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Rowing faster by surface treatment

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Abstract

The largest part of hydrodynamic drag during rowing, sailing or canoeing is the turbulent skin friction (80-90%). Higher velocities can be achieved by reducing the friction drag as a result of surface treatment. This research focuses on the development, characterization, and testing of drag-reducing surfaces, like nano- and micro-structured surfaces with hydrophobic or hydrophilic properties. This paper explains the Taylor-Couette set-up as a testing facility and discusses the first results in drag changes for several commercial products.

Keywords: Rowing; sailing; hydrodynamics; boundary layer; drag reduction

1. Introduction

The speed during a rowing race is determined by the balance between propulsive power delivered by the rower and the power losses. The propulsive power is a result of athlete aerobic and anaerobic condition, its maximum strength and training methods. The power losses are caused by inefficient rowing technique, low propulsive efficiency of the blade, and drag forces on the boat. This last aspect is for a large part determined by boat design. The shape of the boat has been redesigned several times over the last decennia, to achieve improved hydrodynamics and less wetted boat surface. Also, new generation materials were introduced to decrease the “dead weight” and to achieve high-performance equipment. However, at this moment, the shape of rowing boats is believed to have a near-optimal design, and further developments seem to stagnate a further reduction of drag.

A field that has not been studied extensively for sports is the interaction between boat and water. A lot of research on this phenomenon has been stimulated in recent years by commercial shipping industry, in order to obtain lower fuel consumption. The main resistance to the forward motion of a rowing boat is caused by skin drag, as hydrodynamic drag and wave drag only contribute for around 10-20% [1] at a typical flow condition for rowing (e.g., a Froude number around 0.2).

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The flow boundary layer between boat surface and water can be defined as highly turbulent. Turbulence in the boundary layer becomes stronger when the flow velocity (i.e., boat velocity) increases, which results in an increase of the associated friction. This turbulent friction leads to high energy losses of the propulsive power. Drag reduction leads to lower frictional losses in turbulent flows and results in lower energy losses of the propulsive power. This makes drag reduction technology an important aspect within fluid dynamics, not only for rowing boats but also for e.g. pipeline transports, process engineering, transport ships (professional and/or recreational), and naval combat ships.

2. Drag reduction methods

It is known that rough surfaces induce more turbulence and friction, and therefore it is preferred to have a smooth surface to maintain the turbulence to a minimum. However, several other methods are capable to restrain the turbulence and further reduce the friction of fluid over a surface.

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. Dissolving small quantities of long-chain flexible polymers into a solution result in drag reduction up to 80% [2]. Also, the injection of (micro)bubbles in channel flows reportedly result in drag reducing effects up to 35% [3].

For the application to ships, these drag reduction methods could lead to significant fuel savings. However, the practical implementation appears to be inefficient and complex. Polymer and air injection into a turbulent boundary layer never showed to be cost effective when applied to actual ships. Polymer concentrations have a continuous downstream decrease, and it thus demands complex injection apparatus to maintain the drag reducing abilities over a significant downstream distance [4]. Air bubbles or films shows similar practical problems. Due to coalescence or break up of air bubbles and films, it is difficult to maintain a constant and stable drag reducing performance [6].

A promising solution to reduce drag and to avoid complex injection methods is the use of specific drag reducing coatings. Much research has been dedicated to superhydrophobic and superhydrophilic surfaces [6,7], which are micron-scaled rough surfaces with a hydrophobic or hydrophilic character and which are inspired by surfaces in nature. Pearl-shaped water droplets are formed on a superhydrophobic surfaces, like droplets on a Lotus leaf. These droplets have contact angles up to 160-175^{o} for superhydrophobic surfaces and 5-15^{o} for superhydrophilic surfaces [8]. Significant darg reduction is shown in external flow experiments by Balasubramanian et al. [6]. They found around 20% drag reduction on flat plates and 10-14% drag reduction on submerged bodies.

Micro-structured surfaces must not be confused with riblet surfaces, which are better known as a “shark skins”; their scale and mechanism to reduce drag are very different. Riblets are small surface protrusions that are aligned in the flow direction [9]. They reduce drag by impeding 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 and are therefore too small to obtain a riblet effect. The drag reducing mechanism of superhydrophobic/philic surfaces is suggested to be the effect of wall slip, or so-called ”apparent boundary slip” [10,11].

