Experimental Quantification of Drag Change of Commercial Coatings Under the Effect of Surface Roughness and Soft Fouling

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Abstract

The paper presents an experimental study of roughness and hydrodynamic characteristics for biocidal and non-biocidal antifouling coatings. In the study both smooth panels (Rt(50)≈40-90 µm) and panels with roughness commonly found on ship hulls (Rt(50)≈110-125 µm) were used. Measurements of drag were obtained from torque measurements in a rotating disc facility and the biocide content (Cu and Zn) of the paint were measured using X-Ray Fluorescence. Preliminary results show that Cu concentration in coatings is between 6700 mg/cm^2 and 9600 mg/cm^2, whereas Zn results are under 900 mg/cm^2.The results of torque measurements shows that typical antifouling biocidal coating with Rt(50) value of 116 µm demonstrated around 19% higher torque coefficient (C_m) at the highest Reynolds number (Re_r) when compared to the smoothest disk with Rt(50) value of 43 µm. In addition, the paper also describes future plans of including microalgal fouling to the tested disks.

1. Introduction

The drag performance data of newly-applied and clean coatings are not sufficient to fully reflect and estimate the drag and consequent fuel efficiency of marine coatings over a typical period between dry-docking, which incorporate the increase in surface roughness and development of different fouling stages.

A comprehensive review of studies on the ship roughness and fouling (available before 1952) is given in MFIP (1952). The review covers laboratory tests and full-scale ship tests on different rough surfaces and fouled surfaces under various conditions. From cited reviewed works, *Beery (1939), Benson et al. (1938), Snyder (1938), Graham (1940),* it follows that the average drag increase during the static submerging is about 0.1 per cent per day during the first 2 month for antifouling paints and about 0.5 per cent per day for a passive (anticorrosive) paint. A useful observation was made in *Hiraga (1934)* that the drag of samples measured directly after submerging was initially larger and the resistance was decreasing to abovementioned values when the top layer of the slime was removed during the towing. From study by *McEntee (1915)* it follows that after 3-4 months of submerging there is a sudden resistance increase with 50% a month and after this time the resistance grows about 30% a month.

In the full-scale tests on Lucy Ashton ship, *Denny (1951), Conn and Lackenby (1953),* the hull was allowed to foul for 40 days, on a coating of bituminous aluminium. Only slime was present after this time and the frictional resistance increased by 5% i.e. 0.125% per day. Similar drag increase rate was obtained by *Lewthwaite et al. (1985)* for 240-day and 600-day trials, where the increase of drag was by 25% and 80% correspondingly.

In *Munk et al. (2009)* drag curves over time for different vessels are analysed and an average resistance increase of 0.5-1% a month is reported. For a tanker, which sat for one month in a port, the drag has increased by 10%. Upon subsequent operation, the self-polishing copolymer coating was activated, and the fouling was reducing over the course of 6 month until the drag change has reached the value of 5%. After this period the drag started to increase as described in previous works with the rate of 1% a month.

The mechanical and physical properties of biofilms will impact the magnitude of the drag they generate, *Towler et al. (2003)*. On fouled flat plates the thickness and community structure of attached biofilm was seen to affect drag, *Schultz and Swain (1999,2000)*. In test on antifouling coatings the effect on increased drag could come either from differences in the properties of the biofilms attached on the various coatings, or to their adhesion to the coatings, due to properties of the coatings.

Marine biofilms contain different species of bacteria, cyanobacteria, diatoms, protozoans and other microorganisms, *Dobretsov (2010), Callow and Callow (2011)*. On a ship hull diatom species like *Amphora* and *Navicula* are present and in some studies these diatoms are found to be tolerant to copper in anti-fouling paint, *Zargiel et al. (2011), Callow (1986)*. Tolerance to copper is also find to differ between diatom species and cyanobacteria, *Barranguette et al. (2010)*. However, it was concluded in the study by *Barranguette et al. (2010)* that the main factor regulating the sensitivity of the biofilm to Cu toxicity during short-term exposures was the physical structure of the biofilm (package of cells and thickness) and not the species composition.

