source density (Adrian & Westerweel, 2011) of $N_s = 0.18$. The water including the seeding particles was mixed at high speeds of the inner and outer cylinders between two sets of recordings for the purpose of having a homogeneous seeding distribution. Then, the system was stopped and the fluid allowed to settle down. After that, the cylinders were taken to the desired rotational speeds and PIV images were recorded after the flow reached a stationary state.

Calibration of the camera system was done by recording images of holes ($\phi = 0.4$ mm) on a
calibration target, which was traversed in the z direction along the gap width. We used a flat plate with a thickness of 1 mm as a target. The dimensions of the plate are 150 × 20 mm², in the axial and the azimuthal directions, respectively. The gap between the cylinders was filled with water during the acquisition of the calibration images, so that the conditions during the measurements are preserved. As a final refinement, we performed the volumetric self-calibration method introduced by Wieneke (2008), which is needed for higher tomographic reconstruction quality (Elsinga et al., 2006).

3. Experimental Parameters

The experimental results presented in this paper have been acquired for seven rotation numbers (Ro) at two shear Reynolds number (Re_s). The rotation and the shear Reynolds numbers (Dubrulle et al., 2005) are given by:

\[ Ro = (1 - \eta) \frac{Re_i + Re_o}{\eta Re_o - Re_i} \]  
\[ Re_s = 2 \frac{|\eta Re_o - Re_i|}{1 + \eta} \]

where \( \eta = r_i/r_o \) is the radius ratio. \( Re_i (= r_i \Omega_i d/\nu) \) and \( Re_o (= r_o \Omega_o d/\nu) \) are the Reynolds numbers based on the inner and the outer cylinders, respectively. \( \Omega_i \) and \( \Omega_o \) represent the angular velocities of the inner and the outer cylinders and \( \nu \) stands for the kinematic viscosity of the fluid in between.

According to their study based on changing the rotation number for a constant \( Re_s \), Ravelet et al. (2010) showed that the friction factor \( c_f \) remains almost constant between \(-0.083 \leq Re \leq -0.035 \) for \( 29000 \leq Re_s \leq 47000 \) (Figure 2). For \(-0.035 < Ro < 0 \), \( c_f \) starts to decrease. Therefore, \( Ro \approx -0.035 \) can be named as “transition point”. Furthermore, van Gils et al. (2011) defined a parameter; \( a = -\Omega_o/\Omega_i \). They showed that, in the case of high Reynolds numbers, \( a \approx 0.4 \) is the situation, where the most efficient angular momentum transportation occurs. Paoletti & Lathrop (2011) reported similar results. The optimal value of \( a \approx 0.4 \) corresponds to \( Ro = -0.033 \) for our geometry, which is very close to the transition point given by Ravelet et al. (2010).

However, for lower shear Reynolds numbers (\( 11000 \leq Re_s \leq 17000 \)), the characteristics of the curves are slightly different. The \( c_f \) values decrease steeper till \( Ro \approx -0.050 \), then remains almost constant in \(-0.050 \leq Re \leq -0.025 \). Similar to higher \( Re_s \), after \( Ro > -0.025 \), \( c_f \) decreases further for increasing rotation numbers. This might be an indication of the presence of two transition points for low Reynolds numbers; one at \( Ro \approx -0.050 \), and the second one at \( Ro \approx -0.020 \).

In this paper, we performed the measurements at two shear Reynolds numbers based on the data of Ravelet et al. (2010). Seven rotation numbers; including only the inner cylinder rotation (\( Ro = -0.083 \)), counter rotation (\( Ro = 0 \)) and only the outer cylinder rotation (\( Ro = 0.091 \)), were investigated (Figure 2). Details of measurement conditions are given in Table 1.

