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Torque in turbulent Taylor-Couette flow for small radius ratios

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Abstract

Turbulent Taylor-Couette flow is investigated for a very wide gap configuration. Using the Top-view Taylor-Couette Cottbus experiment the angular momentum transport is measured by means of the torque acting to the inner cylinder wall. The results of torque for radius ratio 0.5 are compared to the findings of Merbold et al. (2013) and the parameter space is extended to radius ratio of 0.357 for inner and outer cylinder rotation. Both experimental setups are in very good agreement concerning the torque for radius ratio 0.5. The torque for radius ratio 0.357 has a similar behaviour with the Reynolds number. Also for slight counter rotation the torque exhibits a maximum for constant shear Reynolds number at angular velocity ratio of $\mu_{opt} \sim 0.1$.

1 Introduction

The concentric rotating Taylor-Couette flow is a well-known system of instabilities in fluid dynamics. In this work the transitions between different three dimensional flows of counter- and corotating Taylor-Couette flow and its dependence on different parameters is investigated. Depending on the rotation rates of the cylinders (Radii R_1, R_2 with angular velocities Ω_1, Ω_2), one is able to create a linear stable (like pipe flox) or unstable flow (like Rayleigh-Bénard (RB) convection). From this background one can see TC flow as a link between RB and pipe flow. A comparison of these three systems by an analytical comparison is also given by (Eckhardt et al. (2007b)). It is possible to calculate the heat flux J_Θ for RB, a transverse momentum flux J_{u_z} for pipe flow, and an angular momentum flux J_ω for Taylor-Couette flow, which have a similar analytical form (Eckhardt et al. (2007a)). Analytically, J_ω has to be independent of all radial positions. So, it is of great interest to quantify the angular momentum flux as a parameter for the flow. At the wall the magnitude of J_ω corresponds to the torque the fluid transfers onto the cylinders: Thus the dimensionless torque $G = T/(2\pi L \rho \nu^2) = \nu^{-2} J_\omega$ can be used to quantify the angular momentum flux. The scaling of the torque with the rotation rates of the system gives the scaling of the angular momentum flux.

The torque grows exponentially with the shear Reynolds number $Re_S = 2R_2R_1d(\Omega_2 - \Omega_1)(R_2+R_1)^{-1}\nu^{-1}$ and reveals a peak at a slight counter rotation of about $\mu = \Omega_2/\Omega_1 = 0.2$ for radius ratio $\eta = R_1/R_2 = 0.5$ (Merbold et al. (2013)). To quantify the different contributions of the large scale structures and the featureless turbulence onto the angular momentum flux, the flow can be observed using flow visualization techniques and quantified using Particle Image Velocimetry (PIV). Using a visualization of the flow in the vicinity of the outer wall the axial-azimuthal flow fields at the cylinder surface are able to be analyzed. In addition azimuthal-radial fields are quantified using PIV in various different heights (Froitzheim et al. (2017)). The contribution of the large scale structures as well as the turbulent fluctuations onto the angular momentum transport is quantified and discussed in Froitzheim et al. (2017).

The purpose of the present work is to extend the parameter space to a wider gap. The torque for the known geometry is measured and compared to the findings of Merbold et al. (2013) to ensure accurate measurements. We discuss the experimental results for the radius ratio $\eta = 0.357$, where torque measurements are performed.

