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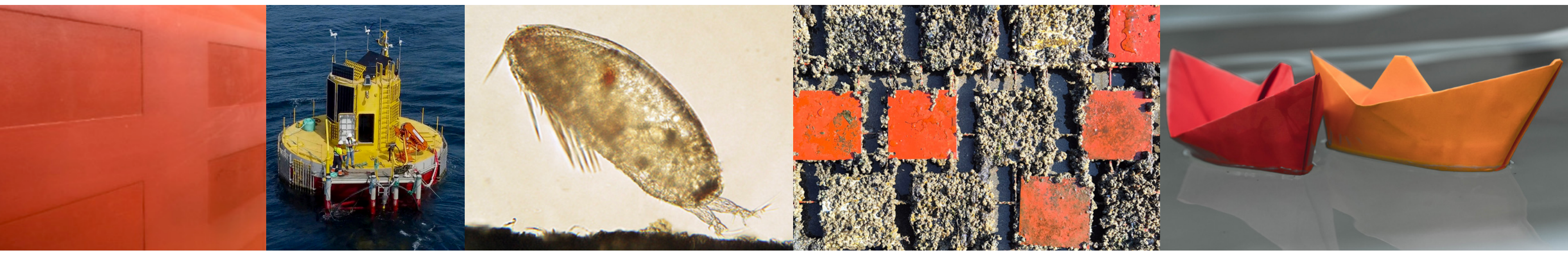

A prestudy carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published December 2025

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Summary

Dynamic conditions are known to have large impact on the formation of marine growth, biofouling, on both natural surfaces and antifouling coatings but are however still understudied. While testing of antifouling coatings in static conditions are widespread and well documented, data from testing under dynamic conditions is more scare and only described in a limited literature (around 30 publications) using various devices, methods and assays.

In this report we analyse the scientific literature on dynamic testing of antifouling coatings to describe how testing in static versus dynamic conditions can influence the results, i.e., measurement of biofouling (type and cover) on panels coated with antifouling.

The report includes a description of the biofouling characteristics (size, attachment strength and motility) of importance for the marine organisms like bacteria, plants and animals when hydrodynamic forces are present in natural environments (ie the ocean). The forces along the hull of a ship moving through the water are schematically illustrated with reasoning on how flow conditions impact the biofouling process ie both during attachment stage and for removal of the biofouling.

Results from the compiled literature showed that testing under dynamic condition primarily impact the lower forms of biofouling often referred to as the 'slime' layer. The slime layer consists of microorganisms (bacteria), microalgae (diatoms) and juveniles (larvae) of larger organisms. The organisms within the slime layer are surrounded by a matrix of ExtraPolymeric Substances (EPS) which is important for their attachment, and the composition of substances within this matrix shift under dynamic conditions compared to static conditions. The buildup of EPS under dynamic conditions creates a more tight and low form of growth and will enhance the ability for smaller biofouling to stay attached.

The attachment very close to a surface is further facilitated by the prevailing reduced water movement in the close vicinity to a surface like the ship hull. To achieve the height of this 'low velocity layer' both hydrodynamic calculations and knowledge about the present biofouling organisms are required. For larger hard type of biofouling (like blue mussels, barnacles and calcareous tubeworms) the structures/features used for attachment differs, where mussels use threads of glue which gives several attachment points while for barnacles and tubeworms the entire underside of the animal adheres to the surface (giving a large attachment area). To fully resolve the forces (flow velocities) needed to hinder attachment and also to remove fouling organisms, a combination of several scientific disciplines (hydrodynamics, surface chemistry and biology) will be needed.

Through the French research platform GDR Biofouling & Environment, established 2025, we are discussing previous knowledge on dynamic testing and the recently developed testing methods and facilities. In ongoing discussions between the antifouling paint production industry and academia, there is consensus that standardisation of dynamic testing is needed for sound interpretation and comparison between results.

An overview of the dynamic devices used today are presented with their advantages and limitations. As a summary we compare static versus dynamic testing and discuss around their use for different types of tests and applications. Finally, we reflect on future development and suggest a multidisciplinary approach to advance work within this area.