The focus of the present study is to develop, characterize and test specific surfaces that can reduce the turbulent drag of water sport objects, such as rowing boats, sailing boats, kayaks, surfboards, and swimsuits. The first part of this research concerned the development and investigation of a testing facility, which is a Taylor-Couette system. Turbulent Taylor-Couette flow is the fluid motion between two co-axial cylinders, having characteristics very similar to a turbulent boundary layer as, for example, a rowing boat [12]. The second part consists of testing and studying several commercially available products that claim to provide drag reduction. In the future, self-developed surfaces will be characterized and tested on their drag reducing effect in the Taylor-Couette facility (lab) and in actual field tests (practice) with rowing and sailing boats.

3. Testing facility

To analyze the drag reducing effect of specific surfaces and products, the Taylor-Couette flow facility of the Laboratory for Aero- & Hydrodynamics at the Delft University of Technology is used as test set-up [12]. Taylor-Couette systems are very useful for drag reduction studies of surfactants, microbubbles, riblets and highly water-repellent walls [13-16].

The Taylor-Couette facility (Fig.1) consists of two co-axial polymethylmethacrylate (PMMA/Plexiglas) cylinders, which are driven independently by two motors. The inner cylinder can be treated with various coatings and products and has a radius r_i = 110±0.05 mm and length L_{in} = 216 mm. The outer cylinder has a radius r_o = 120±0.05 mm and length L_{out} = 220 mm. The Taylor-Couette gap between the cylinders is $d = r_o - r_i$ = 10 mm, so the gap ratio is $\eta = r_i/r_o$ = 0.917. The system is closed at both ends where the top and bottom end-plates are rotating with the outer cylinder. The total torque (T_{Tot}) is measured on the inner cylinder by a co-rotating torque meter on the inner cylinder shaft. For the current study the Taylor-Couette system was filled with water.

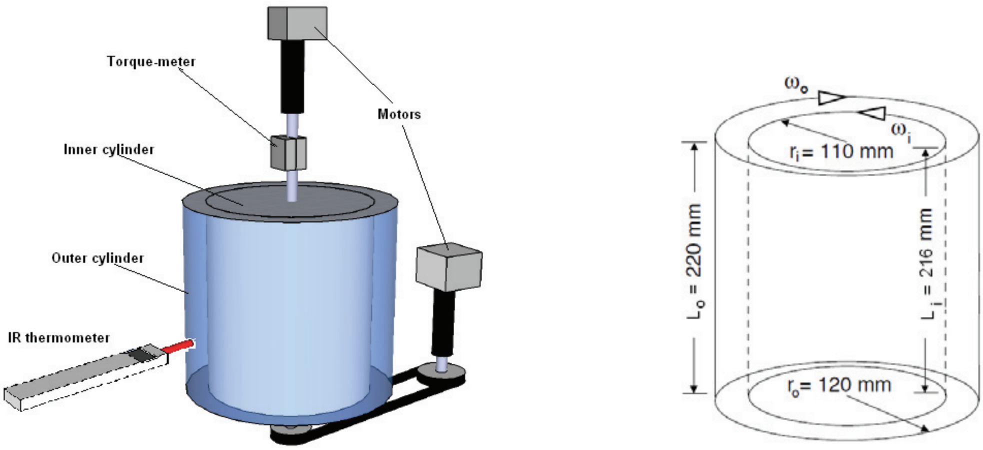


Fig. 1. (a) Schematic picture of the Taylor-Couette facility; (b) Schematic picture with dimensions. Ref [12]