4. Results

Examples of the time-averaged azimuthal velocity (\( v \)) curves for measurement points “A1” to “F1” are shown in Figure 3 and they are in accordance with the results presented by Wereley & Lueptow (1994). So-called “mushroom-shaped” profiles are present in plots of the rotation numbers of \(-0.083 \) and \(-0.05 \). In the case of \( Ro = -0.083 \), they tend to fold around each other in the transition zone. This trend decreases for increasing rotation numbers. Further increment
Table 1. Parameters of tomographic PIV measurements. See Figure 2 for measurement points.

| Meas. Point | Re_s   | Ro    | Re_i  | Re_o  | Ω_i   | Ω_o   |
|-------------|--------|-------|-------|-------|-------|-------|
| A1          | 11000  | -0.083| -10543| 0     | -9.74 | 0     |
| B1          | 11000  | -0.050| -8538 | 2187  | -7.92 | 1.88  |
| C1          | 11000  | -0.025| -7019 | 3843  | -6.47 | 3.27  |
| D1          | 11000  | -0.012| -6260 | 4672  | -5.78 | 3.96  |
| E1          | 11000  | -0.005| -5804 | 5169  | -5.34 | 4.40  |
| F1          | 11000  | 0     | -5500 | 5500  | -5.09 | 4.65  |
| G1          | 11000  | 0.091 | 0     | 11498 | 0.0   | 9.74  |
| A2          | 29000  | -0.083| -27796| 0     | -25.38| 0     |
| B2          | 29000  | -0.050| -22510| 5765  | -20.29| 4.78  |
| C2          | 29000  | -0.025| -18505| 10133 | -16.71| 8.36  |
| D2          | 29000  | -0.012| -16502| 12316 | -14.70| 10.05 |
| E2          | 29000  | -0.005| -15301| 13627 | -13.51| 10.99 |
| F2          | 29000  | 0     | -14500| 14500 | -12.75| 11.87 |
| G2          | 29000  | 0.091 | 0     | 30312 | 0     | 24.50 |

Figure 2. Friction factor $c_f$ as a function of rotation number (redrawn after Figure 8 of Ravelet et al. (2010)); blue ◊: $Re_s = 11000$, red ◇: $Re_s = 14000$, green ○: $Re_s = 17000$, black ★: $Re_s = 29000$, magenta □: $Re_s = 36000$, cyan ▽: $Re_s = 47000$. Tomographic PIV measurements are performed for $Re_s = 11000$ and 29000 at the rotation numbers marked by the lines named as “A” to “G”.

of the rotation number results in the change from the mushroom shape towards a wavy pattern (Figure 3(c)-(f)). The amplitude of the waves decrease till the counter-rotation case ($Ro = 0$). For only the outer cylinder rotation ($Ro = 0.091$), the azimuthal velocity is homogeneous in the axial direction and is a function of only the radial position as expected (Ravelet et al., 2010).

The radial velocity ($w$) profiles, which are shown by cross-sections in Figure 3 - 6, are in relation with the azimuthal velocity patterns and the large-scaled vortical structures. The behaviour of $w$ significantly changes with the rotation number. Inflow and outflow regions are distinctive and higher in the magnitude for $Ro = -0.083$ and $-0.05$. Increment of the rotation numbers results in notably decrement of their strengths, and broadening of the in- and outflow regions. In the case of the only outer cylinder rotation ($Ro = 0.091$), the radial velocity profiles show no axial dependence.

Instantaneous plots of the Q-criterion (Hunt et al., 1988) show that the flow is fully turbulent,
Figure 3. The isosurfaces for constant values of the azimuthal velocity, $v$, determined by time averaging 200 instantaneous velocity fields for $Re_s = 11000$. (a) $Ro = -0.083$, isosurface: $v = 0.52 \text{ m/s}$, (b) $Ro = -0.050$, isosurface: $v = 0.32 \text{ m/s}$, (c) $Ro = -0.025$, isosurface: $v = 0.18 \text{ m/s}$, (d) $Ro = -0.012$, isosurface: $v = 0.11 \text{ m/s}$, (e) $Ro = -0.005$, isosurface: $v = 0.04 \text{ m/s}$, (f) $Ro = 0.0$, isosurface: $v = 0.0 \text{ m/s}$. Color coded cross sections represent the radial velocity; red is outflow, blue is inflow. All axes are non-dimensionalised according to the gap $d$ between the cylinders.

disorganised and dominated by small scale structures for all $Ro$ numbers (Figure 4). The size of the vortices are significantly smaller than the gap between the cylinders. The flow lacks of organised Taylor vortex-like structures. The intensity of the turbulent fluctuations increases with increasing rotation number. These findings are consistent with the previous studies (Dong, 2007, 2008; Ravelet et al., 2007, 2010). Our measurements with even higher $Re_s$ numbers revealed a similar pattern.

