EXPERIMENTAL STUDY OF SURFACE MODIFICATION IN A FULLY TURBULENT TAYLOR-COUETTE FLOW

Arnoud Greidanus[1], Rene Delfos[1], Sedat Tokgöz[1] & Jerry Westerweel[1]
[1]*Laboratory for Aero and Hydrodynamics, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands*

Abstract Friction measurements were performed in a Taylor-Couette setup. Drag reduction was obtained with a riblet surface and indicated a drag reduction for a wide range of shear Reynolds numbers, with a maximum of 5.3% at $Re_s = 4.7 \times 10^4$ ($s^+ = 14$). Tomographic PIV verified that the friction coefficients are strongly related to the flow regimes and structures. The bulk fluid rotation was changed by the application of the riblets, as the wall-bounded flow conditions at the inner cylinder wall were changed due to the surface modification and is called the rotation effect. A simple model was used to indicate the averaged *bulk* velocity shift (1.4%), after which the drag changes due to the rotation effect (-1.9%) and the riblet effect (-3.4%) were determined. The bulk velocity shift of 1.4% was verified by PIV measurements. Compliant surfaces will be further investigated to check their required conditions for drag reduction of wall-bounded flows.

INTRODUCTION

Reduction of wall friction in turbulent flows has remained an interesting subject for researchers over the last decades. Applications may particular be relevant to industrial devices to reduce the pressure drop in pipe flows, as to transport vehicles to decrease fuel consumption. Substantial energy savings may have ecological and economical benefits.

We discuss the investigation of the Taylor-Couette facility as an easy-to-use experimental instrument to measure drag change of turbulent wall-bounded flows due to surface modification [1, 4]. The turbulent flow is investigated via tomo-PIV measurements, which identify the change in flow structures and velocity profile between two counter-rotating cylinders.

EXPERIMENTAL SETUP

The experimental setup consists of two coaxial closed cylinders that both can rotate independently and was used in previous investigations [3, 6]. The radius of the inner cylinder is $r_i = 110$ mm and total length $L_i = 216$ mm. The outer cylinder has a radius $r_o = 120$ mm and length $L_o = 220$ mm. The inner cylinder is assembled within the outer cylinder with high precision; the gap between the two cylinders in radial direction (TC-gap) and in axial direction (vK-gap) is $d = r_o - r_i = 10.0$ mm and $h = (L_o - L_i)/2 = 2.0$ mm, respectively. Hence, the radial gap ratio is $\eta = r_i/r_o = 0.917$ and axial aspect ratio is $\Gamma = L_i/d = 21.6$.

The desired angular velocities of the inner and outer cylinders are regulated by two independent motors that are controlled by a software program. The total torque M on the inner cylinder is recorded with a co-rotating torque meter (abs. precision ± 0.01 Nm) that is assembled in the shaft between the driving motor and inner cylinder. The torque and rotation rate signal of the inner cylinder are recorded at a sampling rate of 2 kHz for 120 seconds. The outside wall temperature T_{out} of the outer cylinder is recorded by an infrared-thermometer and the fluid temperature T_f is indirectly determined via heat transfer calculations.

Tomographic particle image velocimetry is used to measure the three velocity components in the instantaneous flow field. The application of the tomo-PIV to Taylor-Couette is described in more detail by Tokgöz *et al.* [5]. Four cameras (Imager Pro X 4M) recorded particle images of a measurement volume between the two cylinders, which has a volume size of roughly $40 \times 20 \times 10$ mm^3 in axial, azimuthal and radial directions. The measurement volume is located at mid-height of the rotational axis to minimize the possible end effects of the Taylor-Couette facility on the measurements.

PIV AND TORQUE MEASUREMENTS WITH RIBLET SURFACE

Riblets with a triangular cross-section, spacing $s = 120$ μm and height $h = \pm 110$ μm, are applied in azimuthal direction on the inner cylinder surface only as it is much easier, faster and more accurate. The outer cylinder surface remains unaltered. The measurements are performed under exact counter-rotation ($\omega_o r_o = -\omega_i r_i$), resulting in a rotation number $R_\Omega = 0$.

The measured drag change $\Delta\tau/\tau_0$ is given in Figure 1. Drag reduction is observed between a riblet spacing Reynolds number $s^+ = 2 - 23$ ($Re_s = 4.0 \times 10^3$ to 8.5×10^4), with a maximum of 5.3% at $s^+ = 14$ ($Re_s = 4.7 \times 10^4$). It is supposed that the riblets enhance drag in the Taylor vortices regime ($s^+ < 2$) due to the presence of large-scale structures with relative large axial flow motions, as was revealed by PIV measurements. For $s^+ > 23$ the riblets are associated with wall roughness compared to the high skin friction and loose their drag reducing benefits.

For the riblet configuration, the inner and outer cylinder surfaces have different wall-bounded flow conditions and modifies the rotation number R_Ω, called the rotation effect. With an identical inner and outer cylinder surface, the core of the flow shows very low azimuthal velocities and indicates an averaged bulk velocity $\bar{U}_b = 0$ (Fig. 2, $*$). When the friction is reduced at the inner cylinder wall due to riblets, the averaged *bulk* fluid starts to co-rotate slightly with the direction of the outer cylinder (Fig. 2, $\circ$).

