Frictional drag measurements of large-scale plates in an enhanced plane channel flowcell

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Frictional drag measurements of large-scale plates in an enhanced, plane channel, flowcell

This paper describes the design of an enhanced, plane channel, flowcell and its use for testing large-scale coated plates (0.6m x 0.22m) in fully developed flow, over a wide range of Reynolds numbers, with low uncertainty. Two identical, hydraulically smooth plates were experimentally tested. Uniform biofilms were grown on clean surfaces to test skin friction changes resulting from different biofilm thickness and densities. A velocity survey of the flowcell measurement section, using Laser Doppler Anemometry, showed a consistent velocity profile and low turbulence intensity in the central flow channel. The skin friction coefficient was experimentally determined using a pressure drop method. Results correlate closely to previously published regression data, particularly at higher speeds. Repeated measurements indicated very low uncertainty. This study demonstrates this flowcell's applicability for representing consistent frictional drag of ship hull surfaces, enabling comparability of hydrodynamic drag caused by surface roughness to the reference surface measurements.

Keywords: hydrodynamic drag, flowcell, turbulent flow channel, calibration, skin friction curves, biofouling

Introduction

A ship experiences skin friction drag due to water streaming along the submerged hull surface. This is principally a shear flow regime over most of the hull form. Therefore, the skin friction characteristics of the hull surface, mainly driven by its topology and roughness, affects the overall drag performance of the ship. Additionally, the roughness of a coated hull surface changes over time due to the effects of ageing, biofouling and damage. This can cause a significant increase in skin friction, which then detrimentally affects the speed-power performance of the ship (Townsin et al. 1981). By developing improved predictive methods to assess the skin friction of realistic hull surfaces, which is the subject of this paper, the performance of a ship coating system can be better evaluated in relation to the overall ship

performance. This enables the future development of better hull surface technologies and also aids with improving the operational efficiency of ships. The outcome is the development of a marine coating testing methodology that may serve to reduce fuel consumption, improve maintenance regimes and contribute to the mitigation of greenhouse gas emissions to the atmosphere (IMO 2009).

ISO 19030 was introduced to standardise the speed-power performance measurements to estimate true ship performance (ISO 19030). The latter represents the total ship resistance at the reference condition, which comprises clean hull, calm weather, without wind or waves, and steady-state straight motion of the ship at its design loading condition. The effect of different loading conditions and environmental parameters, as well as the hull surface conditions (roughness, biofouling), need to be measured in real-time and used to normalise the speed-power relationship to the calm weather condition. The accuracy of the true ship performance assessment, therefore, strongly depends on those in situ measurements, as well as reference data. As environmental parameters cause added resistance, reference data should be utilised to separate the added resistance from the measured data (Carchen et al. 2017).

Existing methodologies, given in ISO 15016:2015 (ISO 15016 2015), have been used to calculate the added resistance due to weather characteristics. However, the added (skin friction) resistance caused by hull roughness and its variation, normally due to inefficient coating performance from ageing and biofouling, is complex and often fails to include all the hydrodynamic aspects of the vessel (Carchen et al. 2017). The complexity of these hydrodynamic performance estimations stems from the fact that, ideally, both environmental conditions (wall shear stress and water properties) and the roughness of the surface topology (both clean and biofouled) need to be replicated (Flack and Schultz 2010). Mimicking authentic conditions in model-scale facilities can be particularly difficult.