The roughness of the substrata will have impact on biofilm formation. At a fine-scale (e.g. 10 μm, 22 μm and 50 μm) roughness, total diatom density (cells per cm^2) were found to be higher on 10 μm while the total biomass did not differ between the three roughness tested, *Sweat and Johnson (2013)*. In the tests by *Sweat and Johnson (2013)* natural biofilms were used consisting of 58 different diatoms species with size (length) span from 14 to 552 μm. In lab tests bacterial biofilms (inoculum from Montana State University duck pond) grown directly on rheometer disks rotated in a chemostat for 12 days resulted in biofilms that were heterogeneous and ranged from 35 μm to 50 μm in thickness, *Towler et al. (2003)*. Natural biofilms including diatoms are much thicker and in riverine water in Netherlands a 1-2 mm thick biofilms were developed during a 3-week colonization period, *Barranguette et al. (2010)*.

The literature survey shows that there are rather many experimental studies on the fouling drag available. However, few of these studies are reporting on correlation of fouling surface characteristics with its drag. Based on the above need, this research aims to understand the fouling attachment mechanisms of ship microalgal species (diatoms and green algae) on commercial biocidal and non-biocidal coatings and resulting drag.

This paper presents the experimental results on surface roughness and drag characteristics of hull coatings with relatively smooth and coarse roughness finishes without the effect of fouling used as baseline measurements. The paper also reports on future plans for the project.

2. Detailed description of experimental work

2.1. Test surfaces

Test disks were of 300 mm diameter. Two smooth, uncoated PVC disks were used as reference surfaces. PVC disks coated with antifouling paints on one side were used as test surfaces and summarized in Table 1. In the table, biocidal and non-biocidal antifouling coatings were denoted as BAC and FR respectively. Disks coated with *BAC-A*, *BAC-B* types were typical antifouling polishing coatings with biocides and *FR-A, FR-B, FR-C, FR-D* types were typical non-biocidal foul-release coated disks. To investigate the effect of roughness ranges, disks with *BAC-A* type only have undergone smooth and realistic rough applications. Biocide containing disks were prepared in two replicates. All FR type coatings were applied on disks using smooth application procedures. FR coated disks were prepared in three replicates. Surface roughness of these mentioned disks were measured by industry type Hull Roughness Gauge.

Table I: The list of antifouling coatings

Application type	Biocidal types	Non-biocidal types
Smooth	BAC-A smooth 1	FR-A smooth 1
	BAC-A smooth 2	FR-A smooth 2
	BAC-B smooth 1	FR-A smooth 3
	BAC-B smooth 2	FR-B smooth 1
		FR-B smooth 2
		FR-B smooth 3
		FR-C smooth 1
		FR-C smooth 2
		FR-C smooth 3
		FR-D smooth 1
		FR-D smooth 2
		FR-D smooth 3
Rough	BAC-A rough 1	-----
	BAC-A rough 2	----

2.2. A campaign of rotary disk tests

A rotating disk facility was used to assess the hydrodynamic performance of coated disks in their clean (i.e. unexposed to fouling) conditions. A schematic of a custom built small-scale rotating disk facility is illustrated in Fig.1, *Atencio (2016)*. The facility capable of measuring a boundary layer over disks by using a micro-PIV (Particle Image Velocimetry) and drag via torque readings. The resisting moment (torque) of rotating disks is measured by a Kistler type 4503A torque meter which is installed on a shaft connecting an electric motor with the rotating disk. The torque sensor operates on a strain gauge principle. The torque meter output is monitored by an analogue-to-digital converter (ADC) controlled by a PC.

