Hidrodinamik Sürtünme Direncinin Araştırılmasında Kullanılacak Deneysel Bir Yöntemin Geliştirilmesi

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Özet

Newcastle Üniversitesi (UNEW) hali hazırda çalışan kapalı çevrim su kanalını geliştirdi. Yeni ölçüm bölümü kaplanmış standart bir test panel yüzeyi (boy x en x kalınlık ölçüler 0.6m x 0.22m x 0.015m) boyunca basınç azalışını (dolayısıyla sürtünme direncini) ölçmeye yarar. Panel hem temiz hem de hafif yosunlanmış olarak test edilebilir. Basınç değişimine bağlı olarak, test edilen yüzeyin sürtünme direnç katsayıları hesaplandı ve sonuçlar kabul edilmiş yöntemlerle karşılaştırılarak basınç azalım yöntemi değerlendirilmiştir.

Bu çalışmada, su kanalının tasarımı ve kalibrasyonu sunulmuş ve kaplamış üç farklı yüzeyin sürtünme dirençleri tam gelişmiş türbülanslı akımda incelenmiştir.

Anahtar Kelimeler: Sürtünme direnci, su kanalı, biyolojik kirlilik pürüzlülüğü

Development an Experimental Method to Investigate Hydrodynamic Drag

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Abstract

Newcastle University's (UNEW's) enhanced the test section of their existing flow-cell facility. New measurement section is to measure the pressure drop (and hence frictional drag) across coated surface of a standard flat test panel (of Length x Width x Thickness: 0.6m x 0.22m x 0.015m in size). The panel can be tested as cleanly coated as well as exposed to light biofilm growth. Based on pressure gradients the calculated skin friction coefficients of these surfaces were compared with the results of the measurements obtained by other well-established methods to predict the skin friction, i.e. measuring boundary layer of the same surfaces using a Laser Doppler Velocimetry (LDV) system in the UNEW's Emerson Cavitation Tunnel (ECT), to evaluate the pressure drop methodology.

This paper presents design and calibration of the flowcell to investigate skin-friction of three different surfaces coatings in a fully developed turbulent flow.

Keywords: Drag, flowcell, biofouling, roughness

1. Introduction

When a sailing ship's submerged part of the hull is concerned, one of the main parameters affects the total resistant is frictional resistance, beside wave-making resistance. Frictional resistance is caused by normal and tangential components of the viscous flow. The normal component of the viscous resistance is affected by the hull shape and it is called form factor in the literature. The tangential component of the viscous resistance (shear stress) is parallel to ship's hull and causes a net force opposing the motion. This phenomenon is also called skin friction (Harvald Sv 1983).

Ships are paying the big economic penalty due to marine biological fouling on their hull. For instance, skin friction can increase 30-40%, depends on the light or hard fouling that lead to consume more fuel or reduce the operation speed (Woods Hole Oceanographic Institution (WHOI) 1952, Townsin 2003, Banerjee, Pangule et al. 2011, Schultz et al. 2011). In fact, increasing fuel consumption causes further trouble as the vessel is not able to satisfy the mandatory regulations for carbon emission of ships e.g. Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

Marine coatings are essential to prevent biofouling development on ships. Self-Polishing Co-Polymer (SPC) and Foul Release (also called non-stick, low surface energy) silicone elastomer are the most common antifouling coatings since Tributyltin (TBT) was completely banned from application in 2003. The effectiveness of the coated hull surface can be differed due to being hydraulically rough and aging as well as fouling. The development of test methodologies for the evaluation of the hydrodynamic performance of fouling control coating is particularly complex. There are several established methods to assess the hydrodynamic performance of a rough and biofilmed surface (Candries 2001, Politis, Atlar et al. 2013). This development has to be designed in such a way to replicate/mimic the physical and environmental conditions that the coating will experience when applied on the surface of the hull of a ship. The most common techniques are flume, circulating water tunnel, towing tank, axy-symmetrical slender body, rotating disk and drum Taylor-Couette flow facility. Among of them rectangular flow channels, generally known as flume (or flowcell), a fast and economical method to test such coatings is a turbulent sea water flow channel.

