Drag reduction by surface treatment in turbulent Taylor-Couette flow

A J Greidanus, R Delfos and J Westerweel
Laboratory for Aero and Hydrodynamics, Delft University of Technology, Leeghwaterstraat 21, 2628 CA, Delft, The Netherlands.
E-mail: a.j.greidanus@tudelft.nl

Abstract. We use a Taylor-Couette facility to study the drag reducing effects of commercial surface products at high shear Reynolds numbers ($Re_s$) under perfect counter-rotating conditions ($r_i \omega_i = -r_o \omega_o$). The correlation between torque contribution of the von Kármán flow and shear Reynolds number is investigated. At this moment no significant drag changes are found for the commercial products. However, further research is needed to exclude uncertainties and errors from the torque measurements.

1. Introduction

Drag reduction of surfaces in turbulent flows is of enormous ecologic and economic importance. Many studies on drag reduction reveal that the addition of polymers, surfactants, and air bubbles/films can reduce the surface friction of turbulent flows. These drag reduction methods show promising results in applications for internal flows, like pipe flows. For example, Virk (1975) showed that 80% drag reduction was achieved by dissolving small quantities of long-chain flexible polymers into a solution. Also for the injection of (micro)bubbles in channel flows (Murai et al., 2007; Gutierrez-Torres et al., 2008) drag reducing effects were reported up to 35%.

Although applications to ships, these drag reduction methods could lead to significant fuel savings, the practical implementation appears to be a large hurdle up till now. Polymer injection into a turbulent boundary layer never showed to be cost effective in ship applications, due to continuous downstream decrease of the polymer concentration and demands complex injection units to maintain the drag reducing abilities over the downstream distance (White & Mungal, 2008).

Further, the pioneering work of McCormick & Bhattacharyya (1973) showed 30% drag reduction on a submerged body by using hydrogen microbubbles induced by electrolysis at the surface. This triggered much research on drag reduction by air bubbles and films over the last decades (Madavan et al., 1985; Merkle & Deutsch, 1992; Latorre, 1997; Latorre et al., 2003; Sanders et al., 2006; Elbing et al., 2008; Ceccio, 2010). Nevertheless, as for polymer injection into the boundary layer, the use of air bubbles or films shows similar practical problems. Due to coalescence or break up of air bubbles and films respectively, it seems to be quite difficult to maintain constant and stable drag reducing performances (Sanders et al., 2006; Wu et al., 2007).
These complex injection methods can be avoided by using coatings with drag reducing abilities. Recently, much research has been done in the area of superhydrophobic and superhydrophilic surfaces (Bonaccurso et al., 2003; Zhang et al., 2008; Byon et al., 2010), in which hydrophobicity or hydrophilicity, and micron-scale surface roughness are combined. The contact angle of a water droplet on such surface typically reaches values as high as 160° to 175° for superhydrophobic and as low as 5° to 15° for superhydrophilic surfaces (Quéré, 2008). Significant reduction of drag is shown in pipe & channel flows (Watanabe et al., 1999), as well as in rheology studies (Choi & Kim, 2006) as in external flow experiments by Balasubramanian et al. (2004). They found around 20% drag reduction on flat plates and 10-14% drag reduction on a submerged body.

These microstructured surfaces must not be confused with riblet surfaces; their scale and mechanism are very different. Riblets are small surface protrusions that are aligned in the flow direction (Bechert et al., 1997). They reduce drag by disturbing the spanwise motion of the flow at the surface and thereby moving turbulent vortices further away from the wall. The microstructures of superhydrophobic/philic surfaces are significantly smaller \((s^+ < 5\text{ compared to } 5 < s^+ < 30\text{ for riblets, expressed in wall units})\) and are therefore too small to obtain a riblet effect (Rothstein, 2010). The drag reducing mechanism of superhydrophobic/philic surfaces is assumed to be the effect of wall slip (Choi & Kim, 2006; Sochi, 2011). This assumption deviates from the traditional theory of no-slip boundary conditions and has lead in literature to controversies and contradicting observations and conclusions (De Gennes, 2002; Neto et al., 2003, 2005). Therefore it is more appropriate to speak about "apparent boundary slip".