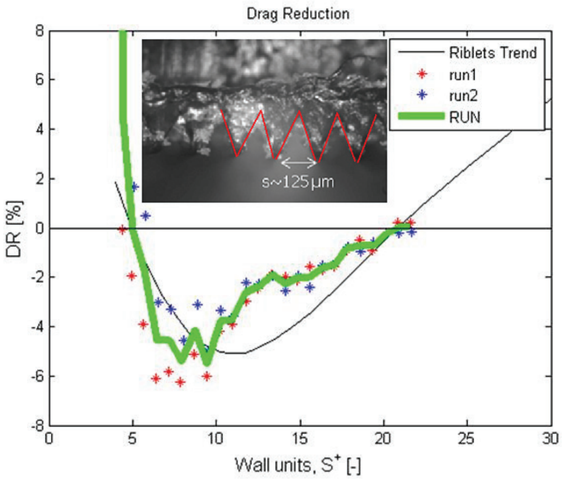
Traditional parameters [17] to describe the flow in the Taylor-Couette gap are inner and outer Reynolds numbers, $Re_i = r_i\omega_i d/v$ and $Re_o = r_o\omega_o d/v$, as well as the shear Reynolds number (Eq.1), with the inner cylinder rotating at a rotation rate ω_i, the outer cylinder at ω_o, and v the kinematic viscosity of water. During the measurements the two cylinders were rotating at the same velocity, but in opposite direction, which is called perfect counter-rotation ($r_i\omega_i = r_o\omega_o$). For perfect counter-rotation, Eq.1 can be simplified to $Re_s = 2 \cdot Re_o = -2 \cdot Re_i$. The counter-rotation was gradually increased up to a shear Reynolds number (Re_s) of 1.0×10^5, which corresponds to a relative flow velocity of 10 m/s. This is controlled by a LABVIEW program. The range of velocities and gap width correspond to typical velocities and boundary layer thickness, respectively, encountered in the water sports mentioned previously.

$$\mathrm{Re}_s = \frac{2\left|\eta\,\mathrm{Re}_o - \mathrm{Re}_i\right|}{1+\eta} \qquad (1)$$

4. Results

4.1. Facility validation by riblet drag measurements.

Many experimental studies [9] show a maximum of 5% drag reduction for a flow over a surface with riblets that have a triangular cross-section. In order to confirm the magnitude of drag reduction in the Taylor-Couette facility, riblet foil was attached on the inner cylinder surface. Figure 2 shows the percentage change in drag (Eq.2) versus the riblet spacing Reynolds number (Eq.3). The riblet spacing Reynolds number is an important parameter that makes the riblet spacing (s) dimensionless with the shear stress velocity at the wall, u_τ. It indicates how far the riblets protrude from the surface into the turbulent boundary layer. The inset in Figure 2 shows a picture of the triangular riblets with a riblet spacing of s = 125 μm. The shear stress velocity u_τ is given in Eq.4, where τ_w is the wall shear stress, T_{Tot} the total measured torque, ρ the density of water, r_i and L_i the inner cylinder radius and length, respectively.



$$DR = \frac{T_{Tot} - T_{Tot,0}}{T_{Tot,0}} \quad (2)$$

$$s^+ = \frac{s \cdot u_\tau}{\nu} \quad (3)$$

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} = \sqrt{\frac{T_{Tot}}{2\pi\rho r_i L_i r_i}} \quad (4)$$

Fig. 2. Drag reduction in Taylor-Couette facility by riblet foil with triangular cross-section, and a spacing s = 125μm (inset). Riblets trend (solid black line) found by Hall [15]

Figure 2 indicates a similar trend as was found in experiments reported by Hall [15]. The onset of drag reduction starts around riblet spacing Reynolds number s^+ = 5 and ends at s^+ = 22, and corresponds with Hall's data. The results are also qualitatively typical for riblet surfaces; at small s^+ the riblets are too small to influence the near-wall turbulence; at moderate values they are active in suppressing the spanwise turbulent velocity fluctuations. At even higher s^+ the surface gradually behaves more as a rough surface, creating even more turbulence [9]. Furthermore the maximum drag reduction of 5% equals the expected result. A small shift of the maximum (from s^+=11 to s^+=9) is attributed to differences in dimensions and the effect of curvature of the cylinders of the two different Taylor-Couette facilities. A riblet spacing Reynolds number s^+ = 10 corresponds with a shear Reynolds number Re_s= 26000. This is equivalent to a flow velocity of u = 2.6 m/s and is somewhat larger than the top speed encountered during an international swimming competition. The small amount of friction in combination with the limited precision of the torque-meter at low flow range, lead to the deviation of data points for s^+<10. This can be solved by replacing water by a more viscous working fluid and will be carried out in the coming months. The overall data shows that the Taylor-Couette facility is capable of predicting qualitative and quantitative drag reduction measurements.

