DESIGN SPECIFICATION, COMMISSION AND CALIBRATION OF THE UNIVERSITY OF STRATHCLYDE'S FULLY TURBULENT FLOW CHANNEL (FTFC) FACILITY

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Measurements in the Fully Turbulent Flow Channel (FTFC) are presented for Reynolds number up to $3.3 \cdot 10^5$, based on the mean bulk velocity and the channel height. The FTFC is a new experimental facility recently installed at the Department of Naval Architecture, Ocean and Marine Engineering of the University of Strathclyde. It is a high aspect ratio flow channel with a three-meter-long testing section, designed for the indirect measurement of the drag caused by surface characteristics. The main advantage of this channel is that the measurements of the pressure drop along the test section can be combined with laser-based boundary layer measurement techniques such as LDA, PIV, etc.
The present work focuses on the design features and the calibration of the new experimental facility, with hydraulically smooth control panels produced on purpose. The interest in these data originates from the fact that channel flow serves as a reference flow for varying special surface structures, such as fouling control coatings, as well as some drag reduction mechanisms such as riblets, dimples, tubercles, in the presence of some biofouling types.

1 Introduction

The efficiency of the hull of a ship is of paramount importance in the evaluation of the overall performance of a marine vehicle, as it is known that skin friction is responsible for the greater part of a ship's resistance. Skin friction depends on the characteristics of the hull surface, including roughness, the surface pattern, coating type and behaviour in different working conditions, biofouling growth and adhesion. Predicting these elements is a fundamental aspect of the design process of marine vehicles, as it has an impact on the choice of the propulsive system, the running costs, and the carbon footprint.

For this purpose, the Department of Naval Architecture, Ocean and Marine Engineering (NAOME) of the University of Strathclyde (UoS) designed and had commissioned the construction of a state of the art Fully Turbulent Flow Channel (FTFC)to simulate the turbulent flow around a ship and evaluate the performance of marine coatings and surface patterns such as riblets, tubercles, etc. The FTFC is a rectangular duct that can provide two-dimensional flow measurements, due to its high aspect ratio, as described in Sec. 2. As Yeginbayeva et al. [4] point out, this type of channels provides a practical experimental setup, especially if compared to similar facilities, e.g. pipe flow facilities. The rectangular duct is far more practical when it comes to testing coating performance and special surfaces, or biofouling. It can also accommodate flat panels in the testing section, which can be easily manufactured and coated, and then tested, giving results that validate with some theoretical solutions for flat plates as well as to replicate local flow conditions on a full-scale ship hull surface, especially in terms of achievable Wall Shear Stress. (τ_w), as shown, for instance, in [5], where a rectangular duct flow channel installed at

Newcastle University is described. Politis et al. built different rectangular duct channels [5-7], with the purpose of studying the adhesion strength and polishing rate of biofouling, coated surface roughness effect on boundary layer and skin friction, and also for ageing, polishing and foul release tests on fouling control coatings [7].

Dean [1] and Zanoun et al. [3] propose exhaustive reviews of experimental work in such channels, the first proposing the famous relation:

$$C_f = 0.073 Re^{-0.25} \tag{1}$$

where C_f is the skin friction coefficient, and Re is the Reynolds number calculated with the channel height and the mean bulk velocity in the test section. Zanoun et al., on the other hand, collect experimental data and propose a slight variation (about 1.8%) of Equation $C_f = 0.073Re^{-0.25}$ (1:

$$C_f = 0.0743 Re^{-0.25} \tag{2}$$

Schultz and Flack [8] also found that their experiments in an 8:1 aspect ratio turbulent channel yield the conclusion that C_f follows the power law at low Reynolds numbers ($Re < 6 \times 10^4$), while it fits better a logarithmic law at higher Reynolds numbers.

2 Design specifications

The FTFC was designed together with the company CTO SA [9], based in Gdansk, Poland. The design specifications were set by UoS, based on the experiences of Politis et al. [5-7]. The FTFC is a single-pump closed-circuit flow circulating facility, with its upper limb downstream of the pump acting as the test section, which accommodates two test panels, described in Section 3.1. The length of the upper limb, i.e. the testing section for a high aspect ratio flume, is extremely important as it must be sufficiently long to ensure the development of fully turbulent flow before it reaches the pressure measurement section where the test panels are located. The main particulars of the UoS FTFC are summarised in Table 1.