An alternative facility to perform surface drag reduction studies, is a Taylor-Couette system. Turbulent Taylor-Couette flow is the fluid motion between two coaxial cylinders and having the same characteristics as a turbulent boundary layer (Ravelet et al., 2007, 2010). Furthermore, the flow can be considered as an infinite boundary layer as is the case for a fully developed channel flow.

Taylor-Couette systems are widely used for fundamental studies of flow transition and stability (Taylor, 1923; Borrero-Echeverry et al., 2010), for flow structure studies (Ravelet et al., 2010). But also for drag reduction studies of surfactants (Koeltzsch et al., 2003), microbubbles (Sugiyama et al., 2008), riblets (Hall & Joseph, 2000) and highly water-repellent walls (Watanabe et al., 2003), Taylor-Couette systems proved to be useful for drag reduction studies.

The focus of the present study is to use the Taylor-Couette system for studying the drag reducing ability of several commercial products that claim to reduce skin drag. This is done by torque measurements of turbulent Taylor-Couette flow (TC flow) under perfect counter-rotation of the cylinders with increasing shear Reynolds numbers. Furthermore, we investigated the torque contribution of the TC flow and the von Kármán flow in the TC system under turbulent flow conditions. The von Kármán flow (vK flow) is the flow in the gap between the ends of the inner and outer cylinder that creates extra torque and will be Reynolds dependent. In the near future, self-prepared coatings can be tested in the TC system for their drag reduction effect.

2. Experimental set-up

Torque measurements were performed at the Taylor-Couette setup of the Laboratory for Aero & Hydrodynamics in Delft University of Technology. This facility is identical to the setup used and reported by Ravelet et al. (2010) (Fig.1). The TC-system consists of two coaxial polymethylmethacrylate (PMMA) cylinders, which are driven independently by two DC-motors. The inner cylinder can be treated with various coatings and products. The radius of the inner and outer cylinders are \(r_i = 110 \pm 0.05\text{ mm}\) and \(r_o = 120 \pm 0.05\text{ mm}\) respectively. The Taylor-Couette gap between the cylinders is \(d = r_o - r_i = 10\text{ mm}\), which makes the gap ratio \(\eta = r_i/r_o = 0.917\). The length of the inner cylinder is \(L_{in} = 216\text{ mm}\). The system is closed at both ends, the top
and bottom end-plates rotating with the outer cylinder. The von Kármán gap between the ends of the cylinders is estimated from the system dimensions. The outer cylinder is 4 mm longer than the inner cylinder and it is suggested that the bottom and top gaps are both 2 mm.

Torque $T_{Tor}$ can be measured on the inner cylinder by a co-rotating torque meter on the inner cylinder shaft. The experiments are performed with the Rotation number at zero ($Ro = 0$), which means perfect counter-rotation ($r_i\omega_i = -r_o\omega_o$) (Dubrulle et al., 2005). During the experiments the counter-rotation is gradually increased up to a shear Reynolds number $Re_s$ of about $1.0 \times 10^5$. This is controlled by a LABVIEW program. The TC system is filled with water for this current study.

![Figure 1](image)

**Figure 1.** Left (a): Sketch with dimensions of the Taylor-Couette set-up (Ravelet et al., 2010). Right (b): Picture of Taylor-Couette set-up. At the top the torque meter on the inner cylinder shaft and above that the motor for the inner cylinder (*not on picture*). At the left the motor for the outer cylinder and at the right the infrared-thermometer.

The measured torque at higher rotation speeds leads to more friction and with that to frictional heating. A rise of liquid temperature will lead to reduction of the viscosity and results in less shear stress as well as a higher shear Reynolds number. However, we are unable to control the liquid temperature or measure the temperature during operation, as the Taylor-Couette facility is a closed system. Therefore we make use of an infrared-thermometer to measure the outside wall temperature. As the produced heat, room temperature and material properties are known, we can estimate the liquid temperature via heat transfer calculations. At the end of each experiment the liquid temperature is measured with a thermometer to verify the estimated liquid temperature. The end temperature of all experiments corresponds with the estimated end-temperature within $0.8^\circ$C. The liquid temperature is presumed to be uniformly as the flow is turbulent and therefore well-mixed.