Newcastle University enhanced the pressure drop flume by replacing its measuring section with a sophisticated pressure drop facility to assess skin friction characteristic of a standard test panel (of Length x Width x Thickness: 0.6m x 0.22m x 0.015m in size) allows easy transportation. The dimension of the panels was chosen to be compatible with different facilities of Newcastle University, i.e. the Cavitation Tunnel, Flowcell, coating aging flume, slime farm and strut arrangement of the RV Princess Royal (Politis, Atlar et al. 2013).

The test panels containing the biofilm samples can be transferred to the UNEW testing facilities in the shortest time in wet containers for hydrodynamic testing when the required amount of biofilms are collected. Therefore, clean and biofouled flat panels can be tested to measure their skin friction in fully turbulent flows by modern experimental facilities is more robust and attractive.

The main purpose of this state of the art device is to investigate skin friction characteristics of flat test panels which can be non-coated or coated as well as they can be in clean or subjected to biofilm in seawater condition. Design and calibration process of the Flowcell were presented in the paper. Further tests were conducted to investigate skin friction of three surfaces coatings, with different roughness profile. Results were given to correlate roughness and hydrodynamic drag performance evaluated by the Flowcell.

2. The flowcell and experimental apparatus

2.1. The UNEW's flowcell

Figure 1 shows the layout of the new pressure drop measurement section of this facility and test panels arrangement. As shown in Figure 1 the measurement section is made of stainless steel with a 2.7 m length and installed between a contraction section with a contraction (cross-sectional area) ratio of 34.7:1 and the settling tank. Two identical test panels can be placed at the top and bottom of the pressured drop section. The rectangular measurement section has 10mm channel height (H) and 180mm width

(W) shows a ratio W/H=18:1. This high aspect ratio ensures the channel flow is two-dimensional (Dean 1978, Zanoun, Nagib et al. 2009). Length to height ratio is 270 that is much higher than recommended channel length for fully developed turbulent flow (Monty 2005). The panel surfaces are flush with the inner walls of the testing section to ensure the channel height remains the same.

Figure 2 shows a picture of this new stainless steel test section installed on the existing flowcell circuit with the new contraction section. A very rigid frame (in blue colors) supports the heavy stainless steel section which provides much rigid, level, steady and quite water channel as opposed to the old, uneven and cracking acrylic measuring section that was at the end of its working life.

The new pressure drop section has a 150 mm long glass window at one side that can be used to measure the flow velocity profiles between the test panels using LDV or other optical devices (e.g. PIV). There are four pressure taps on the bottom wall and nine pressure taps on one of the side walls of the test section that enable to collect a wide range of pressure drop data using differential pressure transducers. An inspection hatch, which is the replica of the hatch for housing the test panels, is also installed in upstream of the latter hatch, for cleaning and maintaining purposes