Sammanfattning

I denna rapport analyserar vi den vetenskapliga litteratur som beskriver tester av antifouling färg under dynamiska förhållanden. Det är sedan länge känt att marin påväxt, s.k. biofouling, påverkas av dynamiska förhållanden men trots det finns förhållandevis få studier inom området. Medan tester i statiska förhållanden är väldokumenterade finns det bara en begränsad mängd (ca 30-tal vetenskapliga publikationer) med data från antifoulingtester under dynamiska förhållanden, vilka är gjorda med olika testmetoder.

I rapporten analyserar vi vetenskaplig litteratur som innehåller tester av antifoulingfärg under dynamiska förhållanden med fokus på att beskriva hur tester utförda under statiska respektive dynamiska förhållanden kan påverka resultaten, dvs de slutvärden man får när påväxten på antifoulingproverna analyseras efter utförda tester. Rapporten innehåller en beskrivning av de karaktärer hos påväxten, som tex organismernas storlek, vidhäftningsstyrka och förmåga att röra sig och dessa karaktärers betydelse för hur organismerna påverkas av krafter från strömmande vatten som förekommer i havet (ffa över fartygsskrov). Även krafterna som skapas kring ett fartygsskrov illustreras översiktligt tillsammans med ett resonemang kring hur påväxtens vidhäftnings-process påverkas, både i steget när de skall limma sig fast och om/när de riskerar att falla/dras av.

Resultaten från vår litteratursammanställning visade att tester under dynamiska förhållanden framför allt har betydelse för bildandet av de lägre formerna av påväxt som ofta kallas ”slime” lagret. Detta lager består av mikroorganismer (bakterier), mikroalger (kiselalger) och juvenila/larvstadier av större organismer. Organismerna i slimelagret omges av en matris bestående av Extra Polymera Substanser (EPS) som är viktigt för deras vidhäftning/adhesion. Sammansättningen av substanser i matrisen varierar med dynamiska förhållanden jämfört med statiska tester. En EPS-matris som formas under dynamiska förhållanden blir tätare och tunnare vilket underlättar för organismer av mindre storlek att sitta kvar.

Vidhäftning av små organismer som sker väldigt nära en yta har dessutom fördelen att de skyddas i ett lager med låga vattenflöden. För att få kunskap om höjden på detta lager med låga strömhastigheter behövs hydrodynamiska uträkningar och kunskap om påväxtorganismerna. För större påväxtorganismer (som musslor, havstulpaner och kalkinlagrande havsborstmaskar) beror vidhäftningsstyrkan på deras olika metoder att fästa sig, där musslor använder limtrådar med flera olika fästpunkter medan havstulpaner och havsbortsmaskar limmar fast ett större område (hela undersidan av djuret omvandlas till en häftplatta). För att beskriva vilka krafter (flödeshastigheter) som behövs för att hindra vidhäftning samt slita bort organismer från ytan behövs en kombination av kunskap från flera vetenskapliga områden (hydrodynamik, ytkemi och -fysik samt biologi).

Genom medverkan i den franska forskningsplattformen GDR Biofouling & Environment, som etablerades 2025, diskuterar vi tidigare kunskap inom dynamiska tester, relevanta testmetoder och utrustning. I pågående diskussioner mellan tillverkare av antifoulingfärg och akademi råder samsyn på att standardiserade tester behövs för att möjliggöra korrekta tolkningar och jämförelser mellan resultat.

En översikt av de metoder, apparater och testanordningar som används idag presenteras tillsammans med deras respektive fördelar och begränsningar. Som summering jämför vi statiska och dynamiska tester och diskuterar kring när de olika sätten att testa kan användas. Slutligen reflekterar vi om framtida utveckling av detta område och föreslår ett tvärvetenskapligt tillvägagångssätt.

Contents

1 Introduction

To find antifouling measures that hinder or reduce the unwanted growth of marine organisms, biofouling, on ship hulls is a large area for research and innovation and has generated a great amount of data and scientific literature during the last decades (for reviews see for example Schultz et al 2011, Lindholt et al 2015).

However, there is today (2025) a common view within the field of antifouling, both in the scientific community and industry as paint manufacturers, that the impact of dynamic conditions on the antifouling properties of coatings in field conditions are understudied. Several studies show that the biofouling differs between static and dynamic conditions, for example Hunsucker et al (2017) found macrofouling communities (severe fouling) on static panels while coatings in dynamic conditions only had biofilms and green macroalgae (less severe fouling). This highlights the importance of using dynamic testing concurrently with static immersion in coating evaluation to better understand how the system will respond to hydrodynamic stresses.