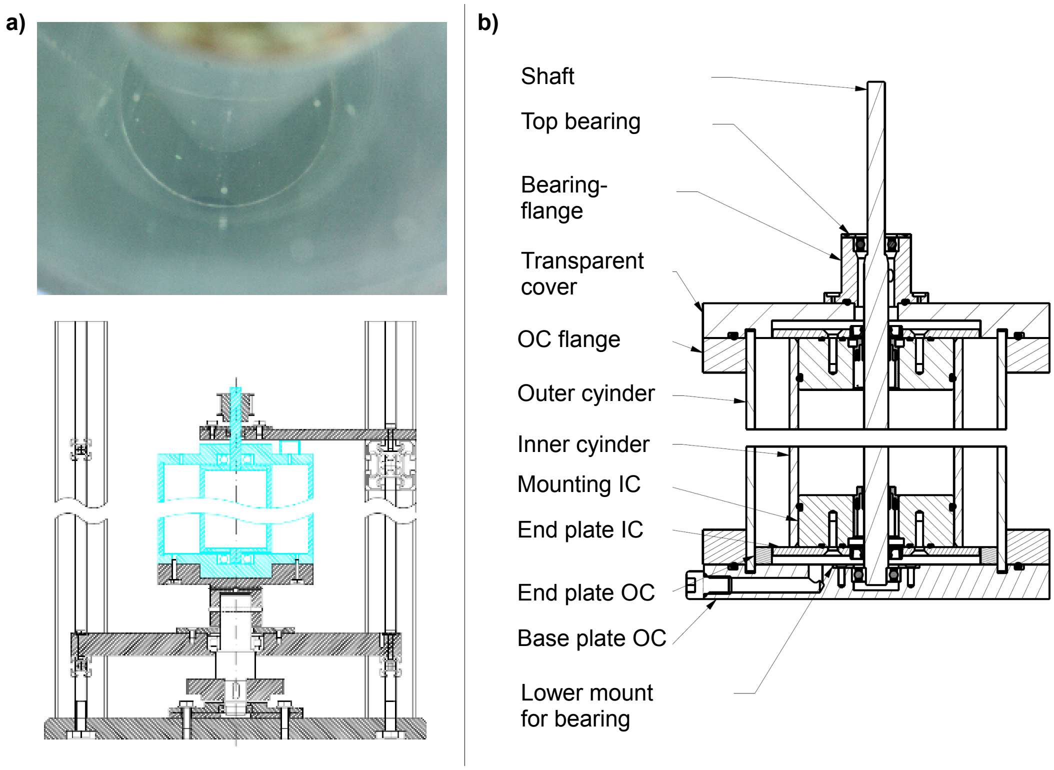

Figure 1: Top view Taylor-Couette Cottbus. a) View through the top end plate into measurement volume and drawing of the whole setup. A more detailed drawing of the highlighted part is shown in b).

2 Experimental apparatus: Top view Taylor-Couette Cottbus

The experiment used in this study is the so called Top view Taylor-Couette Cottbus (TvTCC) system. Its main advantage is the variation of the inner cylinder radius and therefore the radius ratio η while inner as well as outer cylinder can rotate. The upper and lower end plates rotate with the outer cylinder. Beside the outer cylinder also the top end plate is transparent to get optical access for LDV and PIV measurements of the azimuthal and radial velocity components, which gives the system its name Top view Taylor-Couette Cottbus (TvTCC). Torque measurements will be performed using a shaft to shaft torque sensor. The exchange of the fluid as well as the change of the geometry can be done rapidly.

The geomtry of the outer cylinder is exactly the same as for the Turbulent Taylor-Couette Cottbus (T2C2) studied in Merbold et al. (2013) ($R_2 = 70mm, L = 700mm$) to perform comparability of both experiments for the same inner cylinder radius and end plate configurations. A drawing of the Top view Taylor-Couette Cottbus is shown in Fig. 1.

The radius of the inner cylinder can be changed. A main shaft of $14mm$ diameter is mounted rotatable inside the outer cylinder. On this shaft different inner cylinders can be mounted. This leads to the minimal radius ratio of $\eta = 0.1$ while the shaft rotates alone. The upper limit we built is $R_1 = 50mm$ leading to $\eta = 5/7 \approx 0.71$, which is comparable to many Taylor-Couette systems with torque measurements in literature (Wendt (1933); Lathrop et al. (1992); Lewis and Swinney (1999); van Gils et al. (2011); Paoletti and Lathrop (2011); van Gils et al. (2012); Brauckmann and Eckhardt (2013b)). In the study given here we use the two cases of $R_1 = 35mm, \eta = 0.5, \Gamma = 20$ and $R_1 = 25mm, \eta = 0.357, \Gamma \sim 15.6$. Inner and outer cylinder are driven by two independent motors with different gearing possibilities. The torque is measured using a shaft to shaft torque sensor (Fig. 2 for measurement range of $\pm 1Nm$ and precision of 0.1%). For this purpose the inner cylinder is beared inside the outer cylinder by only two low friction bearings against the outer cylinder and one against the stativ, it has no dynamic shaft sealing to reduce the mechanical torque for the running experiment. Running the system with air at different rotation speeds of both cylinders the mechanical drag of the experiment is determined. For the torque measurements used with liquids this determined friction is substracted.