Table 1 - Main particulars of UoS FTFC facility

Name	**Unit**	**Dimensions**
Length (Tolerances)	(mm)	3000 (±0.05)
Height (Tolerances)	(mm)	22.5 (±0.05)
Beam (Tolerances)	(mm)	180 (±0.05)
Speed range	(m/s)	2-13.5
Flow rate	(l/s)	10-60
Channel height based Reynolds number	ND	0.3e+6
Material		Stainless steel (316L)

Figure 1: CAD representation of the FTFC (top) and commissioned at the Kelvin Hydrodynamics Laboratory of the University of Strathclyde (bottom)

The aspect ratio of the UoS FTFC testing section is 8:1, that is considered enough to achieve two-dimensional flow, according to Dean [1]. In order to allow tests replicating marine environment, the facility was designed to withstand the use of seawater, as is the single pump, a 22kW centrifugal pump, Grundfos type.

The positioning of the panels is of paramount importance, as these have to be flush with the surface of the FTFC, and without gaps. Otherwise, the presence of these imperfections would trip the flow, creating unwanted turbulence, that would cause a bias in the test results. In order to avoid this, an *ad hoc* structure was designed, as shown in Figure 2. The bottom test panel is held by six frames, and its alignment and flushness with the surface can be checked by removing the top panel. The top panel can be first placed in a removable structure, which allows to check the alignment and flushness with the surface before placing it on the FTFC.

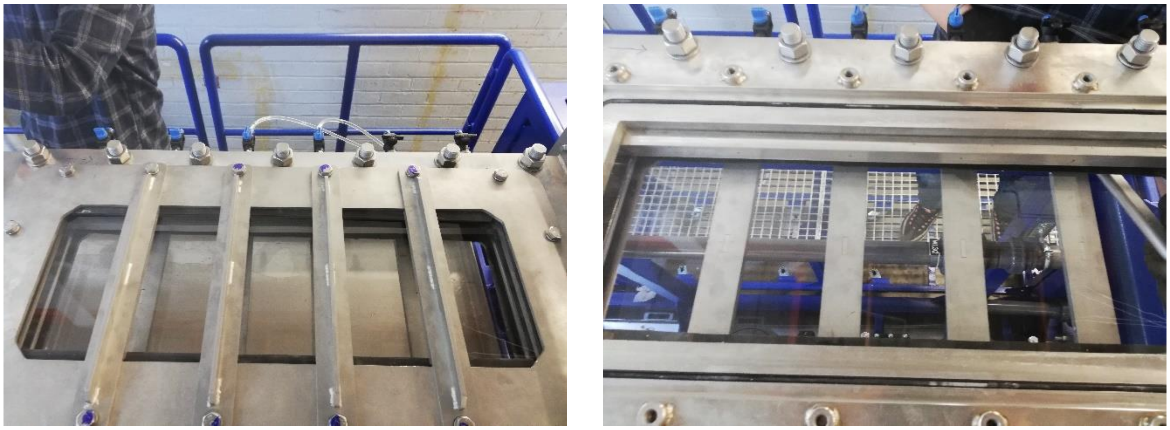

Figure 2: Left: top test panel fixed with its frame and structure; right: bottom test panel, fixed with beams

One side of the measuring section, for the full length of the panel, is equipped with an interchangeable Perspex window, allowing visual check of the channel height and the flow quality, and also access to laser beams for the use of Laser Doppler Anemometer (LDA) or Particle Image Velocimetry (PIV) equipment (Figure 3).

Figure 3: Side window in the measuring section of the FTFC

The assessment of the flow quality (i.e. presence of bubbles, etc.) in the measuring section can be also made by inspecting through the interchangeable hatch placed downstream of the test panels, which also accommodates a Pitot Tube for the measurement of centreline velocity.
The measuring section wall opposite to the Perspex window is fitted with six pressure taps along the length of the measuring section, with a distance of 120 mm between each couple of taps. Two taps at a time can be connected to a differential pressure transducer (as described in Section **Error! Reference**

source not found.), to measure the pressure drop along the length of the test panels. The FTFC is equipped with a total of three differential pressure transducer, which are used to measure the pressure drop at the contraction (17:1) upstream of the upper limb and at the test section, and in the pitot tube, respectively.