One challenge within this field of research is that knowledge from several disciplines needs to be combined to perform dynamic studies of antifouling coatings. The characterization of the hydrodynamic conditions is needed for useful comparisons between different test setups (both in lab and field). Another challenge lies in the application of results from test conditions (biofouling roughness) when translated to the predicted impact for a moving ship. The biofouling consists of both hard and soft, living and growing marine organisms, and can therefore not directly/in a simple way be translated into a roughness coefficient to be used further in hydrodynamic modelling.

The process of biofouling takes place in the interphase between water and the hull surface under flow conditions and all aspects that will impact this process are of importance. This requires collaboration between several fields of research like marine ecology, ecotoxicology, surface/interphase chemistry, fluid dynamics, optimally also with data from paint producers and naval architects at hand. Understanding of the hydrodynamic forces that impact a larvae (for example a barnacle larvae) when approaching a surface is crucial. However, there are multitudes of marine organisms with an "attached lifeform" (attached way of life) with different forms of larval stages, of different size, ability to swim and various attachment structures. Knowledge of several processes: attachment mechanism and adhesion strength, tolerance to toxins and surface characteristics, duration of larval stage, swimming or "propelling" capacities together with the character of the surrounding hydrodynamic/flow conditions and their correlated forces, are needed for the complete picture.

1.1 Overview of studies on antifouling coating under dynamic conditions

Here we summarize the present (2025) literature around the topic of static vs dynamic testing and evaluation of antifouling coatings by different facilities/devices and methods.

Several dynamic methods for testing antifouling coatings are available using facilities such as power boat (Florida, US), rotating drums (Denmark, France, Netherlands, South Korea), flow channels (Newcastle/Strathclyde, US, Sweden). In chapter 4 we present the towing tank that is used for model ship trials within ship-building, and other facilities together with short explanations of characteristic and development status of respective method.

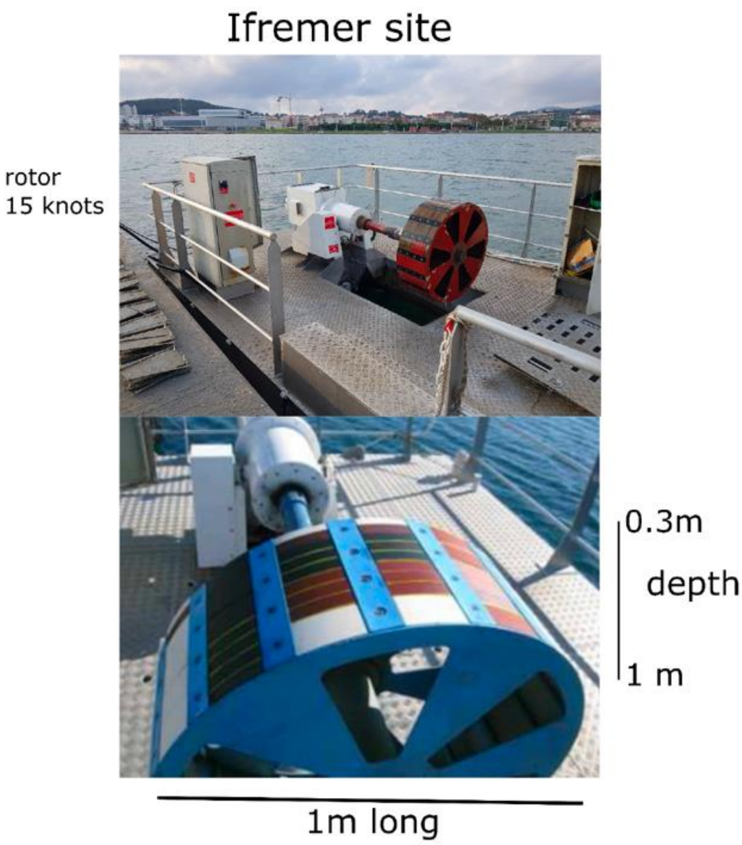


Figure 1.1: Example of device, rotor for testing efficacy of antifouling coatings in the field at Ifremer site in France, North Western Mediterranean (from Catao et al 2019).