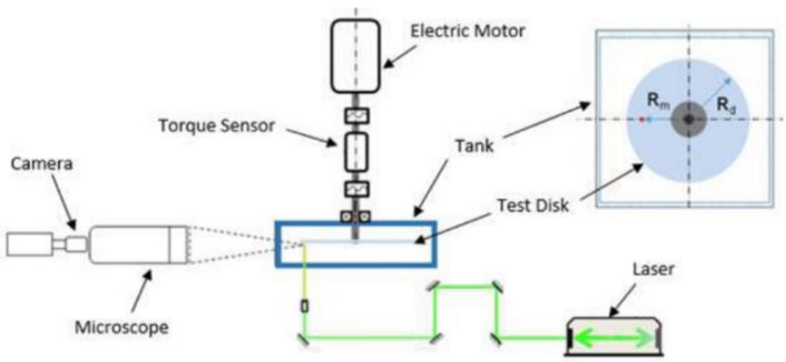
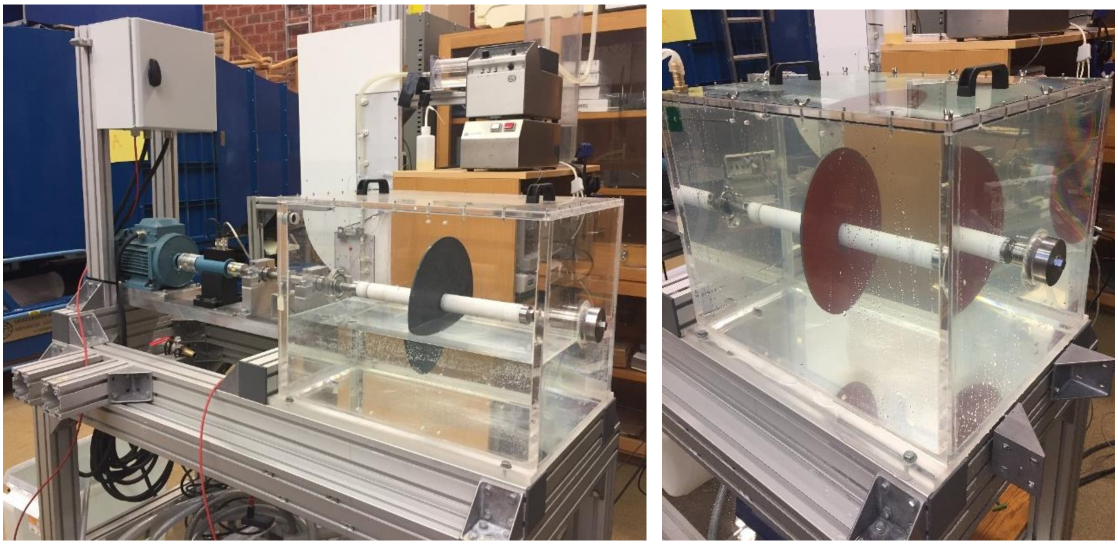


Fig.1:Rotating disk rig with torque and micro-PIV measurement capability, *Atencio (2016)*

Before the drag measurements, all the air from the tank was evacuated and the bearings were lubricated. The facility was warmed-up at 600 rpm together with the measurement electronics for at least 20 minutes. First, the torque from the shaft together with bearings and seals (but without a disk) was measured. These readings were later subtracted from the total measured torque to obtain the torque of the disks. Following, the torque contribution from the disk’s cylindrical edge was also subtracted in order to estimate the drag of only coated part of disks. A water tank filled with tap water and torque data for coated disks as well as reference PVC disk were collected at different motor speeds as shown Fig.2. The water viscosity and density was evaluated analytically based on the temperature in the tank, which was logged during the tests.



(a) (b)

Fig.2: Installation of the reference PVC disk (grey) on the shaft of the rotating rig for torque measurements (a). The photo of coated disk taken during experiments (b).

Torque data were collected at nominal rotational velocities of 450, 600, 900 and 1200 rpm. At 450, 600 and 900 rpm data were collected twice (during the increase and decrease of rotational velocity). Since current test disks were coated on one side, additional post-processing procedure was introduced to subtract the torque of the smooth side.

The moment coefficient is obtained from Eq.(1):

$$C_m = \frac{4M}{\rho r_0^5 (\phi\omega)^2} \tag{1}$$

M is the torque of one side of the disk, r_0 is the radius of the disk, ω is the angular velocity and ρ is the density of the fluid. For a disk rotating in a container a swirl may develop which reduces the effective angular velocity to $\phi\omega$ where ϕ is a swirl factor for enclosed rotating disk $\phi^2 = C_{m,en}/C_{m,\infty}$. The swirl factor in the tank is equal to 0.97. However, typically, the precise value of the swirl factor is not crucial for the roughness characterisation, since differences are considered.