A considerable amount of literature has been published on hydrodynamic performance of rough surfaces (Schultz and Myers 2003). The roughness function, defined as the skin friction difference between a smooth wall and rough wall, can be utilised to estimate skin friction resistance of a full-scale ship (Granville 1987). The roughness function can be indirectly estimated by measuring torque and resistance using either a rotating disk (Candries et al. 2003), Taylor-Couette (Greidanus et al. 2015; Benschop et al. 2018) and towing-tank flow facilities (Schultz 2004; Demirel et al. 2015). Previously, direct measurements of roughness functions of coated and biofouled surfaces were carried out in circulating water tunnels (Unal 2012; Yeginbayeva 2017). The relationship between smooth surface skin friction and mean flow velocity has been widely investigated in rectangular flow channels (Dean 1978; Zanoun et al. 2003; Monty 2005). Rectangular flow channels have recently gained popularity for hydrodynamic drag performance testing (Schultz et al. 2015; Gose et al. 2016; Yeginbayeva 2017; Li et al. 2018) since these facilities can reach high Reynolds numbers and develop fully turbulent flows over flat test surfaces. Therefore, flow channels are able to mimic the flow conditions experienced on ships' hulls.

Traditionally, skin friction data extrapolation relies heavily on the friction data of flat surfaces. After pioneering works of Davies and White (1928) and Laufer (1948), there have been numerous investigations into measuring the turbulence quantities in channel flows (Johansson and Alfredsson 1982; Willmarth and Velazquez 1983). Dean (1978) described the link between the main dimensions of the measurement section and the two-dimensionality of the channel. The aim of Dean's (1978) study was to determine the most suitable curve to describe the behaviour of the skin friction coefficient of a smooth surface with the Reynolds number variation. Both Dean (1978) and Zanoun et al. (2003) applied the power-law curve-fits to their smooth surface data in order to describe the change of skin friction within a wide range of Reynolds numbers (based on channel height and channel bulk velocity). Recently,

Schultz et al. (2015) and Gose et al. (2016) utilised a rectangular channel apparatus to determine the skin friction characteristics of biofilms on commercial coatings and specifically fabricated superhydrophobic surfaces. Channel flow facilities were also used by Gowing et al. (2018) to measure the drag of biofouled panels printed from laser scans of fouled ship hull sections. The panels tested included models of barnacles, oysters, and tubeworms, with different sizes and spatial distributions. Gowing et al. (2018) used uniform sand grains to model roughness effects of biofouling and to numerically predict the hull drag.

This paper provides the design and calibration of a modified rectangular flow channel, referred to as the flowcell. Flow field measurements to investigate the velocity profile and turbulent intensities in the channel flow are presented. The method for growing biofilm is described. The application of laboratory-grown biofilm on smooth flat surfaces is described and results of the skin friction resistance characteristics of clean smooth and fouled surfaces are presented in this paper.

Materials and methods

Rationale

This section presents the design and calibration of a plane flow channel operated at Newcastle University (UNEW). This was modified from an earlier setup designed to study adhesion tests and detachment characteristics of marine organisms on microscope slides (75mm x 25mm) in fully developed turbulent flow (Politis et al. 2009). New stainless steel test and contraction sections were installed in the existing flowcell circuit. Figure 1 (a) shows the general configuration of the modified flowcell with hydraulically smooth reference test panels placed in the measurement section. A very rigid frame was added to support the modified stainless

steel measurement section, providing a level and steady water channel as opposed to the previous acrylic measurement section. The measurement section was modified to accommodate larger-scale test panels (600mm x 220mm) whilst maintaining the same ability to test microscope slides using a specially designed insert shown in Figure 1 (b). The use of larger sized panels allowed the development of fully turbulent flow on the target surfaces.

[Figure 1 near here]

Figure 1. (a) The modified flowcell with two parallel smooth test panels installed in place for the calibration; (b) the microscopic slide adapter of the flowcell; (c) boundary layer measurements on the same surfaces using a special ‘high-speed insert’ set-up in the UNEW’s Emerson Cavitation tunnel and Laser Doppler Anemometry (LDA); (d) the moon pool strut: the dynamic biofilm growing equipment located on the research vessel ‘The Princess Royal’.