Two recent review papers have described and compared the available dynamic testing methods. i) Lindholt et al 2015 included the following test set ups: Rotating disc, Rotating cylinder, Towing tank, Water tunnel, Static and Dynamic testing on boat and Pipes (Advantages, Disadvantages and Uncertainty). ii) Yeginbayeva et al 2019 did a comparison between the above-mentioned devices and in addition Flow channel, Floating element force balance and Flat plate BL method (Test quality and Cost).

The compilation of literature performed here therefore focus on recent studies (mainly from 2020 and later) that has been published after the reviews by Lindholt and Yeginbayeva, performed under dynamic conditions and with focus on the specific results due to testing in such regime.

Table 1.1: References with specific findings due to dynamic conditions

Paper (Author, year)	**Biofouling type**	**Dynamic Setup**	**Finding**
Lee et al 2021	Diatoms	Flow channel	Good agreement in Lab and Field assays
Yeginbayeva et al 2020	Natural biofilms	Cultivation chamber (lab) on ship (field) Test in Flow channel	Lab cultivated biofilm fluffy Field cultivated biofilm tenacious
Zhang et al 2013	Diatoms *Ulva* spores	Rotating drum	Diatoms good agreement in lab and field test
Davidsson et al 2020	Natural biofilms	Flume test	Long stationary periods give severe fouling
Portas et al 2023	Whole natural community	Natural environment and Acoustic Doppler Current Profiler (ADCP)	Richness of biofouling (prokaryotes and eukaryotes) higher in stronger currents
Catao et al 2019	Bacteria	Rotor, field	Differences between coatings and shear stress a driver
Bae et al 2022	Macrofouling (invertebrates: ascidians and bryozoans)	On yachts	Less biofouling on superhydrophobic coatings
Yeginbayeva et al 2019	Natural biofilms	Rotating discs, lab	Difference between coatings
Casse and Swain 2006	Natural bacteria	Rotating drum	More on static than dynamic, more heterogenous on FR

1.2 Findings from previous studies

Table 1.1 presents the key studies from the reviewed literature, the biofouling organisms, dynamic setup and the findings in short (to be more elaborated in Chapters below). A short explanation of the most common biofouling organisms used in antifouling studies and their characteristics will follow in Chapter 2 The Biofouling (Biology). The natural biofouling communities found in the ocean are believed to contain around 4 000 different species (Yebra et 2004) while only a share of those can be kept in laboratory *1.3 Lab and field comparisons*. The length (minutes, days, weeks, months, years) and seasonal timing of testing is important *1.4 Timeframe of testing* and finally there are different biofouling species present in different biogeographical regions *1.5 Geographical location of testing*.

1.3 Lab and field comparisons

In a study by Zhang et al 2013 the lab dynamic assay with diatoms was found in accordance with the field dynamic tests concluding diatoms as a candidate organism to evaluate Foul Release coatings. Similar results were also found in a study focusing on Foul Release (FR) coatings by Lee et al 2021 (also testing diatoms) between laboratory test and seawater immersion with conclusion that laboratory-scale microalgae fouling tests and circulating seawater channel tests are suitable for evaluating the antifouling performance of FR coatings. When Zhang et al (2013) did the same comparison (dynamic assay lab and field) for the green alga Ulva, the same agreement was not found. In a study from UK, biofilms (identification of organisms not conducted) grown under controlled dynamic conditions in laboratory were seen to be fluffy in structure and easily removed at the highest shear flow in the used water tunnel, while natural biofilm samples collected from the open sea were seen to be tenacious (closely adhering) Yeginbayeva et al 2020.

1.4 Timeframe of testing

Static in field

The time (length in months) and season (in temperate areas) for conducting experiments will be critical for the amount and sort of biofouling that can settle onto the panels. Panels exposed during longer time allow for higher growth and easy identification of adult fouling organisms. On the other hand, long-term testing (several months) also risks to include "over growth" (fouling in several layers) and grazing effects by for example fish and birds. Both the effects of attachment and detachment will be included and interact, which can make interpretation of results difficult. A way to partly solve this is by a frequent (monthly) addition of clean control panels that will show the "new" fouling organisms for the month.