The angular velocity is calculated using Eq.(2):

$$\omega = 2\pi \frac{RPM}{60} \tag{2}$$

The Reynolds number is defined as in Eq.(3):

$$Re_r = \frac{r_0^2 \omega \phi}{\nu} \tag{2}$$

The water density ρ and kinematic viscosity ν are evaluated at actual water temperature of the experiment.

2.3. Measurements of Cu and Zn concentrations in biocidal antifouling coatings

A method based on XRF spectrometry was used to determine the concentration of metals, namely copper (Cu) and zinc (Zn) in biocidal coatings applied on 300 mm diameter disks. XRF is an acronym for X-ray fluorescence, a process whereby electrons are displaced from their atomic orbital positions.

This process is accompanied with a release of burst of energy. Each element (e.g. metals) has its specific energy bursts, which is registered and identified by the detector in the XRF instrument, https://www.bruker.com/products/x-ray-diffraction-and-elemental-analysis/handheld-xrf/how-xrf-works.html. The method utilizing a handheld XRF analyser has recently been developed for the in-situ measurement of release of metallic biocides from antifouling paints, *Ytreberg et al. (2017).*

As shown in Fig.3, the handheld XRF (DELTA-50, InnovX) was directly positioned on the coated disk and a total of 6 points in 4 places per disk were analysed using 50 kV beam. Each measurement point which was a circular area was measured during a 30 s time. The concentration of metals such as Cu and Zn in the coatings are expressed in mg per square centimeter (mg/cm^2).

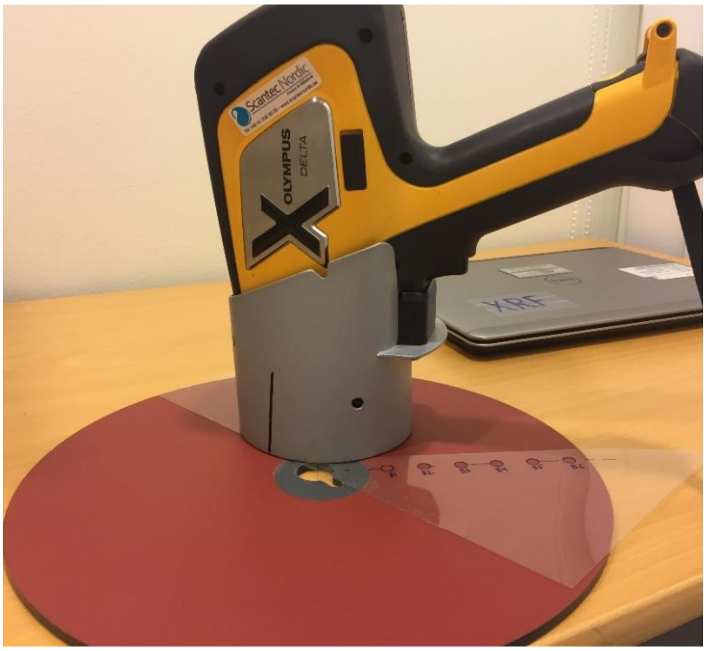


Fig.3: XRF measurements of Cu and Zn in *BAC-A* type applied on disks

For the XRF film analysis, it is important to define the film thickness beyond which the X-ray signal is absorbed by the sample and is not detected by the instrument. This thickness is also known as critical thickness, d_{thin}. *Ytreberg et al. (2017)* designed an experiment to determine this d_{thin} for Cu and Zn in antifouling coatings. Their study recommended that the dry film thickness of coating should be under 40 μm to avoid absorption effects and consequent underestimation of metal concentration in coatings.

In this study, the thickness of coatings applied on test disks exceeds the critical thickness d_{thin}, why we would have an uncertainty in XRF readings. But still results can be used as screening tests for relative comparisons of Cu and Zn concentration between different biocidal coatings.

2.4. Results and discussions

2.4.1. Roughness measurements

The maximum peak-to-valley height roughness values over a 50 mm sampling lengths (*Rt50*) was collected on test disks using an industry gauge hull roughness analyser, https://www.tqc.eu. In marine industry, this parameter has been adopted as a standard measure of hull roughness. In total 20 measurements were obtained by moving the sensor unit of TQC hull roughness gauge in straight lines around disks.