The panel size is compatible with different facilities. For instance, boundary layer measurements can be conducted on the same panel using a special set-up, high-speed insert, in the UNEW’s Emerson Cavitation tunnel and Laser Doppler Anemometry (LDA) as shown in Figure 1 (c) (Atlar and Seo 2011). In order to explore the effect of biofilm on coating performance, the standard sized panels can be attached to two devices, a slime farm (Yeginbayeva et al. 2015) and a strut arrangement on the research vessel (Atlar et al. 2015; Turkmen et al. 2016) (Figure 1 (d)). These unique devices effectively facilitate growing and collection of biofilms, on standard test panels, under authentic conditions.

Flowcell Apparatus

The flowcell apparatus has been adapted from a previous setup, which could only test drag on microscope slides. A new testing section with a corresponding sized contraction section was designed to be installed in the existing flowcell circuit. Figure 2 shows the layout of the new pressure drop measurement section and the arrangement of the test panels.

[Figure 2 near here]

Figure 2. Top view (top) and side view (bottom) of the new measurement section. The numbers given in millimetres represent the main dimensions of the flowcell. Indicated in red points are the lifting hooks for cranes for the installation of the flowcell, whereas green points indicate bolts and nuts.

A 2700 mm long (L) and 180 mm wide (W) stainless steel measurement section runs between the contraction section (contraction ratio=34.7:1) and the settling tank. Two identical UNEW standard test panels ($L=0.6$ m and $W=0.22$ m) can be placed at the top and bottom of the pressure drop section. This is important because the flow developed between two flat panels will be symmetrical with respect to the centreline of the channel under a constant pressure gradient (dp/dx) and zero gravity.

The channel height (H) of the rectangular measurement section is 10 mm. The panels sit on the sidewalls of the measurement section. This installation ensures that the distance between panel surfaces is the same as the channel height. The high aspect ratio ($W/H=18:1$) ensures that the channel flow is two-dimensional (Dean 1978, Zanoun et al. 2009). The length to height ratio ($L/H=270$) is much higher than the recommended channel length (Monty 2005).

The new pressure drop section has a 150-mm long glass window at one side that can be used to measure the velocity profiles over the test panels using Laser Doppler Velocimetry (LDV). There are four taps on the bottom wall and nine pressure taps on one of the sidewalls of the test section shown in Figure 3. These taps enable the collection of a wide range of pressure drop data using differential pressure transducers. An inspection hatch installed upstream is used for cleaning purposes and maintenance.

[Figure 3 near here]

Figure 3. Location of the side (S) and bottom (B) pressure taps. Crosshatching indicates the LDA window.

Pressure drop measurements were taken using differential pressure transmitters. Two XMD differential pressure transmitters (IMPRESS 2016) were installed for the range 0-75mbar and 0-500mbar with the accuracy of 0.1% to measure the static pressure differences (pressure drop) between two interchangeable pressure taps. The high range pressure transmitter also monitors the water temperature. The pressure drop data can be recorded with a sampling rate of 100Hz. A 15 kW pump (Apex Pumps, UK) provides a flow rate up to 80 l s⁻¹ at 8m of the head.

The data acquisition system (DAQ) was built based on a National Instruments CA-1000 platform to log both pump speed and the pressure drop values. An overview of the data logging system and measurement equipment for the pump speed and pressure drop is given in Figure 4.

[Figure 4 near here]

Figure 4. Experimental apparatus layout for main pump speed drive and pressure data logging.

Analogue signals simultaneously fed from the pressure transducers and the pump are converted into digital numeric values by the DAQ. Digital numeric values are visualised with LabVIEW software and stored in a table including pump speed and pressure readings.

Calibration of the measurement section

There were two main objectives of the calibration. The first was to determine a suitable curve

to describe the behaviour of skin friction, C_f , over a range of Reynolds numbers. The second objective was to examine the flow development by measuring velocity profiles using non-intrusive flow velocimetry at different locations. This measurement helps to observe whether the flow is uniform, turbulent, and fully developed. The flow components are further investigated to encounter any secondary flows in the corners of the rectangular duct.