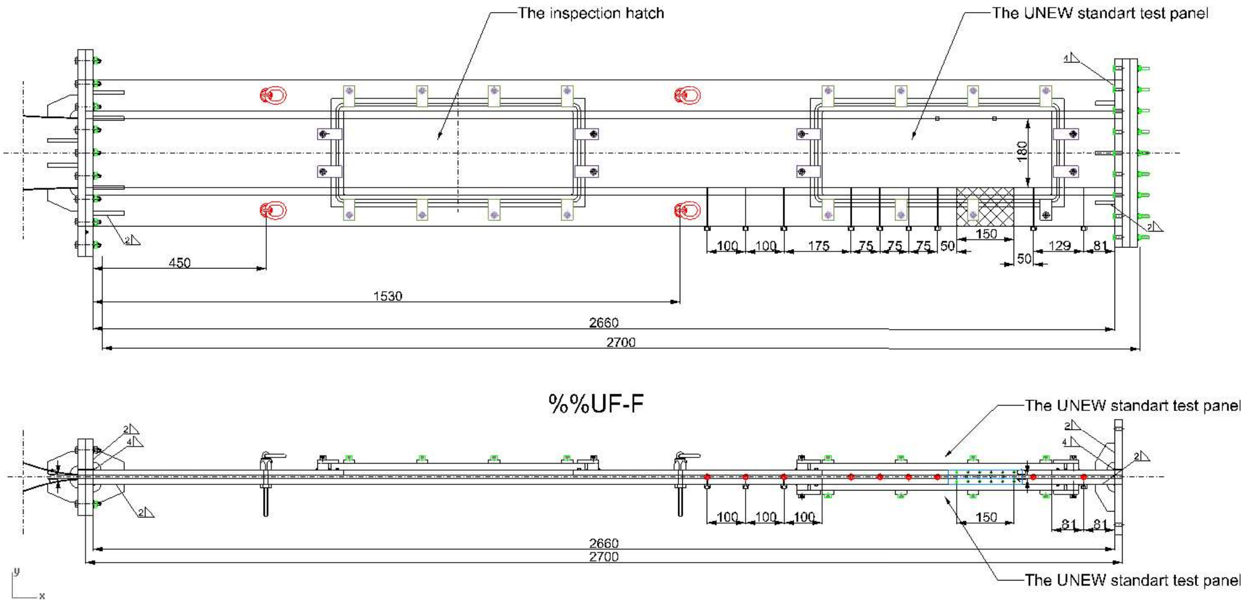

Fig. 1. Pressure drop section with contraction (inlet) and discharge (outlet)

Fig. 2. A view of new test section of the UNEW Flow Cell

2.2. Measuring equipment

Pressure drop measurements are taken by using differential pressure transmitters (transducers) with different pressure ranges. The water temperature is monitored during the tests to avoid extreme temperature rise. The inflow speed measured in the test section is presented as a function of the pump speed. In fact, the calibration curves mentioned in Section 3.1 were represented in this manner. A data acquisition system (DAQ) is used to log both pump speed and the pressure drop values.

Flowcell has a 15kW pump which can provide flow rate up to 300l/s. In practice, the user relates the channel inflow speed to the pump speed as stated inthe calibration curve.

Differential type pressure sensors are used to measure the pressure differences (pressure drop) between interchangeable two pressure taps. The range of the pressure drop was defined by computational fluid dynamic calculation. Two XMD differential pressure transmitters were installed for the range 0-75mbar and 0-500mbar with the accuracy of 0.1%. The pressure drop data was also recorded with a sampling rate of 10Hz. An overview of the data logging system and measurement equipment for the pump speed and pressure drop is given in Figure 3.