Figs.4 and 5 present boxplot diagrams for *Rt(50)* values collected on biocidal and non-biocidal coated disks respectively. In the boxes the median, which is a measure for the center of *Rt(50)* values, are represented by the mid-line. Observed mean and medium *Rt(50)* values for all coatings are very close except some disks. As it can be seen in Fig.4, mean values for *Rt(50)* for biocidal coatings ranged from 72 µm (*BAC-B smooth 1*) to 123 µm (*BAC-A rough 2*). Looking at the boxplot it is obvious that *BAC-A* type coating which had rough application finishes were the roughest amongst the biocidal group. Two way Analysis of Variance (ANOVA) was carried out to determine whether smooth and rough applications of the same *BAC-A* type coating were significantly different from each other. ANOVA test are run with an α level (or significance level) of 0.05 (5%). According to the result, the 0.05<*p*-value was found to be significantly smaller than specified α level meaning that differences in *BAC-A-smooth* and *BAC-A rough* applications were achieved.

Looking at the pattern of box plots, *BAC-B* coating replicates show wide range in data spread. This might be explained by trip of TQC' sensor tip that resulted in high variation of readings.

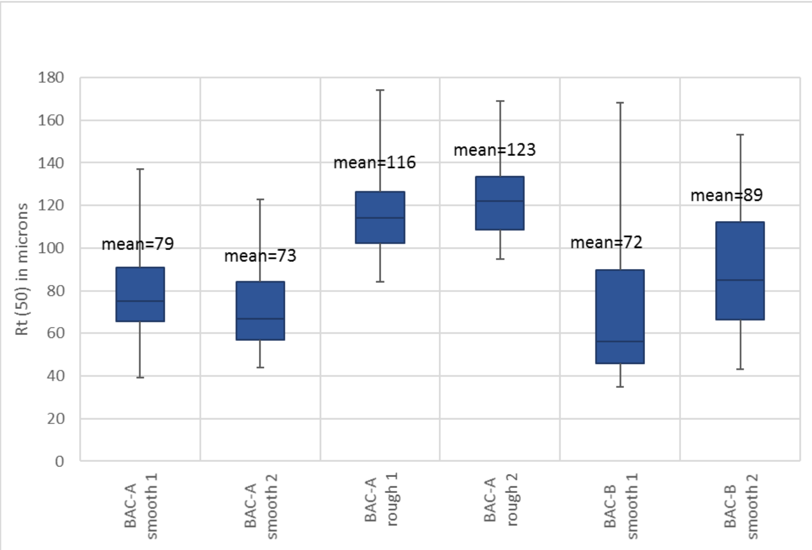


Fig.4: Boxplot diagrams of *Rt(50)* expressed in microns (µm) for biocidal coatings

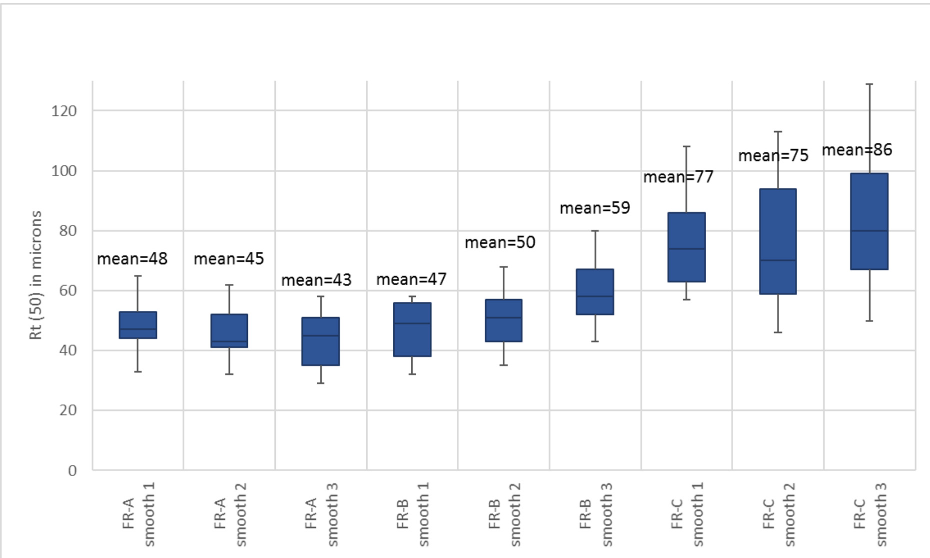


Fig.5: Boxplot diagrams of *Rt(50)* expressed in microns (µm) for non-biocidal coatings