The working fluids applied to this experiment are water and silicone oils of different viscosity. In

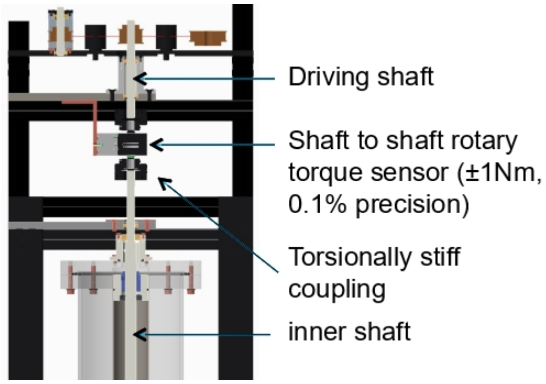

Figure 2: Drawing of the implementation of the shaft to shaft torque unit in the Top view Taylor-Couette Cottbus.

this study silicone oil with a nominal viscosity of $\nu = 10mm^2/s$ and $20mm^2/s$ (at 25C) are used, the fluid temperature is measured during experiments to correct the actual fluid viscosity. For running the cylinders we use two different motor-gearing configurations, leading to cylinder rotation frequencies between 100rpm (using slow gearing) up to 2600 rpm (using fast gearing). The angular velocity is kept constant with an accuracy of less than 0.5%.

3 Torque measurements for radius ratio 0.5

In Merbold et al. (2013) the torque for a wide range of shear Reynolds numbers and rotation ratios was measured using the Turbulent Taylor-Couette Cottbus (TTCC) experiment. The given experiment is not variable towards wider gaps. However, the torque behaviour in this geometry is of interest. The Top-view Taylor-Couette Cottbus (TvTCC) experiment was designed to fill this gap. The inner cylinder can easily be changed to smaller radii while also the top end plate enables optical measurement techniques. The torque sensor installed to the TvTCC system had to be verified. Both torque sensors work in a different way. In the TTCC strain gauges are installed into the rotating inner cylinder, measuring the torque only for a middle segment along the axis to neglect the end effects of the end plates. The sensors are calibrated for an accuracy of 0.1mNm. The torque sensor in the TvTCC is measuring all the torque needed to run the inner cylinder against the outer cylinder, including the mechanical torque of the bearings and the end plate effects. As the system is quiet long (in any case the aspect ratio is always larger than 10) the end plate effects are considered to be small. The mechanical torque is measured for the system running without working fluid and substracted from the final torques. The verfication of the torque measurement has been done using the exact same geometry as for Merbold et al. (2013): $R_1 = 35mm, R_2 = 70mm, L = 700mm, \eta = 0.5, \Gamma = 20$. The comparison of the torques are given in Figure 3. Already the torque of the numerical simulations and experimental measurements in Merbold et al. (2013) have been of a very good agreement concerning that they have been achieved independently and for different end wall configurations. However, the measurements of the TvTCC are also in a very good agreement. This shows that the shaft-to-shaft torque sensor measures precise and the parameter space can be extended to wider gaps. It has to be mentioned, that due to decreasing cylinder size the real torque decreaces immense. Using high viscous oils compensated this, but this leads to decreasing maximal shear Reynolds numbers as the radius ratio shrinks.

4 Torque measurements for radius ratio 0.357

The measurements of the torque is extended towards wider gaps. This is the only known study quantifying the angular momentum transport by means of hard torque measurements for Taylor-Couette setups with radius ratio less than $\eta = 0.5$. For constant shear Reynolds numbers the ratio of angular velocities was varied and the torque has been measured. The results of this are given in Figure 4. Again a similar behaviour as for $\eta = 0.5$ can be detected. The torque is maximal for a slight counter rotation. Brauckmann and Eckhardt (2013b) did formulate an understanding for the maximal torque explaining it by enhanced large scale circulation. For known experiments the prediction made by this was in agreement with the experiments