The Q-criterion plots of the time-averaged volumes for measurement points “A1” to “F1” are given in Figure 5. The averaging was performed over 200 instantaneous velocity fields. As reported in the literature (Dong, 2007, 2008; Ravelet et al., 2010), the Taylor vortices are present in the measurement volume for the two smallest rotation numbers that are investigated; $-0.083$ and $-0.05$ (Figure 5(a) and (b)). Dong (2008) explained their presence by the cumulative effect of the small-scale vortices. The size of the vortices are comparable with each other and the gap width for both rotation numbers. Similar to previous studies (Ravelet et al., 2010), the shape of the Taylor vortices are not exactly circular, but inclined ellipsoidal. The inclination axes are making an angle of $\pm 25^\circ$ with the axial direction of the cylinders. Their directions coincide with the inflow and outflow regions in the radial direction. Moreover, two separate vortical zones with higher concentration are present inside of each Taylor vortices.
Figure 4. The isosurfaces for constant values of the Q-criterion at $Re_s = 11000$, determined from the measured instantaneous flow fields. (a) $Ro = -0.083$, measurement point: “A1”, isosurface: $Q = 1250 \text{ s}^{-2}$, (b) $Ro = 0.091$, measurement point: “F1”, isosurface: $Q = 2500 \text{ s}^{-2}$. Color coded cross sections represent the radial velocity; red is outflow, blue is inflow. All axes are non-dimensionalised according to the gap $d$ between the cylinders.

Figure 5. The isosurfaces for constant values of the Q-criterion for $Re_s = 11000$, determined by time averaging 200 instantaneous velocity fields. (a) $Ro = -0.083$, isosurface: blue $Q = 30 \text{ s}^{-2}$, red $Q = 300 \text{ s}^{-2}$, (b) $Ro = -0.050$, isosurface: blue $Q = 30 \text{ s}^{-2}$, green $Q = 150 \text{ s}^{-2}$, (c) $Ro = -0.025$, isosurface: blue $Q = 30 \text{ s}^{-2}$, (d) $Ro = -0.012$, isosurface: blue $Q = 30 \text{ s}^{-2}$, (e) $Ro = -0.005$, isosurface: blue $Q = 30 \text{ s}^{-2}$, (f) $Ro = 0.0$, isosurface: blue $Q = 30 \text{ s}^{-2}$. Color coded cross sections represent the radial velocity; red is outflow, blue is inflow. All axes are non-dimensionalised according to the gap $d$ between the cylinders.
Figure 6. The isosurfaces for constant values of the Q-criterion for $Re_s = 29000$, determined by time averaging 200 instantaneous velocity fields. (a) $Ro = -0.083$, isosurface: blue $Q = 100$ s$^{-2}$, red $Q = 1200$ s$^{-2}$, (b) $Ro = -0.050$, isosurface: blue $Q = 100$ s$^{-2}$, red $Q = 1200$ s$^{-2}$, (c) $Ro = -0.025$, isosurface: blue $Q = 100$ s$^{-2}$, (d) $Ro = -0.012$, isosurface: blue $Q = 100$ s$^{-2}$, (e) $Ro = -0.005$, isosurface: blue $Q = 100$ s$^{-2}$, (f) $Ro = 0.0$, isosurface: blue $Q = 100$ s$^{-2}$. Color coded cross sections represent the radial velocity; red is outflow, blue is inflow. All axes are non-dimensionalised according to the gap $d$ between the cylinders.

Increment in the rotation number results in a deformation of the shape of the Taylor vortices (Figure 5(c) and (d)). In parallel, the roughness of the vortices increase and their radii decrease. After $Ro > -0.005$, (i.e. “E1”, “F1” and “G1”), further increment of the rotation number results in the absence of the Taylor vortices (Figure 5(e) and (f)). Measurements with only the outer cylinder rotation ($Ro = 0.091$) are consistent with this trend.