The flow characteristics in the measurement section were captured using 2D Dantec Laser Doppler Velocimetry (LDV) system. The flowcell was filled with fresh water for the calibration, and the water was seeded with silver coated glass particles of 2-micron size. As can be seen in Figure 1 (a), the optical access to the measuring section was provided from the top of this section, where two smooth acrylic test panels were installed parallel to each other. The transparent panel at the top allowed the laser beams to penetrate so that the flow field could be measured at any required location of the narrow channel.

In the current study, PVC material was used to build the standard size panel for the pressure drop measurements. Previously acrylic has been used, but the stiffness of the acrylic material was found to cause fitting problems as the finishing process of the acrylic fabrication involves heat treatment, which might result in deformation on the panel surface and fluctuating panel thickness. Acrylic is also very sensitive to stress concentrations, which can lead to propagating a crack if the panel is overtightened. PVC is also a rigid but not very hard material (Harper 2002). These material properties make PVC fit better into the measurement section than acrylic.

The arithmetic mean of the roughness (R_a) or total height of the profile on the evaluation length (R_t) was measured to describe general surface roughness. The R_a and R_t values were measured as 0.72 μm and 6.99 μm for the acrylic reference surfaces and 1.6 μm and 13 μm for the PVC reference surfaces, respectively.

As shown in Figure 5 (left), the LDV probe with 500 mm focus length, and a traverse driving the LDV probe at any desired point(s), were controlled using BSA flow software (DANTEC DYNAMIC 2006). The incident beam from the laser source was separated into green ($\lambda = 514.5$ nm) and blue ($\lambda = 488$ nm) beams with a 40MHz frequency difference. Since the streamwise velocity was the most important parameter for flow characterisation, the laser beam arrangement was set to improve the accuracy in streamwise velocity readings by aligning the blue beam streamwise. The blue beam has a shorter wavelength than the green beam and hence generates smaller probe volume (height $\delta z=0.4$ mm, width $\delta x=0.05$ mm and length $\delta y=0.05$ mm) than the green beam ($\delta z=0.89$ mm, $\delta x=0.05$ mm and $\delta y=0.05$ mm).

[Figure 5 near here]

Figure 5. The LDV arrangement during calibration of the flowcell (left) and locations of flow measurement points along the pressure drop section (right).

The flow velocity components, streamwise (U) and spanwise (V), as well as their respective turbulence intensities, were taken at three streamwise (x) positions (Pos1, Pos2 and Pos3) with 150 mm intervals, and nine spanwise (y) positions with 22.5 mm intervals for each mentioned streamwise positions. The location of the measurement points is shown on the right side in Figure 5.

The pressure drop methodology

In order to obtain the wall shear stress, τ_w , the pressure drop per unit of length was divided by the distance between the pressure taps. The streamwise pressure gradient is used to determine the local wall shear stress as given in Equation 1.

$$\tau_w = -\frac{H}{2} \frac{dp}{dx} \quad (1)$$

where H is the channel height, dp is the pressure drop (or pressure difference) between two pressure taps and dx is the distance between two pressure taps used to measure the pressure differences. The friction velocity (u_τ) is introduced for the velocity scale as a function of the wall shear stress and density (see Equation 2):

$$u_\tau = \left(\frac{\tau_w}{\rho} \right)^{0.5} \quad (2)$$

where the water density ρ is taken as 998 kg/m³ (at 22°C). The friction coefficient (C_f) for a rectangular duct is defined as a function of the wall shear stress, bulk (mean) velocity ($\bar{U}$) and the density of the water:

$$C_f = \left(\frac{\tau_w}{0.5\rho\bar{U}^2} \right) \quad (3)$$

The skin friction coefficient C_f can also be obtained by combining Equation 2 and Equation 3 as follows in Equation 4:

$$C_f = 2 \left(\frac{u_\tau}{\bar{U}} \right)^2 \quad (4)$$

The Reynolds number based on H and $\bar{U}$ is denoted as Re_m in Equation 5:

$$Re_m = \frac{H\bar{U}}{\nu} \quad (5)$$

where ν is the kinematic viscosity of the water ($0.908 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$).