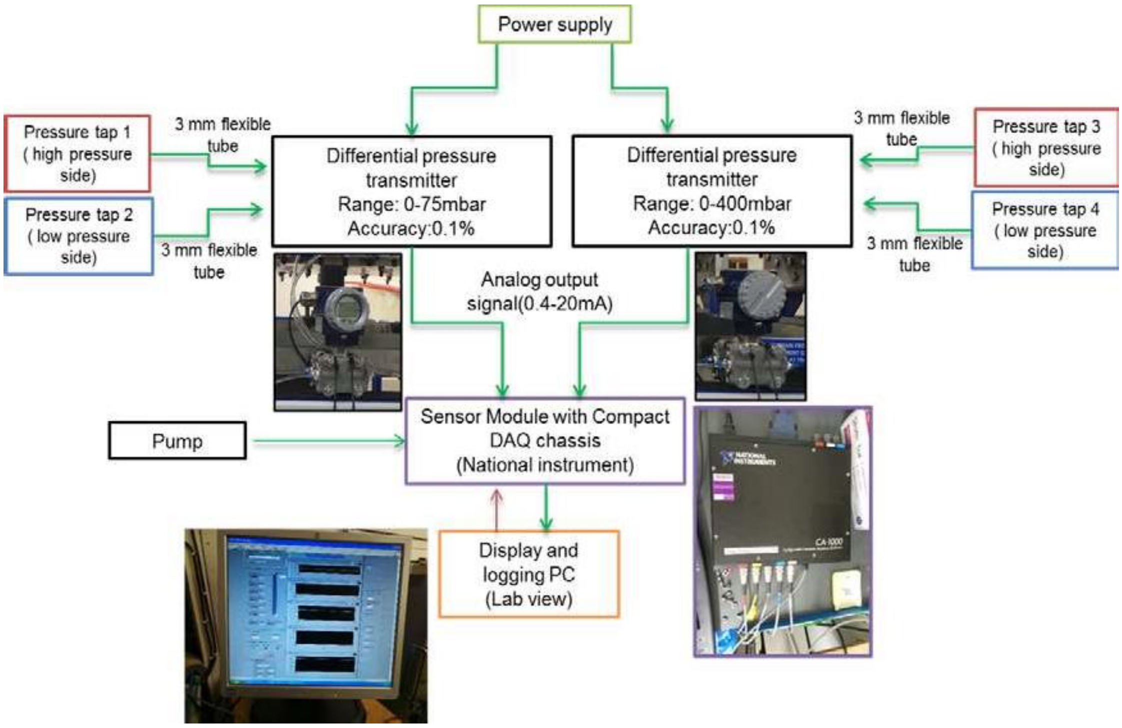

Fig. 3. Experimental apparatus layout for main pump speed drive and pressure data logging.

2.3. Calibration

There are two main objectives of the calibrations. The first is to relate the flow details (i.e. flow velocity and turbulence components as well as the pressure drop) over the reference smooth surface at the measuring section to the entire range of the main pump speeds since the pump speed is the most practical driver for the flowcell user.

It is expected from a flume that can generate fully develop turbulence flow over the panels. This is possible when the measurement section is long enough. Although dimension of the standard panel is significantly bigger than former test panels (75mm x 25 mm, microscopic slides) flow field was measured at different cross section along the measurement section. Therefore, the second objective of the calibration is to prove fully developed turbulence flow is generated in the measurement section.

Hydrodynamic characteristics of the flow in the measurement section were captured by using 2D Dantec Laser Doppler Velocimetry (LDV) system. Although there are other flow measurement devices (e.g. pitot tubes, hot wire anemometry, ultrasonic devices) the LDV system has the biggest advantage of being a non-intrusive device as well as taking time-dependent point measurements at any specific point. The flowcell was filled with fresh water for the calibration and the water was seeded for the LDV with silver coated glass particles of 2-micron size.

LDV measurements were taken at three longitudinally selected frames with 150 mm intervals and at nine transverse positions with 22.5mm intervals. Figure 5 shows the LDV probe (500 mm focus length) and traverse that drives the LDV probe at any desired point(s) using a computer control with a great accuracy and efficiency. During the calibrations, the traverse was located next to the measurement section for easy reach. The flow velocity components, streamwise (U) and transverse (V), as well as their respective turbulence intensities were measured at these points. The location of the measurement points is demonstrated in Figure 4.