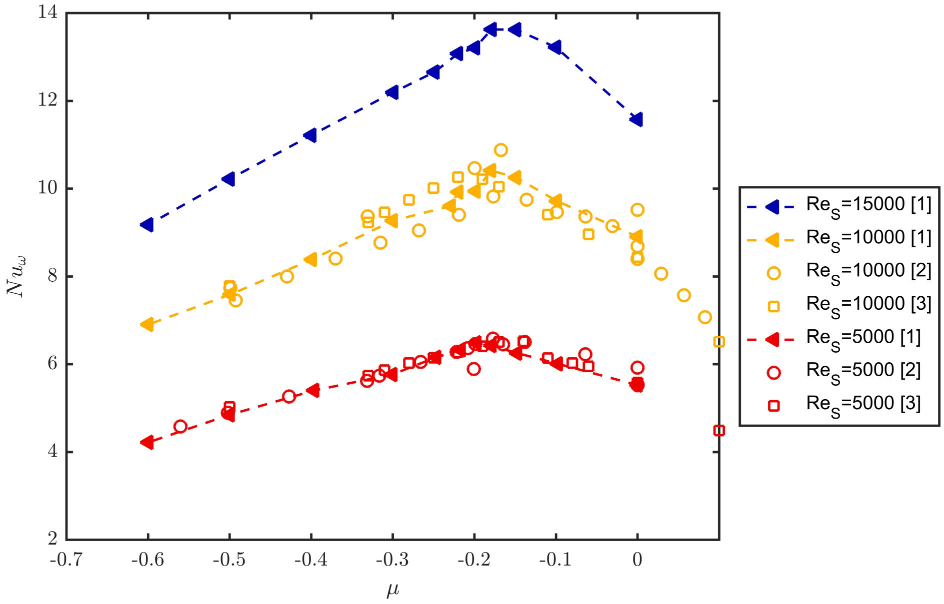

Figure 3: Quasi-Nusselt number from torque measurements against ratio of angular velocities for different constant shear Reynolds numbers for $\eta = 0.5$ of this study [1] in comparison to the experiments [2] and numerical results [3] in Merbold et al. (2013)

and numerical findings up to an upper limit. The prediction for radius ratio of $\eta = 0.357$ leads to a rotation ratio of $\mu_{max,pred} = -0.1063$. As shown in Fig. 4 the experimental measured torque supports the prediction very well. In the measured range of Reynolds numbers the torque has a maximum close to the predicted value.

5 Conclusion

Summarizing our study, the torque measurements of the TvTCC has been verified comparing to results of the same geometry. In addition the angular momentum transport was first measured for radius ratio $\eta = 0.5$. For constant shear Reynolds number also for this wide gap system the torque has a maximum for slight counter rotation. It decreases into stronger counter rotation. The behaviour of the torque with the shear Reynolds number for a constant rotation ratio will be discusses in a different work as well as a study of the flow behaviour using flow visualisation techniques and high-speed recordings of the flow as well as Particle Image Velocimetry.

Acknowledgements

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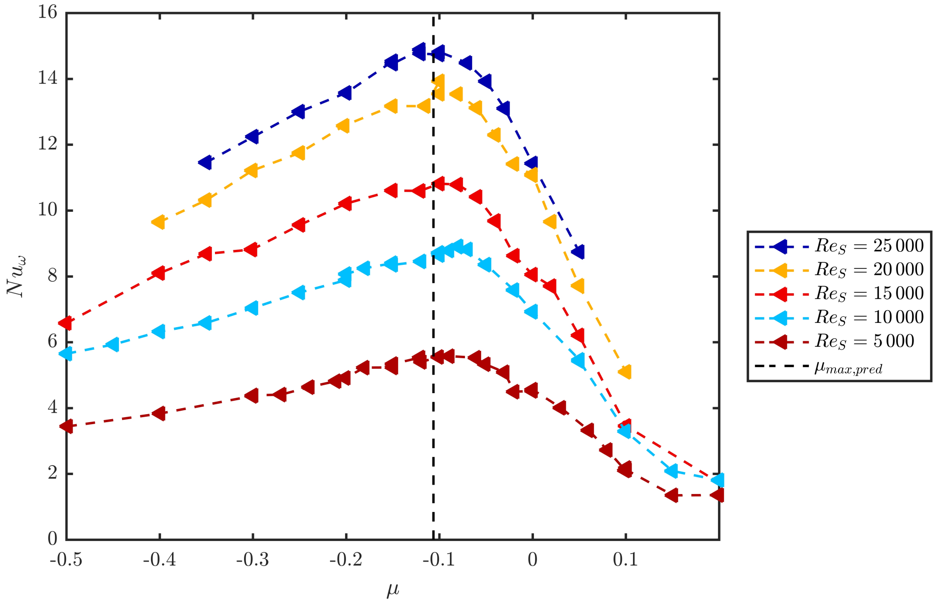

Figure 4: Quasi-Nusselt number from torque measurements against ratio of angular velocities for different constant shear Reynolds numbers for $\eta = 0,357$. The dashed line indicates the predicted torque maximum using the enhanced large circulation by Brauckmann and Eckhardt (2013b) which leads to $\mu_{max,pred} = -0.1063$.

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