The flow velocity along the FTFC circuit is measured at the contraction using a differential pressure gauge, and in the lower limb with a magnetic flowmeter from which the mean bulk velocity U_m in the measuring section is calculated.

The FTFC is also equipped with a thermometer, to monitor the temperature of the water and calculate its density and viscosity for each sample, according to [10]. Also, the main tank of the facility is equipped with a ready-to-use cooling system for temperature control. A coil heat exchanger is in place, ready for connection to an external unit.

3 Experimental work

3.1 Test Panels

The test panels are produced on purpose. Their dimensions are specified in Table 2 below, and showed in Figure 4.

Table 2 - Test plates dimensions

Item	**Size (mm)**
Inner length	598
Inner breadth	218
Inner thickness	14
Outer length	662
Outer breadth	282
Outer thickness	16
Tolerance	0.1

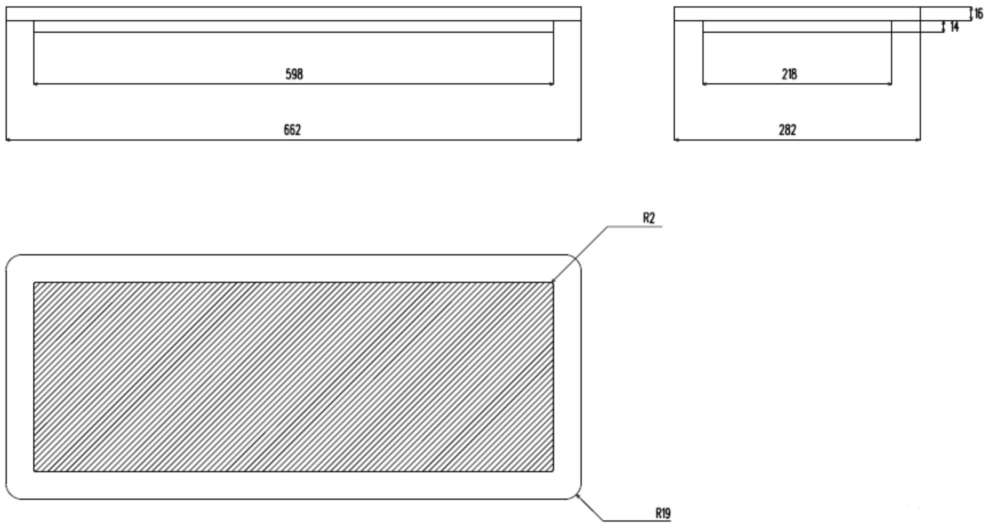

Figure 4: Test panel dimensions

The test panels can be made from any material but are preferred to be made from acrylic for the sake of being light, easy to machine and hence easy to handle etc. Figure 4 shows the dimensions of a typical test panel with a shaded area which is in contact with the channel flow. Thus, this area needs to be accurately machined and polished to get a smooth flat finish that sits flush with the inner surface of the measuring section. The polishing also makes the panel transparent, so that it can be used, not only as a hydraulically smooth reference surface but also to provide access to the laser beams if an LDA or PIV will be used for detailed flow analysis.

3.2 Pressure drop measurements and skin friction analysis

In order to calibrate the FTFC, the pressure drop measurements and hence skin friction analysis are conducted by using hydraulically smooth acrylic test surfaces. The pressure drop along the panels is measured by connecting two of the six pressure taps to a differential pressure transducer manufactured by Aplisens . The transducer has a 0-400 mbar range. The pressure difference between the two taps is used, in relation to the linear distance between them, to evaluate the frictional resistance of the testing panels. Figure 5 below shows the pressure taps, connected to the pressure transducer through plastic hoses.

Once the streamwise pressure drop between the two pressure taps is measured, the wall shear stress, τ_w, can be calculated as

$$\tau_w = -\frac{H}{2}\frac{dP}{dx} \tag{3}$$

where H is the channel height, dP is the measured pressure drop and dx is the longitudinal distance between the two pressure taps. Then the skin friction coefficient C_f can be calculated as

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$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_m} \qquad (4)$$

where ρ is the water density and U_m is the mean bulk velocity of the flow in the test section.