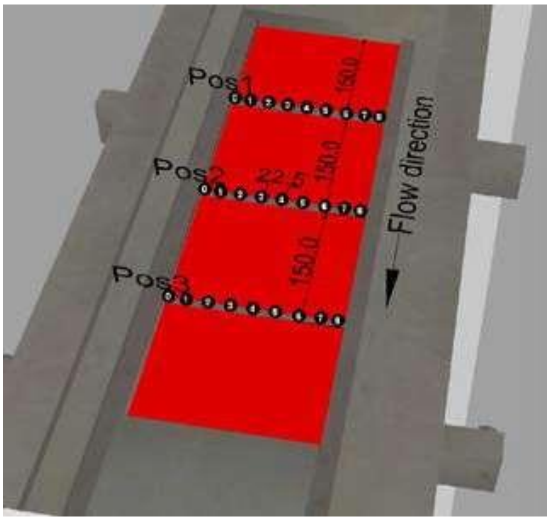

Fig. 4. Locations of flow measurement points along the pressure drop section

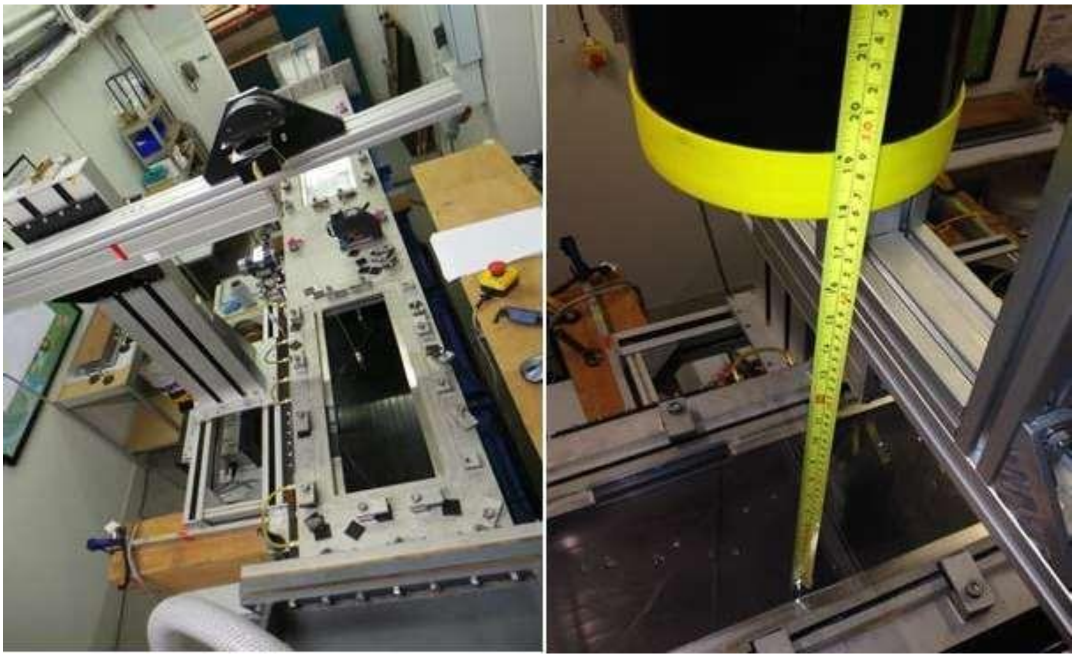

Fig. 5. Traverse arrangement of LDV during calibrations

Monty (2005) stated that a study comparing turbulence statistics at a number of streamwise stations is necessary to determine the point of full development. Figure 6 presents the flow speed in streamwise (U) and transverse (V) direction, respectively, for the pump speed of 600rpm. Whereas Figure 7 shows the streamwise (U) velocity vector distribution in a vertical and transverse direction at the three different longitudinal positions (Pos1, Pos2 and Pos3) overlapping with the mean U velocities at these positions. Calibration tests showed that the new test section can effectively develop fully turbulent flow at the pressure drop measurement section.