Contact angle measurements were performed by drop shape analysis. The substrate samples are made of polymethylmethacrylate (PMMA), corresponding with the same material as the inner cylinder of the Taylor-Couette facility. Optical magnification is done by image recording using commercial software (DAVIS 7.2) and a LaVision camera (Imager Pro). Contact angles are determined by fitting liquid-solid-vapor interface lines and calculating the slope of the tangent to the droplet, which is done manually in MATLAB. Increasing and decreasing the volume of a droplet ($1\mu l/s$) gives the advancing and receding angle with the surface respectively. The difference between these two angles is called contact angle hysteresis and indicates the surface stickiness. Low hysteresis is desired for droplets to roll-off the surface easily.
3. Results

We study the turbulent Taylor-Couette flow in perfect counter-rotation, $r_i \omega_i = -r_o \omega_o$. The shear Reynolds number $Re_s$ is defined by Dubrulle et al. (2005) and given by:

$$Re_s = \frac{2\eta |Re_o - Re_i|}{1 + \eta}$$  \hspace{1cm} (1)

where

$$Re_o = \frac{r_o \omega_o d}{\nu}$$  \hspace{1cm} (2)

and

$$Re_i = \frac{r_i \omega_i d}{\nu}$$  \hspace{1cm} (3)

represents the outer and inner cylinder Reynolds numbers. Furthermore, $\omega_o$ and $\omega_i$ are the angular velocities of the outer and inner cylinder, $\nu$ the kinematic viscosity and $d$ the gap width ($r_o - r_i$).

The measured torques behave non-linearly with increasing shear Reynolds number $Re_s$, as expected for high turbulent flows. The total torque can be split up in a contribution of the Taylor-Couette flow ($\beta_{TC}$) and of the von Kármán flow ($\beta_{vK}$). To distinguish these contribution at several shear Reynolds numbers, we performed a linearisation method. This is done by torque measurements at three different water volumes (800ml, 1200ml and 1600ml). The measured torque is plotted against the corresponding volume for every shear Reynolds number (Fig.2).

![Figure 2. Linear plot of the measured torque vs. volume (800ml, 1200ml, 1600ml) for shear Reynolds number $Re_s = 0$ (bottom line) to $Re_s = 10.5 \times 10^4$ (top line).](image)

As $\Delta V = 2\pi (r_o^2 - r_i^2) \Delta L$, we can calculate the contribution of the TC-flow torque ($T_{TC}$) by $T_{TC} = \Delta T / \Delta L \cdot L_{in}$. The friction factor $C_f$ of the TC-gap is given by $C_f = T_{TC} / \left(2\pi \rho r_i^2 L_{in} U^2\right)$ with $U = Re_o \nu / d$. It is known that at high Reynolds numbers ($Re_s > 5 \cdot 10^3$) the friction factor scales with $C_f \propto Re^{-1/4}$ (Ravelet et al., 2010). In Figure 3 we plot the friction factor of the TC-gap $C_f$ vs. the shear Reynolds number $Re_s$. For $Re_s < 7 \cdot 10^4$ the friction factor $C_f$ scales according to the expected behaviour. We observed visually that for higher shear Reynolds numbers the water level is disturbed and mixed with air in the TC-gap. This was also seen in the results as additional torque. This implicates that air-bubbles has a drag increasing effect.

![Figure 3. Friction factor of the TC-gap $C_f$ vs. the shear Reynolds number $Re_s$.](image)
It is believed that the additional torque is caused by a rise in water level due to the air-bubbles, which means that $\Delta L$ is larger than presumed in advance ($\Delta L \propto \Delta V$). The results are corrected to the power-law behaviour $C_f \propto Re^{-1/4}$ for $Re_s > 7 \cdot 10^4$ (Fig.3).