The measurements with higher shear Reynolds number ($Re_s = 29000$) revealed similar results, except the higher intensity of the vortices (Figure 6). However, at $Ro = -0.025$ (Figure 6(c)) the relative smooth shape of the Taylor vortices somewhat still preserved. Furthermore, indication of very rough Taylor vortices are still present at higher rotation number of $-0.005$ (Figure 6(e)). But their radii are smaller. Since the intensity of the fluctuations in the mean flow increase as well, the order of the strength of the Taylor vortices became comparable with small-scale vortices.

In the light of our visualisations, we can comment on the relation between the flow structures and given $c_f$ values. For $Re_s = 11000$, the deformation of the Taylor vortices can be observed between $Ro = -0.050$ and $-0.025$. This indicates an transition point at $Ro < -0.025$, which is in agreement with the findings of Ravelet et al. (2010) and might be a hint of the peak mentioned by van Gils et al. (2011). Furthermore, the minor differences between $Ro = -0.025$
and \(-0.012\) implies the plateau of \(c_f\) in the approximate region of \(-0.035 < \text{Ro} < -0.010\). Since the difference between \(\text{Ro} = -0.012\) and \(-0.005\) is relatively higher and the rate of the change of the flow structures seems to be constant for \(\text{Ro} > -0.005\), it might be an indication of the existence of a second transition point at \(\text{Ro} \approx -0.010\).

In the case of \(Re_s = 29000\), the shape of the vortices gradually change at \(-0.083 \leq \text{Ro} \leq -0.025\). This is the region where \(c_f\) is almost constant. However, the size and the smoothness of the vortices decrease faster for further increment of \(\text{Ro}\). The Taylor vortices are found to be heavily deformed at \(\text{Ro} = -0.012\). There is a sudden transition between \(\text{Ro} = -0.025\) and \(-0.012\), which is not the case between \(\text{Ro} = -0.050\) and \(-0.025\). This might be an indication of two things; either the transition point is slightly higher than \(\text{Ro} = -0.035\), which was reported by Ravelet et al. (2010), or there might be a second transition point at \(-0.025 < \text{Ro} < -0.012\). Since the transition from \(\text{Ro} = -0.050\) to \(-0.025\) is similar to the case of \(Re_s = 11000\), the latter explanation seems more reasonable. However, further investigation with better resolution of rotation numbers is needed for any conclusion.

In case of further increment of \(\text{Ro}\), we see a steep decrement of the friction factor. In parallel, the flow gradually becomes dominated by small scale vortices. But the rate of change is somewhat lower than it is in \(Re_s = 11000\). This can be related to the small difference of the \(c_f\) slopes at the \(0.0 \leq \text{Ro} \leq 0.091\) region.

5. Conclusion

In this paper, we studied the effect of flow structures to the measured torque values of fully turbulent Taylor-Couette flow. We performed tomographic PIV measurements at different cylinder rotation rates and Reynolds numbers. The qualitative results showed that the flow structures are strongly influenced by the rotation number, as well as by the Reynolds number.

The instantaneous snapshots of the flow revealed the domination of small-scale vortices, with the absence of organised large-scale structures for all rotation and Reynolds numbers. On the other hand, the analyses of the time-averaged flow showed that Taylor vortices are present in the flow for the two smallest rotation numbers, as reported (Dong, 2007, 2008; Ravelet et al., 2010). Deformation of the Taylor vortices was observed for increasing rotation numbers. As a consequence, no sign of organised Taylor vortex-like structures were experienced in the region between exact counter rotation and only the outer cylinder rotation.

We showed the contribution of the organised vortices to the measured torque values, as well. We confirm the previous works of Delfos et al. (2009); Ravelet et al. (2010), where they proposed the transition point on the friction factor curve is closely related with the transition between the large scale structures and the fluctuations. Especially for the large scale structures, we observed sudden changes of the flow patterns in the vicinity of the transition points. Additionally, slight change of the rate of the deformation proposed the presence of a second transition point at a relatively higher rotation number. Nevertheless, further quantitative investigation, with an improved rotation number resolution, is needed for the confirmation.

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