The shift in averaged bulk velocity δ due to the change of shear stress $\Delta\tau$ at the inner cylinder wall is determined by $\delta = (1 - \sqrt{(1 + \Delta\tau/\tau_0})/(1 + \sqrt{1 + \Delta\tau/\tau_0})$, with $\delta = \bar{U}_b/U_{out}$. The maximum drag reduction of 5.3% corresponds with an averaged bulk velocity $\delta = 0.014$. PIV measurements confirm a similar shift of the averaged bulk velocity (inset Fig. 2). The shift results in an apparent rotation number $\hat{R}_\Omega = 0.0012$, which is very small but sufficient enough to play a substantial role in the total measured drag change. The drag change due to the rotation effect is -1.9% for a measured drag change of -5.3% [3] and leads to a maximum net riblet drag reduction of 3.4%. The net drag change is determined for all measured drag values (Fig. 1, $\circ$).

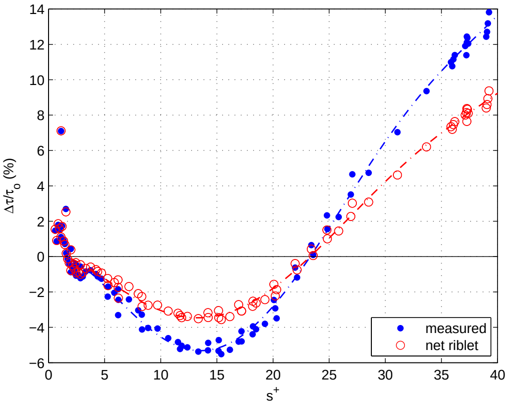

Figure 1: Measured and determined drag change by riblet inner cylinder under exact counter-rotation *vs.* riblet spacing Reynolds number s^+ $(= su_\tau/\nu)$. Maximum drag change at $s^+ = 14$.

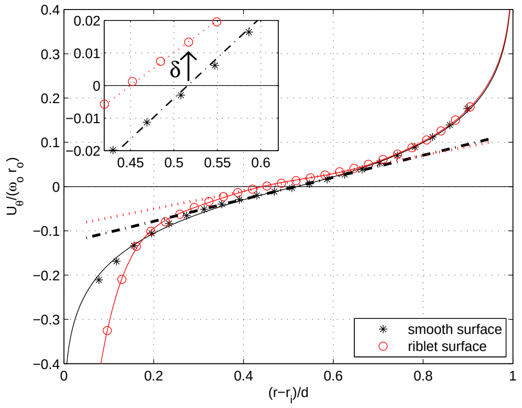

Figure 2: Averaged normalized velocity profile of smooth and riblet surfaces at $s^+ = 14$ ($Re_s = 4.7 \times 10^4$) under exact counter-rotation conditions. Inset: Zero-crossing of the azimuthal velocity profiles.

FLOW MOTIONS AND DRAG CHANGE BY A COMPLIANT WALL

The surface of a compliant wall is deformed by the flow phenomenon of the fluid above it. The pressure and friction on the wall caused by the flow deforms the compliant surface, which in turn interact with the near-wall flow. These surface motions can have favorable effects to reduce the skin friction in turbulent flow [2].

Several compliant coatings will be investigated to check the required conditions for drag reduction of wall-bounded flows. PIV measurements may indicate the interaction of the compliant wall with the near-wall flow.

References

[1] AJ Greidanus, R Delfos, S Tokgöz, and J Westerweel. Turbulent Taylor-Couette flow over riblets: Drag reduction and the effects of bulk fluid rotation. Submitted to Experiments in Fluids.

[2] Euiyoung Kim and Haecheon Choi. Space–time characteristics of a compliant wall in a turbulent channel flow. *Journal of Fluid Mechanics*, **756**:30–53, 2014.

[3] Florent Ravelet, Rene Delfos, and Jerry Westerweel. Influence of global rotation and Reynolds number on the large-scale features of a turbulent Taylor-Couette flow. *Physics of Fluids (1994-present)*, **22**(5):055103, 2010.

[4] Siddarth Srinivasan, Justin A Kleingartner, Jonathan B Gilbert, Robert E Cohen, Andrew JB Milne, and Gareth H McKinley. Sustainable Drag Reduction in Turbulent Taylor-Couette Flows by Depositing Sprayable Superhydrophobic Surfaces. *Physical Review Letters*, **114**(1):014501, 2015.

[5] S Tokgöz. *Coherent Structures in Taylor-Couette Flow: Experimental Investigation*. PhD thesis, TU Delft, Delft University of Technology, 2014.

[6] S Tokgöz, GE Elsinga, R Delfos, and J Westerweel. Spatial resolution and dissipation rate estimation in Taylor-Couette flow for tomographic PIV. *Experiments in fluids*, **53**(3):561–583, 2012.