We measure the total torque of the TC facility ($T_{Tot}$) when the TC system is completely filled with water; the experiments are done at the same shear Reynolds numbers. The extra torque caused by the von Kármán flow ($T_{vK}$) can now be determined by $T_{vK} = T_{Tot} - T_{TC}$. In Figure 4a, the torque contributions of the Taylor-Couette flow $\beta_{TC} = T_{TC}/T_{Tot}$ and the von Kármán flow $\beta_{vK} = T_{vK}/T_{Tot}$ vs the shear Reynolds number $Re_s$ is plotted. Figure 4b shows a similar profile for an air-water system, with the von Kármán flow only at the bottom end plates. The air-water interface experiments are studied for the influences of air on the drag reducing abilities of specific coatings and surfaces.

These torque contribution data $\beta_{TC}(Re_s)$, as shown in Figure 4, are used for the drag reduction experiments. The contribution of the von Kármán flow to the torque seems to be dominant for very low shear Reynolds numbers ($\beta_{vK} > \beta_{TC}$), but decreases when the shear Reynolds number rises. From $Re_s = 7 \cdot 10^4$ the TC flow contribution implicates to be limited to $\beta_{TC} = 0.74$ for case 1 (top- & bottom-gap von Kármán flow) and $\beta_{TC} = 0.82$ for case 2 (only bottom-gap von Kármán flow), but this is the effect of the correction which is made to match the scaling $C_f \propto Re^{-1/4}$. We further have to keep in mind that if $L_{in} \to \infty$, the von Kármán torque contribution $\beta_{vK}$ will be negligible and $\beta_{TC} \to 1$.

Commercial products are tested on their drag reduction effects. All products are commonly used in watersports or the automobile industry to keep surfaces clean and smooth. For each product a new inner cylinder was used to prevent errors in the torque measurements due to impurities of other products. The inner cylinders are treated with the commercial products by spraying and/or waxing. From the torque data we obtained $T_{TC} = T_{Tot} \cdot \beta_{TC}(Re_s)$, and consequently the friction factor $C_f$. In Figure 5-7 the friction ratio $C_{f,coat}/C_{f,uncoat}$ as a function of $Re_s$ for the three commercial products is presented.

No significant drag change is visible. We observe for the watersport products Starbrite and McLube a friction ratio $C_{f,coat}/C_{f,uncoat} < 1$, which means drag reduction, in the lower shear Reynolds number region. At this moment we are not sure if these results are correct due to
Figure 5. Friction ratio $C_{f,\text{coat}}/C_{f,\text{uncoat}}$ vs. $Re_s$ of Starbrite Marine Polish. Left (a): Only water. Right (b): Air-water interface.

Figure 6. Friction ratio $C_{f,\text{coat}}/C_{f,\text{uncoat}}$ vs. $Re_s$ of McLube Hullkote. Left (a): Only water. Right (b): Air-water interface.

Table 1. Static contact angles (CA) and contact angle hysteresis of commercial products.

| Product                  | Static CA (°) | CA hysteresis (°) |
|--------------------------|---------------|-------------------|
| PMMA (blanco)            | 74 ± 3        | 27 ± 6            |
| Starbrite Marine Polish  | 92 ± 2        | 43 ± 6            |
| McLube Hullkote          | 79 ± 4        | 33 ± 3            |
| ProVision RainClear      | 66 ± 3        | 28 ± 4            |

Uncertainties of torque measurements in the lower shear Reynolds region. The results of McLube (air-water, Fig.6b) show a jump in friction rate at around $Re_s = 5 \cdot 10^4 – 7 \cdot 10^4$, which is believed is the moment where formed air bubbles start to mix with the water. We suggest that the air-bubbles will stick to the surface of the inner cylinder and creates roughness that results to this friction jump. This occurs much less at higher shear Reynolds numbers, where the bubbles release much easier from the surface. This is not the case for the other products.
Table 1 represents the results of the contact angle measurements on the commercial products. The root-mean-square (rms) of the measured angles indicates the deviation of the contact angles at different spots on a surface. The values of the contact angles do not correspond with the properties of superhydrophobic/-philic surfaces; these products create just normal hydrophilic/hydrophobic characteristics. We notice a change in contact angles by treating the surfaces with a commercial product. Starbrite and McLube increase the static contact angle as well as the contact angle hysteresis, while ProVision RainClear decreases the contact angle and maintains the contact angle hysteresis.