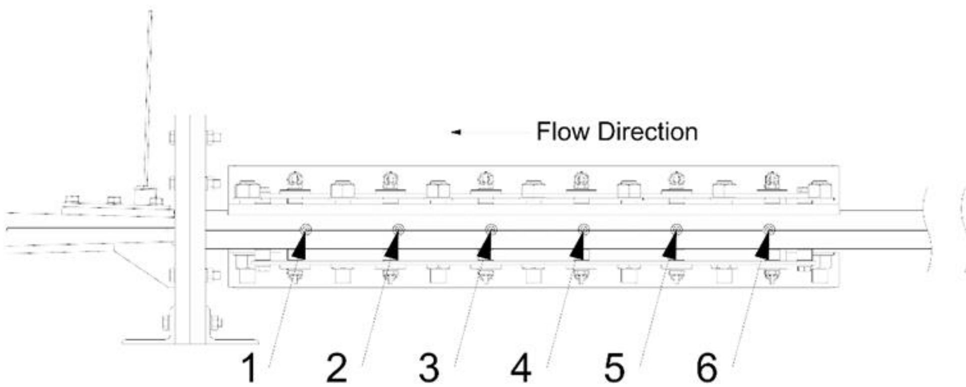

Figure 5: Drawing of the FTFC's measuring section, with the pressure taps numbered from 1 to 6

3.3 Uncertainty analysis

The results presented in this paper are the mean values obtained after considering all the repeated measurements, and they lie in a 95% confidence interval, calculated according to the procedure described in [11]. In addition, the uncertainty for the values of the pressure drop Δp was calculated, initially for motor frequency of 16 Hz (mid-range) and the tap configurations with lower uncertainty were identified as 2-5, 2-4, 1-6. Configuration 2-5 had the lowest uncertainty, as expected, so the analysis was carried out also for frequencies of 10 Hz and 39 Hz, i.e. the two limits of the range. Table 3 shows the uncertainties for the different configurations. Configurations 1-2, 1-3, and 5-6 were not included to avoid the inconsistent readings due to the end effects between those specific taps.

Table 3: Uncertainty calculated for representative speeds and different tap configurations

Motor Freq. [Hz]	Tap Configuration	Uncertainty
16	ΔP @ 1-6	2.01%
	ΔP @ 1-5	3.42%
	ΔP @ 1-4	3.85%
	ΔP @ 2-5	1.40%
	ΔP @ 2-6	2.15%
	ΔP @ 2-4	1.55%
	ΔP @ 2-3	4.93%
	ΔP @ 3-6	2.24%
	ΔP @ 3-5	3.57%
	ΔP @ 4-5	4.95%
10	ΔP @ 2-5	1.48%
39	ΔP @ 2-5	1.23%

3.4 Results

The calibration campaign of the FTFC included 11 sets of pressure drop measurements with different tap configurations and at different pump frequencies. Since the user is allowed to control the pump rate only, U_m is calculated and Figure 6 shows the linear correlation between pump frequency and mean bulk velocity in the test section.