Biofilm growth methodology

Cultures of *Navicula incerta* were originally isolated from the beach at Llantwit Major, Wales, UK (Mieszkina et al. 2012). Cells of *N. incerta* were cultured to log phase in F/2 medium, in 250-ml conical flasks, at 20°C, in a 18:6 hour light:dark cycle, with a photosynthetic light intensity of $25 \mu\text{M m}^{-2} \text{s}^{-1}$ (Guillard and Ryther 1962). The biofilms were washed three times in filtered artificial seawater (ASW) (Tropic Marin), re-suspended in fresh ASW, and then filtered through 20 μm pore size nylon netting to remove clumps of cells, and to ensure that the resulting biofilm would have an even coverage of cells. The suspension was diluted with ASW to 0.5 L and a chlorophyll content of $0.25 \mu\text{g ml}^{-1}$. Chlorophyll a was measured using solvent extraction and the spectrophotometric equations of Jeffrey and Humphrey (1975). This suspension was further diluted by mixing with 10 L of half-strength F/2 medium made up in ASW in a plastic container. The test panels were then immersed in the container and cells allowed to settle on their surfaces. After 24 hours, the panels were moved to an illuminated 20°C culture room with 18h light-dark cycle and cultured for 10 days. An airstone was inserted into the container to maintain dissolved gases within the ASW. Two panels were exposed to different light intensities (25 and $15 \mu\text{M m}^{-2} \text{s}^{-1}$) producing biofilms of different cell densities and thicknesses.

After 10 days the cells were examined by fluorescence microscopy. Biofilms were either imaged directly on the panels or samples of biofilm were removed from the margins of the test panel and imaged on glass slides. The thickness of biofilm was gauged by the difference between focusing heights for the base and top edge of the biofilm. Panels with biofilms attached were secured in the frame of the flowcell and measurements were made of pressure drop between related ports.

Results

Flow field evaluation

Laser Doppler Anemometry (LDA) measurements, presented in [Figures 6, 7 and 8 near here]

Figure 6 to Figure 8 (top), show the streamwise velocity vector distribution at the three different longitudinal positions (Pos1, Pos2, and Pos3), overlapping with the mean U velocity vectors at these positions for the pump speed of 600, 1200 and 1600rpm. The U mean flow velocity distribution demonstrates the effect of the boundary layer development by comparing the plots at Pos1, Pos2, and Pos3. The sidewall effect on the flow field ceases at 10 to 12% of the total width. This implies that fully developed flow exists in the measurement section (Monty 2005).

The measurement section has a very long channel length and high width to height ratio to ensure the development of fully turbulent flow with a uniform character. A secondary flow development at the corners of the rectangular cross-section of the measurement channel is still possible. The velocity component in the spanwise direction is also presented from [Figures 6, 7 and 8 near here]

Figure 6 to Figure 8 (bottom part). Spanwise velocity is mainly caused by this secondary flow effect, which appears to be less than 5% of the mean U velocity. This suggests a uniform flow in the channel with a small disturbance caused by the secondary flow effect. Further details of the streamwise velocity profiles taken at the central line of the measurement section are shown in Supplementary Figure S1. Supplementary Fig S2 shows the streamwise velocity distribution between the sidewalls of the channel at half-height for seven pump speeds; the flow near the mid-span indicates a constant value for each corresponding pump speed.

[Figures 6, 7 and 8 near here]

Figure 6. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 600rpm (U_{max} 3.4 m s⁻¹ and U_{mean} 2.87 m s⁻¹).

Figure 7. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 1200rpm (U_{max} 7.75 m s⁻¹, U_{mean} 6.29 m s⁻¹).

Figure 8. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 1600rpm (U_{max} 10.16 m s⁻¹, U_{mean} 8.3 m s⁻¹).