According to **Error! Reference source not found.** *Rt(50)* values for non-biocidal coatings were small. A minimum of 43 µm and maximum of 86 µm was observed for *FR-A smooth 3* and *FR-C smooth 3* respectively. The *Rt(50)* values for *FR-B* type coatings were in the mid-range. Fig.5 does not show values for *FR-B* type since Authors could not take any measurements on this particular coating type due to its sticky nature not allowing the tip to move forward.

2.4.2. XRF results

In total 24 measurements points per disk were used to collect the XRF readings presented in Fig.6. This figure graphically demonstrates the mean values (also standard deviations in black vertical lines) for concentration of Cu and Zn for three biodical type coatings.

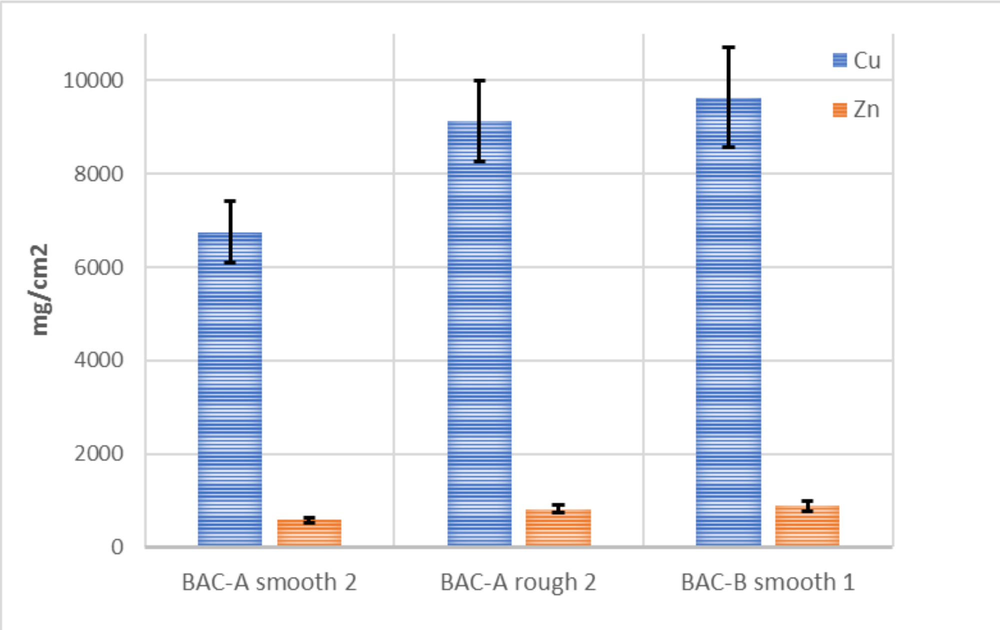


Fig.6: Concentration (expressed in mg/cm^2) of Cu and Zn in biocidal coatings applied on disks

Preliminary results show that *Cu* concentration in coatings is 6700 to 9600 mg/cm^2, whereas *Zn* results are under 900 mg/cm^2. As mentioned earlier in XRF section, the thicknesses for coatings were above critical thickness of 40 μm. Moreover, the coating thicknesses vary between *BAC* coatings types. Therefore, the current results were not compared with previous studies.