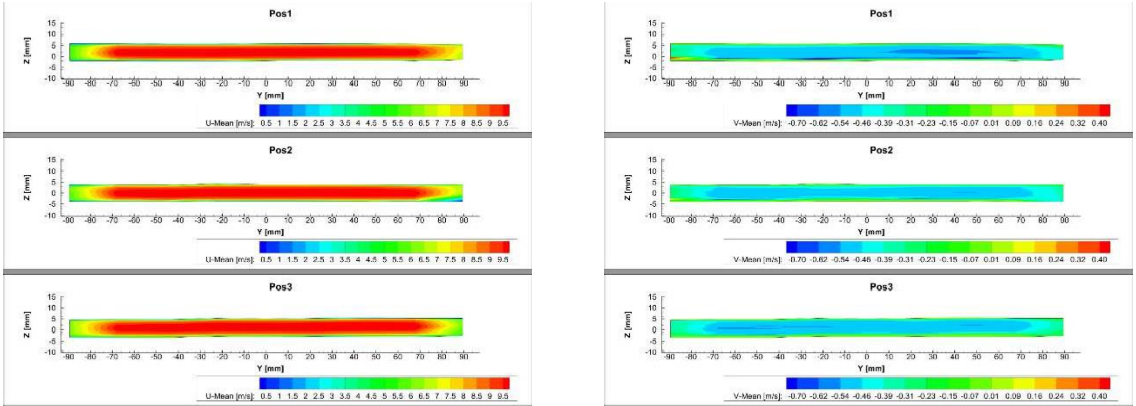

Fig. 6. The flow speed in U (right) and V (left) axis at pump speed of 1600rpm

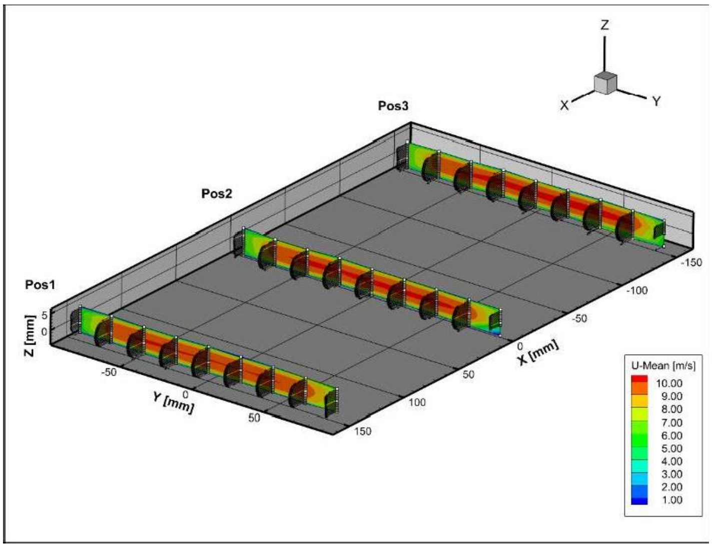

Fig. 7. The development of the velocity boundary layer between target plates at pump speed of 1600rpm

3. The pressure drop methodology

In order to obtain the static pressure gradient $\frac{dp}{dx}$ (ratio of the pressure drop per unit of length), the pressure drop (i.e. p1-p2) is divided by observation length l (distance between the taps in the side of the channel). The relationship between the wall shear stress (τ_w) and the static pressure gradient may be obtained by Equation 1 (Nikuradse 1933).

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

where H is the channel height, dp is the pressure difference between two pressure taps and dx is the distance between the two pressure taps used to measure the pressure differences. The friction velocity u is introduced as a function of the wall shear stress and density.

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

where, the water density ρ is taken as 998 kg/m3 (at the temperature 20°C). The friction coefficient Cf for a rectangular duct is defined as a function of the wall shear stress, bulk (mean) velocity $\bar{U}$ and the density of the fluid:

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

The skin friction coefficient Cf can be rewritten from Equation 2 and Equation 3 as:

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

The Reynold's number can be also described based on the full height (H) of the measurement section and bulk mean velocity $\bar{u}$ (or mean velocity):

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

where ν is the kinematic viscosity of the water (1.004x10^{-6} m^2/s).

3.1. Description of test surfaces

For the evaluation of the pressure drop methodology the pressure drop data were measured over three different surfaces described as follows:

1. Hydrodynamically smooth, clean acrylic panel, which is referred as "Reference" surface (indicated as "Surface A" in presentations)

2. Clean, newly applied Foul Release (FR) coated panel to represent low to medium range rough surface (Indicated as "Surface B" in presentations);

3. Clean, newly applied Self Polishing Copolymer (SPC) coated panel with introduced extra roughness to represent a rough surface (indicated as "Surface C" in presentations).

The three surfaces each in two replicates of the UNEW test panels were placed onto the flowcell pressure drop section for the calibration as shown Figure 8: top panel on the left (replicate 1 of Surface A); bottom panel on the right (replicate 2 of Surface A).