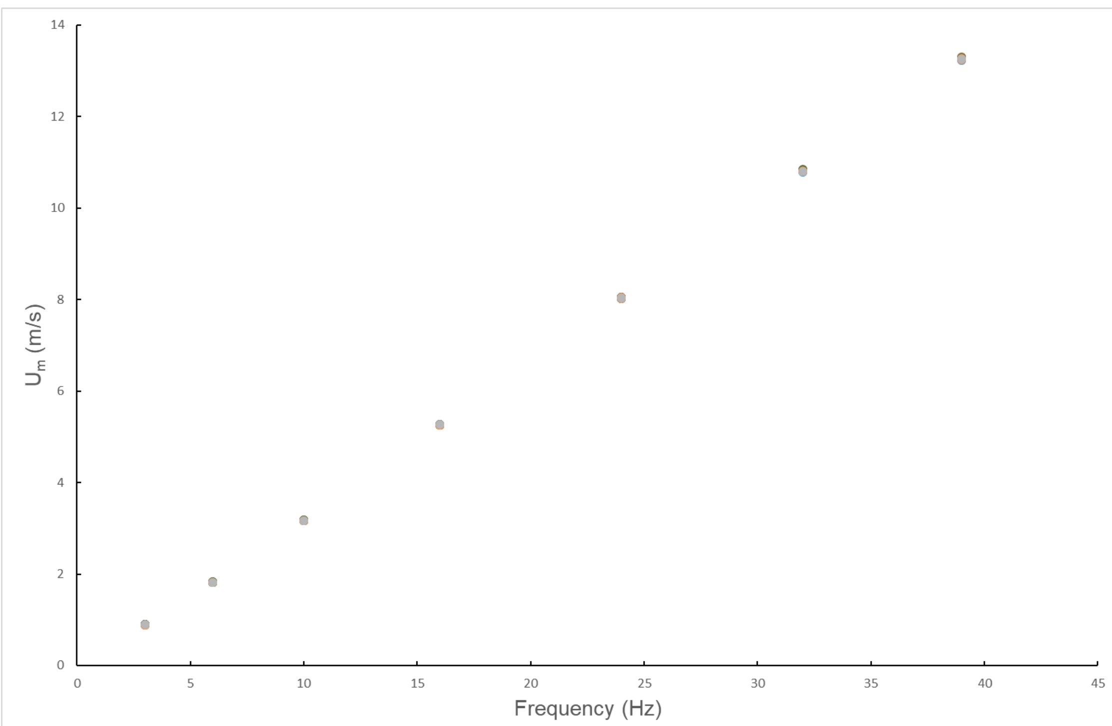

Figure 6: Mean Bulk Velocity (U_m) vs pump frequency

Figure 7 shows the linearity of the distance between the taps and the pressure drop along the test panels. In the Figure, the distance between the taps is expressed as a ratio of the actual distance x and the channel height H, while the pressure drop Δp is expressed in mbar, as measured by the transducer. Figure 7 shows that the flow is fully developed when it reaches the test panels at the end of the test section.

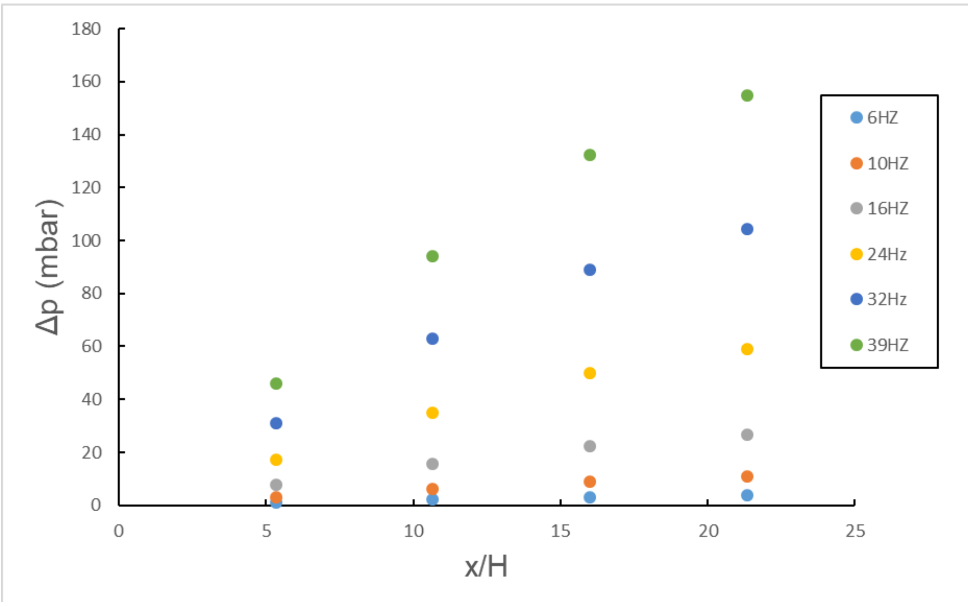

Figure 7: Pressure drop at different U_m

In order to validate the pressure measurements and the technique used to calculate the frictional coefficient of the smooth test panels, the results are compared to the formulations for C_f proposed by Dean [1] and Zanoun et al. [2, 3].