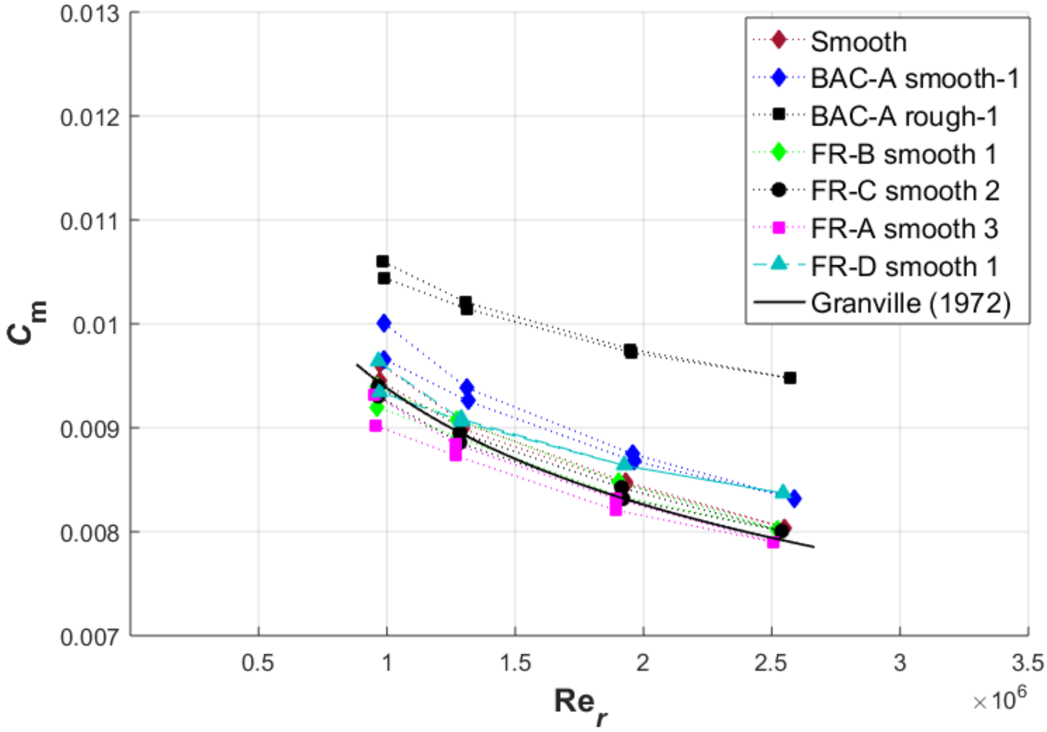


Fig.7: Change of non-dimensional torque coefficient for coated disks as function of Reynolds number

2.4.3. Torque measurements using the rotating disk rig

Fig.7 shows the torque coefficient (C_m) in non-dimensional variables plotted against Reynolds number, Re_r for all coated tested disks. In these results the torque of shaft, bearings, disk edge and uncoated side is subtracted, so that the drag effect of only coatings are present. As seen the results for smooth uncoated disk given in red-diamond curve agree well with the theoretical curve of *Granville (1972)*.

From these preliminary results, it can be inferred that drag effects of coatings are dictated by their surface heights. As an example, one replicate of *FR-A* type coated disk seems to perform better than the smooth PVC reference disk and the rest of the coated disks. When *Rt(50)* values were compared the same *FR-A* type replicates were found to be the smoothest amongst all coated disks. For other coated disks a gradual increase in drag was noticed according to their *Rt(50)*parameter. Overall, an increase of around 19% in C_m at the highest Reynolds number was noticed for the replicate of rough biocidal coating (*BAC-A rough 1*) as opposed to the smoothest disk coated with non-biocidal coating (*FR-A smooth 3*).

3. Future work

More drag data collection on different coatings with different roughness and fouling is planned using a flow channel facility based on flat plates, which is being manufactured during spring 2018.

In the planned experiment, we will work both with natural assemblages of microfouling from Port of Gothenburg and controlled lab-grown biofilms consisting of the diatoms *Amphora* and *Navicula* together with young stages of the green alga *Ulva.*

For the XRF measurements a calibration is planned which will enable measurement of metal concentration of films with the critical thickness d_{thin} >40 µm. This calibration will allow the accurate estimations of Cu and Zn in paints before and after they have been exposed to polishing.

This study has a potential to adding to knowledge on long term performances of hull coatings to guide in management strategy for ship operators.

Acknowledgements

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