4. Conclusion & perspectives

In this paper, we studied the drag reduction of commercial surface coating products in a turbulent Taylor-Couette flow under perfect counter-rotating conditions. First, we investigated the torque contribution of the Taylor-Couette flow and von Kármán flow at high shear Reynolds numbers $Re_s$. The torque contribution of the Taylor-Couette flow $\beta_{TC}$ is dependent on $Re_s$ and is limited to $\beta_{TC} = 0.74$ in a water-filled TC system and $\beta_{TC} = 0.82$ in an air-water TC system, for $Re_s = 7 \cdot 10^4$. Torque measurements show no significant drag reduction for the commercial products compared to the surfaces used by Balasubramanian et al. (2004), who reported reductions in the range of 10-20%. Further research is needed in the lower $Re_s$ ranges due to the torque measurement uncertainties and errors, as well in the higher $Re_s$ ranges due to the correction that had to be made for the air-disturbances at higher $Re_s$.

In order to confirm the magnitude of drag reduction in the Taylor-Couette facility, we are testing riblet foil attached on the inner cylinder as a drag reducing surface. Many experimental studies confirm a maximum 5% drag reduction with riblets of the type triangular cross-section, which occurs around $s^* = 15$ wall units (Bechert et al., 1997). Our future work involves the synthesis methods, characterization and friction-testing of superhydrophobic/philic and porous surfaces in the Taylor-Couette set-up.

Acknowledgments

This research makes part of the project "Drag Reduction in Watersports" and is supported by InnosportNL and DSM.
References

Balasubramanian, AK, Miller, AC & Rediniotis, OK 2004 Fluid dynamics-microstructured hydrophobic skin for hydrodynamic drag reduction. *AIAA Journal-American Institute of Aeronautics and Astronautics* 42 (2), 411–413.

Bechert, DW, Bruse, M., Hage, W., Van Der Hoeven, JGT & Hoppe, G. 1997 Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. *Journal of Fluid Mechanics* 338, 59–87.

Bonaccorso, E., Butt, H.J. & Craig, V.S.J. 2003 Surface roughness and hydrodynamic boundary slip of a newtonian fluid in a completely wetting system. *Physical review letters* 90 (14), 144501.

Borrero-Echeverry, D., Schatz, M.F. & Tagg, R. 2010 Transient turbulence in taylor-couette flow. *Physical Review E* 81 (2), 025301.

Byon, C., Nam, Y., Kim, S.J. & Ju, Y.S. 2010 Drag reduction in stokes flows over spheres with nanostructured superhydrophilic surfaces. *Journal of Applied Physics* 107 (6), 066102–066102.

Ceccio, S.L. 2010 Friction drag reduction of external flows with bubble and gas injection. *Annual Review of Fluid Mechanics* 42, 183–203.

Choi, C.H. & Kim, C.J. 2006 Large slip of aqueous liquid flow over a nanoengineered superhydrophobic surface. *Physical review letters* 96 (6), 66001.

De Gennes, P.G. 2002 On fluid/wall slippage. *Langmuir* 18 (9), 3413–3414.

Dubrulle, B., Dauchot, O., Daviaud, F., Longaretti, P.Y., Richard, D. & Zahn, J.P. 2005 Stability and turbulent transport in taylor–couette flow from analysis of experimental data. *Physics of Fluids* 17, 095103.

Elbing, B.R., Winkel, E.S., Lay, K.A., Ceccio, S.L., Dowling, D.R. & Perlin, M. 2008 Bubble-induced skin-friction drag reduction and the abrupt transition to air-layer drag reduction. *Journal of Fluid Mechanics* 612, 201–236.

Gutierrez-Torres, CC, Hassan, YA & Jimenez-Bernal, JA 2008 Turbulence structure modification and drag reduction by microbubble injections in a boundary layer channel flow. *Journal of Fluids Engineering* 130, 111304.

Hall, T. & Joseph, D. 2000 Rotating cylinder drag balance with application to riblets. *Experiments in fluids* 29 (3), 215–227.

Koeltzsch, K., Qi, Y., Brodkey, RS & Zakin, JL 2003 Drag reduction using surfactants in a rotating cylinder geometry. *Experiments in fluids* 34 (4), 515–530.