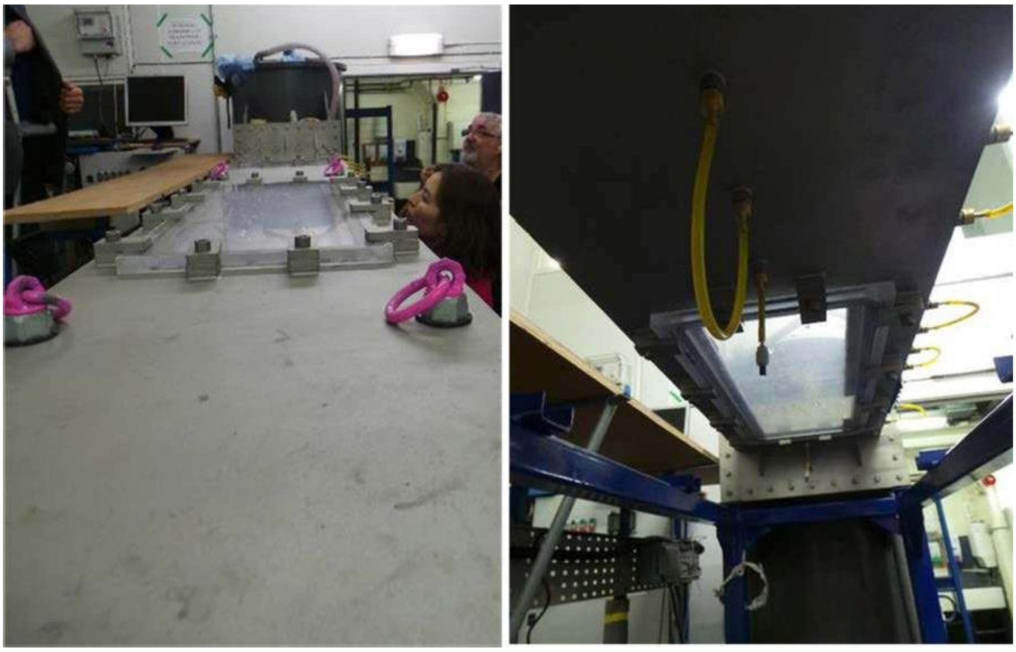

Fig. 8. Two parallel smooth test panels (Surface A and its replicate) in place, top panel (left); bottom panel (right)

3.2. Roughness measurements

The roughness measurements of the three surfaces were carried out using Uniscan's OSP100 device. This instrument is a non-contact, laser-based, high accuracy surface profiling system, used to measure and analyse the roughness. The arithmetic mean of the roughness (Ra) is the general way to describe general surface roughness. From the measured surface profiles the mean Ra values are calculated by comparing all the peaks and valleys to the mean line and then averaged over the entire cut off length of 5 mm. Table 1 shows the results of the mean Ra values as well as other roughness parameters of the three surfaces measured. Surface A, the clean acrylic surface, gives to the smallest Ra of 0.72 µm as being the hydraulically smooth "Reference" surface. The Ra value of Surface B (low to medium rough surface) is 1.94 µm representing a newly coated foul release surface. The third surface, Surface C, is the roughest one with an average Ra value of around 29 µm and representing a coated surface "in-service" conditions.

Table 1. Intervals of design variables

	Ra(µm)	Rq(µm)	Rt(µm)	Sk	Ku
Surface A	0.72	1.09	6.99	0.8	5.98
Surface B	1.94	2.35	12.77	0.17	3.59
Surface C	28.83	33.93	125.83	0.29	2.82

4. Measurements, analyses and presentation of results

The pressure drop measurements were carried out for a range of pump speeds. Equation 5 was used to calculate the Reynolds number (Re_m) varying from 24000 to 113000. The skin friction coefficient (C_f) of the tested panels were plotted against to Reynold's number in Figure 9. The hierarchy amongst the tested surfaces as a function of the surface roughness is clearly apparent as expected by considering the roughness characteristics of these test surfaces.