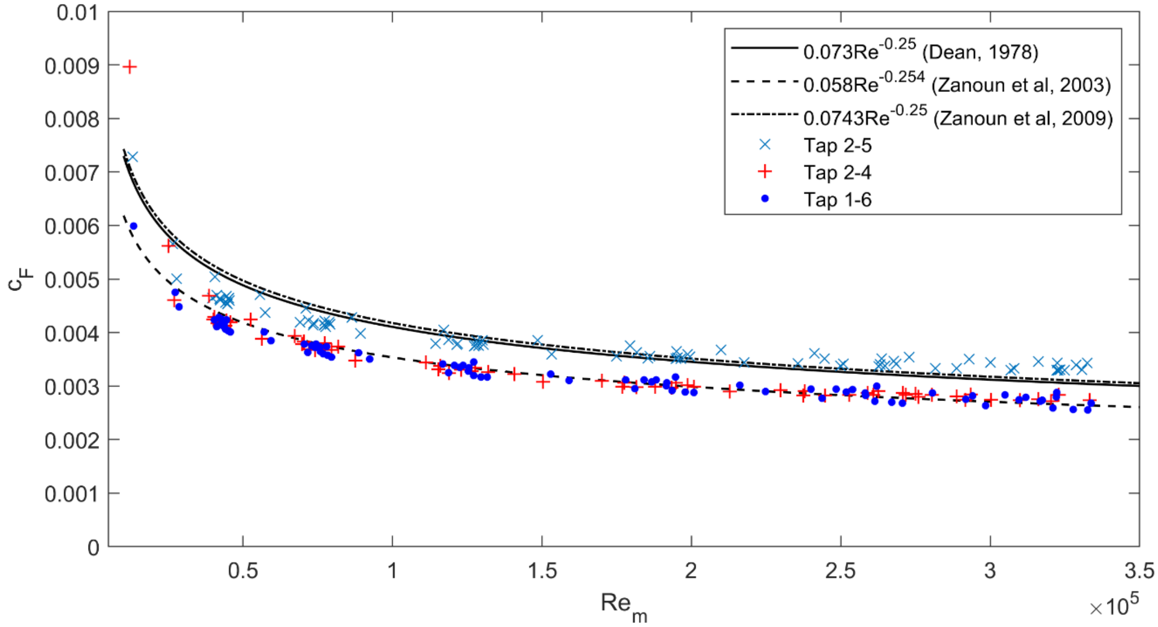

Figure 8: C_f vs Re_m for tap configurations 2-5, 2-4, 1-6, compared to the empirical formulations in [1-3]

Configuration 2-5 shows a good agreement with both curves proposed in [1, 3], while configurations 2-4 and 1-6 fit better the formulation proposed in [2].
The results clearly show that the FTFC can be employed for skin friction experiments at high Reynolds numbers, as it matches very well the benchmark curves that appear in the literature.

4 Comparison of WSS values to full scale flat plates

The FTFC can be employed to assess the performance of coatings in full scale conditions, by achieving the same WSS as that of a flat plate with the length of a full-scale ship, sailing at the ship's cruise speed. In order to show this is possible, Figure 9 shows a comparison of the WSS achieved in the FTFC with that calculated with the 1957 ITTC skin friction formulation [12] for a 200-metre-long flat plate. The WSS for the plate is calculated from the skin friction coefficient, by using Equations $C_F = \frac{0.075}{(\log_{10} Re - 2)^2}$ (5 and $\tau_w = C_F \frac{1}{2} \rho U^2$ (6:

$$C_F = \frac{0.075}{(\log_{10} Re - 2)^2} \quad (5)$$

$$\tau_w = C_F \frac{1}{2} \rho U^2 \quad (6)$$

Figure 9 shows how the WSS of the flat plate at full scale speed can be achieved in the FTFC at a lower flow speed, allowing the evaluation of the performance of the test panels in a realistic full-scale scenario, regardless fo the purpose of the experimental campaign is to test a marine coating or a special pattern on the panels' surface. This figure can be used to select the appropriate flow speed in the FTFC to evaluate the frictional resistance and the performance of a ship in full scale at cruise speed.