Latorre, R. 1997 Ship hull drag reduction using bottom air injection. *Ocean engineering* 24 (2), 161–175.

Latorre, R., Miller, A. & Philips, R. 2003 Micro-bubble resistance reduction on a model ses catamaran. *Ocean engineering* 30 (17), 2297–2309.

Madavan, NK, Deutsch, S. & Merkle, CL 1985 Measurements of local skin friction in a microbubble-modified turbulent boundary layer. *Journal of Fluid Mechanics* 156 (1), 237–256.

McCormick, M.E. & Bhattacharyya, R. 1973 Drag reduction of a submersible hull by electrolysis. *Naval Engineers Journal* 85 (2), 11–16.

Merkle, C.L. & Deutsch, S. 1992 Microbubble drag reduction in liquid turbulent boundary layers. *Applied Mechanics Reviews* 45, 103.
Murai, Y., Fukuda, H., Oishi, Y., Kodama, Y. & Yamamoto, F. 2007 Skin friction reduction by large air bubbles in a horizontal channel flow. *International Journal of Multiphase Flow* **33** (2), 147–163.

Neto, C., Craig, VSJ & Williams, DRM 2003 Evidence of shear-dependent boundary slip in newtonian liquids. *The European Physical Journal E: Soft Matter and Biological Physics* **12**, 71–74.

Neto, C., Evans, D.R., Bonaccurso, E., Butt, H.J. & Craig, V.S.J. 2005 Boundary slip in newtonian liquids: a review of experimental studies. *Reports on Progress in Physics* **68**, 2859.

Quéré, D. 2008 Wetting and roughness. *Annu. Rev. Mater. Res.* **38**, 71–99.

Ravelet, F., Delfos, R. & Westerweel, J. 2007 Experimental studies of turbulent taylor–couette flows. In *Proceedings of the 5th International Symposium on Turbulence and Shear Flow Phenomena, Munich*, p. 1211.

Ravelet, F., Delfos, R. & Westerweel, J. 2010 Influence of global rotation and reynolds number on the large-scale features of a turbulent taylor–couette flow. *Physics of Fluids* **22**, 055103.

Rothstein, J.P. 2010 Slip on superhydrophobic surfaces. *Annual Review of Fluid Mechanics* **42**, 89–109.

Sanders, W.C., Winkel, E.S., Dowling, D.R., Perlin, M. & Ceccio, S.L. 2006 Bubble friction drag reduction in a high-reynolds-number flat-plate turbulent boundary layer. *Journal of Fluid Mechanics* **552**, 353–380.

Sochi, T. 2011 Slip at fluid-solid interface. *Arxiv preprint arXiv:1101.4421*.

Sugiyama, K., Calzavarini, E. & Lohse, D. 2008 Microbubbly drag reduction in taylor–couette flow in the wavy vortex regime. *Journal of Fluid Mechanics* **608**, 21–41.

Taylor, G.I. 1923 Stability of a viscous liquid contained between two rotating cylinders. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* **223**, 289–343.

Virk, PS 1975 Drag reduction fundamentals. *AIChE Journal* **21** (4), 625–656.

Watanabe, K., Takayama, T., Ogata, S. & Isozaki, S. 2003 Flow between two coaxial rotating cylinders with a highly water-repellent wall. *AIChE Journal* **49** (8), 1956–1963.

Watanabe, K., Udagawa, Y. & Udagawa, H. 1999 Drag reduction of newtonian fluid in a circular pipe with a highly water-repellent wall. *Journal of Fluid Mechanics* **381**, 225–238.

White, C.M. & Mungal, M.G. 2008 Mechanics and prediction of turbulent drag reduction with polymer additives. *Annu. Rev. Fluid Mech.* **40**, 235–256.

Wu, S.J., Hsu, C.H. & Lin, T.T. 2007 Model test of the surface and submerged vehicles with the micro-bubble drag reduction. *Ocean Engineering* **34** (1), 83–93.

Zhang, X., Shi, F., Niu, J., Jiang, Y. & Wang, Z. 2008 Superhydrophobic surfaces: from structural control to functional application. *Journal of Materials Chemistry* **18** (6), 621–633.