The bulk flow speed (U_{mean}) at the pressure drop section was calculated from the streamwise velocity profiles measured at all points of the three cross-sections (i.e. Pos1, Pos2 and Pos3) as in Equation 6:

$$U_{mean} = \frac{\int U(y,z) dA_c}{A_c} \quad (6)$$

where, $U(y,z)$ is the streamwise velocity profile, A_c is the cross-section area. Determination of the bulk flow velocity in the channel based on velocity profiles is also recommended by Dean (1978) and discussed by Zauoun et al. (2009). The main pump speed, corresponding bulk flow speed and Reynolds number are given in Table 1.

[Table 1 near here]

Table 1. Pump speed, corresponding bulk flow speed and Reynolds number

Turbulence intensity is a measure of the root mean square of the local velocity fluctuations (U') relative to the mean or reference velocity and indicates the level of turbulence $\frac{\sqrt{U'^2}}{U}$. [Figure 9 near here]

Figure 9 shows the turbulence intensity distribution of the streamwise flow velocity component at pump speeds of 600rpm, 1200rpm and 1600rpm, from top to bottom at Pos 1. The turbulence intensity in the channel decreases moving away from the walls and shows similar patterns at each speed. Comparable turbulence intensity values, varying within a close range from wall to the centre of the channel, have been found in previous research (Laufer 1954; Klebanoff 1955).

[Figure 9 near here]

Figure 9. The axial turbulence intensity profiles at pump speeds of 600, 1200 and 1600rpm from top to bottom.

Skin friction coefficient

The differential pressure measurements were taken from the pressure taps S4-8 and S5-7. The wall shear stress was calculated based on the pressure drop measurement results (see Equation 1). C_f was calculated by utilising Equation 3. Analytical solutions of C_f exist for smooth surfaces, which were tested in rectangular cross-section flow channels based on the power-law (Dean 1978; Zanoun et al. 2003; Zanoun et al. 2009). In [Figure 10 near here]

Figure 10, the calculated C_f based on the measured pressure data of the current study is compared with the results of the Schultz and Flack (2013) measurements and the empirical formula of Zanoun et al. (2009). With the exception of the low Reynolds number range (i.e. $Re_m < 25000$), there is a good correlation between the C_f values obtained from the three

studies

[Figure 10 near here]

Figure 10. The comparative friction coefficient of test panels as a function of flow speed.

There are likely to be precision (random) and bias (fixed) errors. One of the potential sources of error is the channel height, which should be constant. Uneven height or step may occur when test panels are not fitted properly. This problem might cause a bias error in the measurement and lead to the incorrect calculation of wall shear stress and frictional resistance coefficient. If the target panels have a uniform surface topology, and the flow rate is constant, the wall shear stress value, which may be obtained from different pressure taps, should remain similar.

As the true value of C_f is unknown, it is recommended that the combined uncertainty (U_c) for C_f should be estimated as a combination of the bias and precision error with 95% confidence interval (Coleman and Steele 1999). The true value of C_f should lie within the interval ($C_f \pm U_c$). According to (Coleman and Steele 1999), U_c in C_f can be defined as follows:

$$U_c(C_f) = \frac{t\sigma_{cf}}{\sqrt{N}} \quad (7)$$

where σ_{cf} , t and N are standard uncertainty of C_f , the two-tailed value and the number of repeated experiments, respectively. In this study, ten replicate measurements were conducted for the whole range of Reynolds number ($17000 < Re_m < 83000$) and t was 2.262 for a required 95% confidence interval (Coleman and Steele 1999). The overall uncertainty in C_f varies between $\pm 0.5\%$ and $\pm 0.8\%$.