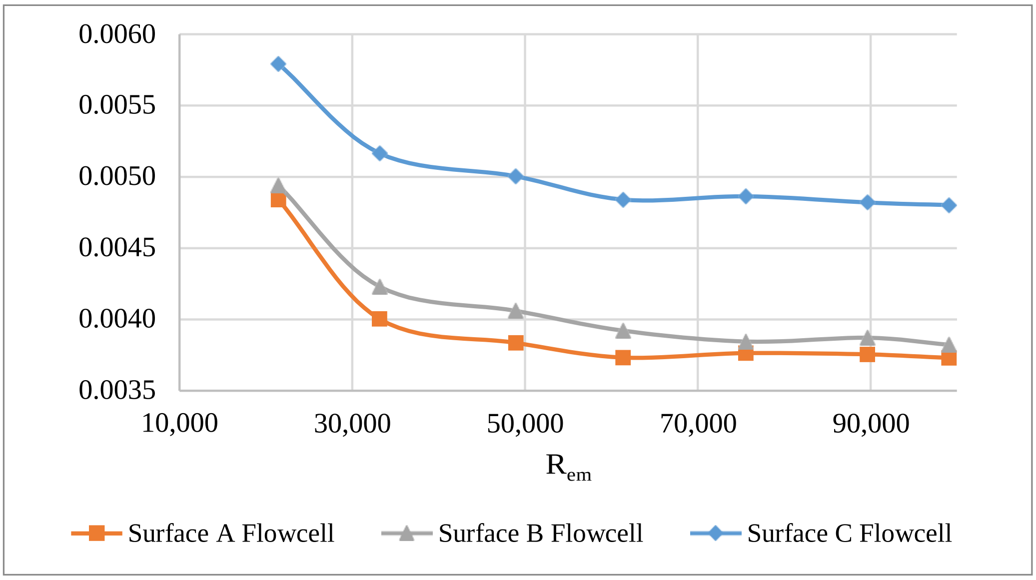

Fig. 9. The comparative friction coefficient of test panels as a function of flow speed.

4.1. The error

Precision uncertainty estimates for the pressure drop measurements were made using repeatability test. Seven replicate measurements were taken on the acrylic and the SPC coated panels. Error in the pressure drop repeatability was estimated based on the measured data by Equation 6. Very small error

(maximum 1.01%) was found and included in Table 3.

$$Error = \frac{Test1 - Test2}{Test1} x100 \tag{6}$$

Table 3. Error of the pressure drop repeatability test

Flow speed (m/s)	1.62	2.87	4.01	5.17	6.29	7.45	8.3
Error (%)	0.92	1.01%	0.08%	0.44%	0.10%	0.01%	0.16%

5. Concluding Remarks

An extensive experimental programme was carried out for the evaluation of the pressure drop methodology by using UNEW's enhanced Flowcell, which was recently modified to accommodate a new pressure drop section, and the Emerson Cavitation Tunnel's boundary layer measurement set-up using LDV. The methodology can be used to calculate the hydrodynamic performance (i.e. skin friction characteristics) of any type of flat surface with different roughness profiles. The skin friction data of these surfaces can be provided in a short time which can substitute the skin friction analysis based on the traditional boundary layer measurement method.

In order to evaluate the new methodology three flat test panels with different surface finishes. The analysed results indicated the following conclusions:

• Calibration tests with the flowcell showed that the enhanced facility with the new stainless still test section can generate the fully tubulent flow at the pressure drop measurement section. The calibration curves for the enhanced flow cell are represented by two reference velocities at the pressure drop measurement section which are the maximum inflow velocity measured at the centre of the pressure drop section and averaged velocity (or bulk velocity) determined from the spatially measured inflow velocities in the same section.

• It was clear that pressure drop methodology displayed the direct relationship between the roughness and the drag characteristics of the tested surfaces: the rougher the surface the higher the measured friction velocities.

• The relative merits of the measured surfaces (i.e. hierarchy of C_f for Surface A, B, C) from the ECT and Flowcell are almost the same. This is extremely encouraging for the new measurement methodology (i.e. Flowcell/Pressure Drop) as it will enable us to evaluate the relative merits of the surfaces with different coatings and biofilms effectively in a very short measurement time.

The future plans is to correlate the roughness characteristics of surfaces with drag performances. The correlation will be able to use the roughness functions for extrapolation of results to full scale.

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