4.2. Measurements of commercial products.

Several commercially available products were tested for their drag reducing effect. All products are commonly used in water sports, with the intention to keep surfaces clean and smooth or to achieve a lower surface friction. Further characteristics of the products cannot be given as confidentiality is at stake. Figure 3a-d show the results in drag reduction versus shear Reynolds number of four different products. As for the riblets experiment, the limited precision of the torque-meter makes the results at low flow range (Re_s<30000) to some extent questionable. At high flow ranges, a small change in drag is seen for Product 1 and 2. However, this is not significant as a 1% change is within the range of the measurement uncertainty. Products 3 and 4 show a larger change in drag at high flow velocities. Product 3 shows an increase in drag of 2-3%. As Product 3 is applied as a viscous liquid, it is suggested that Product 3 may induce an increase of friction due to a certain surface roughness on a perfectly smooth PMMA-surface. Product 4 shows a decrease in drag of 2-4%. The manufacturer of Product 4 claims that the coating consists of small nano-particles, which attach to the surface and is water-repellent, and therefore reduces the friction between water and surface. This seems to be plausible [6]. As with the riblet data, also these data will be validated in the coming months.

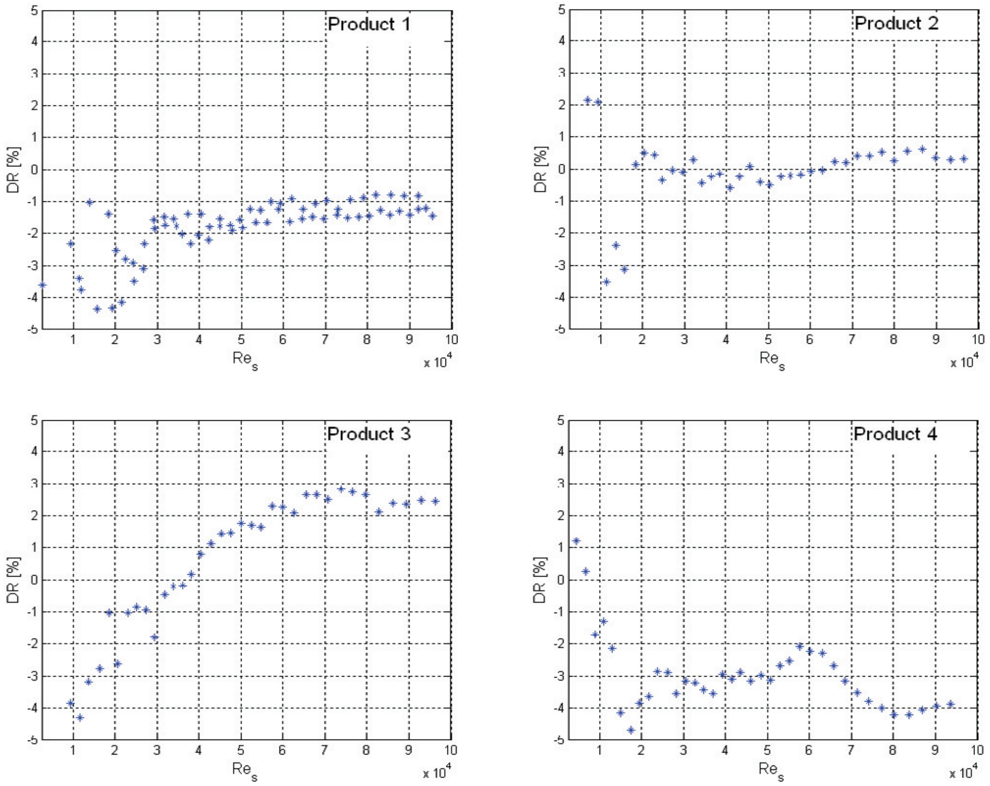


Fig. 3. Drag reduction of (a) product 1; (b) product 2; (c) product 3; (d) product 4

5. Conclusion & Future work

The Taylor-Couette testing facility of the Laboratory for Aero- & Hydrodynamics at the Delft University of Technology proved to be useful to analyze the drag reducing effect of specific surfaces and products. The data with riblets show a similar trend and a maximum of 5% drag reduction, as was found by Hall

[15]. This demonstrates the applicability of our testing facility to measure small variations in drag of around 1-5%. The accuracy of the results of drag reduction measurements at low flow ranges (Re_s<30000) will be improved in the coming months by working with a slightly more viscous working fluid. However, the results at higher flow ranges are very useful, as rowing and sailing competition also occurs at higher velocities (u > 3 m/s). Only one commercial product shows favorable results to reduce drag (Product 4), which can be attributed to the surface structure and character.

In the future, self-developed coatings will be characterized and tested on their drag reducing effect. Micro-structured surfaces with a hydrophobic/-philic character seem promising as surface treatment to go faster!

Acknowledgements

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