A previous study by Li et al. (2018), using the new measurement section, reported that the total uncertainty in C_f ranged up to $\pm 5.1\%$ at the low Reynolds number and $\pm 1.9\%$ at the high Reynolds number. The main difference between the current study and the study by Li et al. (2018) is the material of the standard uncoated panel. Li et al. (2018) used a cast acrylic panel for evaluating the reference C_f , which may have resulted in fitting problems as commented on in *Calibration of the measurement section*. The lower uncertainty results in the current study compared to Li et al.'s study (2018) confirm that there may be a differing effect of acrylic and PVC standard panels regarding the uncertainty.

Fouling effect

Two clean uncoated PVC panels, with biofilms of different thickness, were obtained as described in *Biofilm growth methodology*. The thicker biofilm (Diatom 1), cultured at the highest light intensity, had a maximum height of approximately 1.1 mm. The cell density of thick biofilms is difficult to assess accurately, but counts indicated that it was in excess of $40,000 \text{ mm}^{-2}$. In contrast, the thinner biofilm (Diatom 2) was less than $100 \mu\text{m}$ in height with a cell density of approximately $2,000 \text{ mm}^{-2}$.

The flowcell was utilised to measure fouling effects on hydrodynamic drag performance of the smooth surface. The uniformly fouled panels installed in the flowcell are shown in Supplementary Figures S3, and S4. Skin friction coefficient results presented in Supplementary Figure S5, indicate that the fouling coverage, height and density on the smooth surface had an effect on the skin friction coefficient. Diatom 1 increased ΔC_f from 15% to 30% over the range of Re_m , whereas Diatom 2 increased in skin friction coefficient ΔC_f from 1% to 7%.

Conclusions

This study set out to modify, calibrate and validate a new pressure drop measurement section for a flowcell. LDA measurements were taken to investigate the velocity profile in the channel flow. Turbulent intensities and bulk velocities were obtained from measured velocity components and related to pump speed. The pressure drop methodology was used to calculate the hydrodynamic performance (eg skin friction characteristics) of the clean, smooth, flat surface and biofilm-covered test panels.

Based on the LDA measurements, streamwise velocity distribution in the flowcell displayed the boundary layer at all three cross-sections (Pos1, Pos2 and Pos3). The investigation of the flow field showed that regardless of Reynolds number, there was little effect on the central flow region due to the sidewall. The streamwise mean velocity profiles were no longer growing and maintaining an equilibrium state, which means the flow condition was fully developed turbulent flow. Turbulence intensity calculations indicated a low level of turbulence. The lateral velocity component, mainly caused by this secondary flow effect, appeared to be less than 5% of the streamwise velocity. This condition leads to uniform flow in the channel with a small contribution due to the secondary flow effect.

The enhanced flowcell meets the essential requirements for the fully developed two-dimensional turbulent flow in the channel measurement section. The flow speed was 10.2 m s^{-1} at the centre of the flowcell and the bulk velocity was 8.3 m s^{-1} at the maximum pump speed. Uncertainty analysis showed a minimal combined bias and precision error, which indicated good pressure drop measurement accuracy. For $Re_m < 25000$ (based on the channel height and mean velocity), the skin friction measured in this study differed by 6-7% compared to previous studies (Schultz and Flack, 2013; Zanon et al. 2009) for the smooth panel. However, a very good agreement was observed for $Re_m > 25000$. This suggests the new

measurement section can be utilised to investigate hydrodynamic drag performance of flat surfaces, with coatings of differing roughness and/or with biofouling.

In this study, the effect of the smooth reference surface on the mean velocity profile and skin friction coefficient are presented. Despite the promising results for the smooth surface, it is suggested that the limiting roughness height needs to be investigated in future studies. A critical roughness height might influence the wall-bounded shear flow by generating bluff body wakes. Further research with more focus on the roughness-induced perturbation to mean velocity profiles and wall shear stress for high roughness is therefore also recommended.