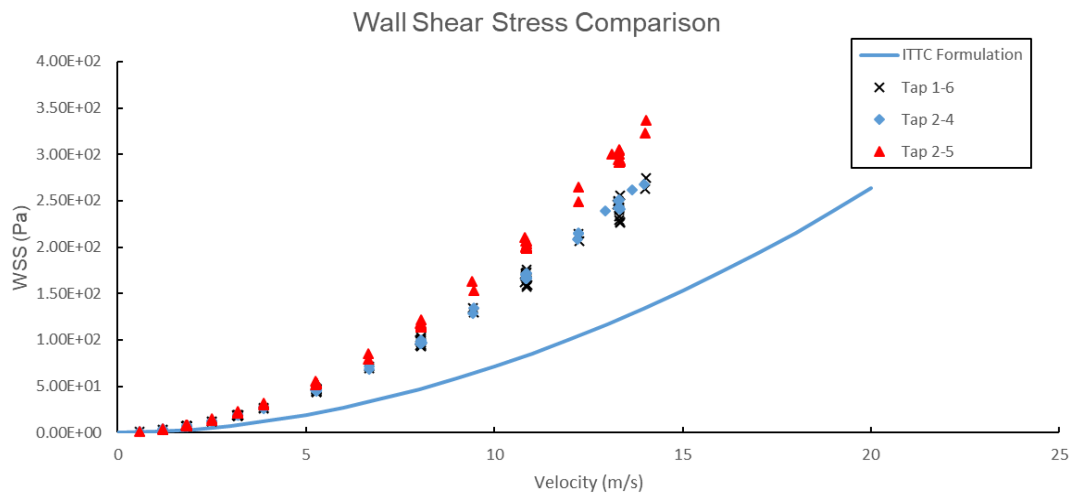

Figure 9: WSS inside the FTFC compared to that of a 200 metre-long towed flat plate, calculated according to (ITTC) formulation

Figure 10 shows, on the other hand, the WSS of flat plates of the length of some particular vessels, for comparison. The length, cruise speed and WSS are summarised in Table 4. The Reynolds numbers for these calculations are obtained considering the characteristics of sea water at 15°C.

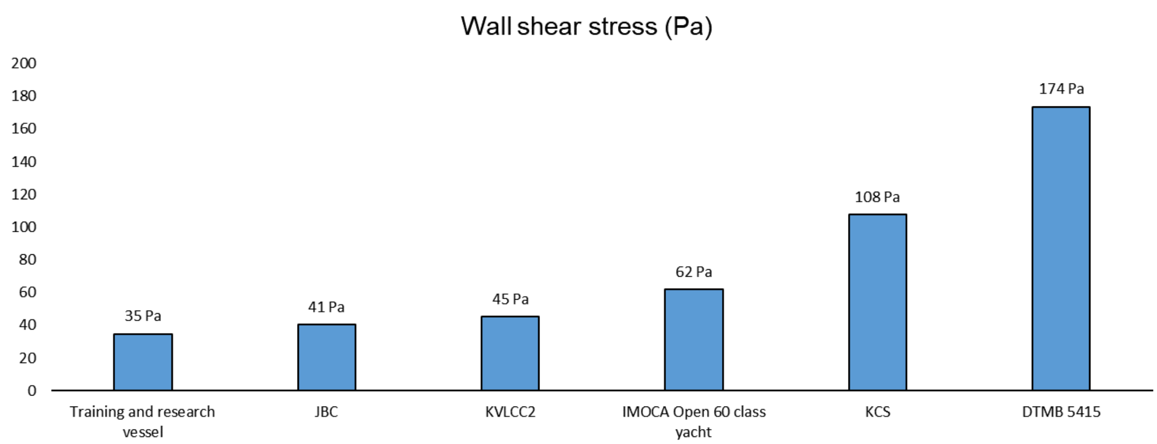

Figure 10: WSS of flat plates of equal length of different vessels

Table 4: Information of the vessels used for WSS comparison

Vessel	L (m)	Speed (m/s)	WSS (Pa)
Training and research vessel	60	6.17	3.48E+01
JBC	280	7.45	4.06E+01
KVLCC2	320	7.97	4.54E+01
IMOCA Open 60 class yacht	20	7.72	6.21E+01
KCS	230	12.35	1.08E+02
DTMB 5415	140	15.43	1.74E+02

5 Conclusions

A new Fully Turbulent Flow Channel was designed and manufactured for the University of Strathclyde, and a campaign of measurements for its calibration was carried out based on hydraulically smooth test panels. The calibration tests with the flow channel showed that the enhanced facility with the 8:1 ratio test section and 3m long development zone (L/H=135) can effectively develop the fully turbulent flow at the pressure drop measurement section. The calibration curves for the enhanced flow cell are represented by reference velocities and the pressure drop measurement curves. The results show that the pressure drop measured along the test panels can be used to calculate the skin friction coefficient of the panels, which accurately matches the theoretical formulations found in literature, with an uncertainty as low as 1.23% within a 95% confidence interval.

It was also shown how the FTFC can be employed to replicate the turbulent flow around a 200-metre-long flat plate, by reaching the same WSS at considerably lower speeds. This implies that the facility can be effectively used to predict the performance of marine coatings and special surface patterns of full scale ships.

6 References

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