The capability of the flowcell to measure the skin friction characteristics of the panels with *N. incerta* biofilms of different cell density and thickness was successfully demonstrated. The biofilm was uniform across the panels forming a largely unbroken film, with only a few bare patches in between. The pressure drop tests showed a proportional relationship between the thickness and density of the biofilm and skin friction magnitude relative to each other, as well as relative to the smooth reference surface. Measurements applied to natural, multispecies biofilms, which likely differ in their biomechanical properties, will be the subject of future studies.

Currently, the Computational Fluid Dynamics (CFD) methods have become very powerful in simulating the full-scale ship performance at sea but still struggle to represent the actual hull and propeller surfaces including the effect of biofouling. Within this context, the hydrodynamic roughness characteristics on the surface (i.e. skin friction and hence roughness function) are the only meaningful and practical input to these methods, that can be obtained from the tests with the flowcell facilities as described in this paper, to simulate the effect of different coatings and biofouling on the full-scale performance of ships (eg Demirel 2015; Song et al. 2019; 2020).

Climate change mitigation, by significantly reducing emissions from international shipping, needs to be the main incentive for future investments in research and development of environmentally friendly and fuel-efficient fouling-control technologies with very low skin friction. These technologies must be tested in a controlled environment to improve accuracy between the *in situ* and prototypical performance. In this sense, the measurement section of the modified flowcell caters for efficient measurements of hydrodynamic drag characteristics of the marine coating under realistic flow conditions, mimicking authentic conditions regarding full-scale ship operations.

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Disclosure statement

The authors declare no conflict of interest.

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Figure 11. (a) The modified flowcell with two parallel smooth test panels installed in place for the calibration; (b) The microscopic slide adapter of the flowcell; (c) Boundary Layer measurements on the same surfaces using a special set-up 'high-speed insert' in the UNEW's Emerson Cavitation tunnel and Laser Doppler Anemometry (LDA); (d) The moon pool strut: dynamically, a biofilm growing equipment of the research vessel 'The Princess Royal'.

Figure 12. Top view (top) and side view (bottom) of the new measurement section. The numbers given in millimetres represent the main dimensions of the flowcell. Indicated in red points are the lifting hooks for cranes for the installation of the flowcell, whereas green points indicate bolts and nuts.

Figure 13. Location of the side (S) and bottom (B) pressure taps. Crosshatching indicates the LDA window.

Figure 14. Experimental apparatus layout for main pump speed drive and pressure data logging.

Figure 15. The LDV arrangement during calibration of the flowcell (left) and locations of flow measurement points along the pressure drop section (right).

Figure 16. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 600rpm (U_{max} 3.4 m s^{-1} and U_{mean} 2.87 m s^{-1}).

Figure 17. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 1200rpm (U_{max} 7.75 m s⁻¹, U_{mean} 6.29 m s⁻¹).

Figure 18. The development of the streamwise (top) and spanwise (bottom) velocity between target panels at a pump speed of 1600rpm (U_{max} 10.16 m s⁻¹, U_{mean} 8.3 m s⁻¹).

Figure 19. The axial turbulence intensity profiles at pump speeds of 600, 1200 and 1600rpm from top to bottom.

Figure 20. The comparative friction coefficient of test panels as a function of flow speed.

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Table 2. Pump speed, corresponding bulk flow speed and Reynolds number.

Pump Speed (rpm)	U_{mean} (m s ⁻¹)	Re_m
408	1.62	16516
614	2.87	29259
816	4.01	40882
1017	5.17	52708
1221	6.29	64126
1426	7.45	75952
1578	8.3	84618

Supplemental material

Supplementary Fig S1. The streamwise velocity distribution between the reference parallel surfaces of the channel for seven pump speeds.

Supplementary Fig S2. The streamwise velocity distribution between the channel's side walls at half-height for seven pump speeds.

Supplementary Fig S3. The fouled surface with Diatom 1 installed in the flowcell.

Supplementary Fig S4. The fouled surface with Diatom 2 installed in the flowcell.

Supplementary Fig S5. Frictional resistant coefficients of fouled surfaces and the clean surface.