Dynamic, rotating device

The rotating devices such as rotating drums and plates are programmed to follow typical operation schemes for ships including still periods in ports. The devices operate on timescales of weeks or months (Hazelback and Hunsucker et al in Florida, DTU Denmark, personal communication) hence they will capture biofouling over longer time/season. For both static and dynamic testing the organisms present (available) in the water will be crucial for the experimental results.

1.5 Geographical location of testing

In general, tropical areas with warmer water and higher salinity have both more fouling species and higher growth rates (hence giving the most challenging biofouling conditions). A recent paper describing the biofouling in Indonesian waters showed three different biofouling regions. In addition, there are regional and local variations in biofouling groups and species.

2 The biofouling (biology)

2.1 Marine biofilms

Diatoms and bacteria are the most common components of marine biofilms and the species and abundance are dependent both on geographical and seasonal variations (Salta et al 2013). The spores of macroalgae and larvae of sessile fouling organisms (like barnacles, mussels, calcareous polychaete worms, ascidians, bryozoans etc) will be present dependent on season and location.

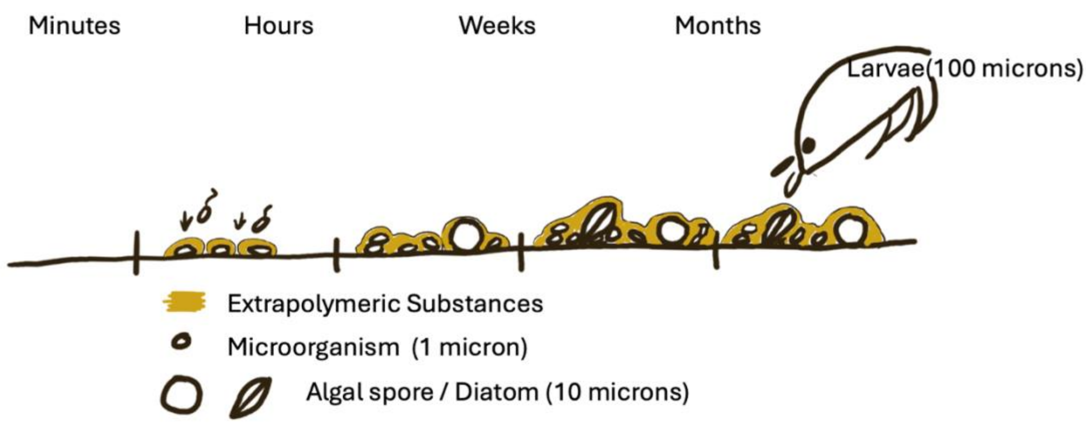


Figure 2.1: Illustration of biofouling stages on a submerged surface with time (bacteria 1micron, spore/diatom 10 micron, larvae 100-500 micron) inspired by Chambres et al 2006

2.2 Characteristics of the biofouling organisms, size, attachment strength and motility

Description of whole biofouling communities formed *in-situ* under controlled hydrodynamic conditions are scarce, however a recent study from North West Atlantic coasts of France (Portas et al 2023) illustrated by use of molecular methods that the composition of biofilms changed with hydrodynamic conditions.

2.2.1 Size and Attachment Strength

Bacteria
The size of marine bacteria is usually between 0.2 micron up to 1 micron in length. Already in the nearly 20 years old study by Casse and Swain (2006) the authors demonstrated that bacterial abundance was similar on four different antifouling coatings after static immersion, with largest decrease in numbers after dynamic immersion on the fouling release coating. Further Casse and Swain (2006) described that the bacterial population on the Fouling Release surface was more heterogeneous than on the biocide-based coatings. As bacteria are embedded in Extra Polymeric Substances (EPS) (see Figure 2.1) the detachment process takes place in form of “sloughing” of parts from the surface. Bacteria are ubiquitously found and their growth depend on availability of nutrients, oxygen etc. In field tests different hydrodynamic conditions (dynamic, cyclic) created by a rotor (see Fig 1) generated different bacterial community compositions (Catao et al 2019). A biofilm matrix

developed in high shear stress were further seen to contain more polysaccharides which is believed to be crucial for biofilm adhesion and cohesion (Portas et al 2023).

Diatoms and macroalgal spores (change in abundance and diversity)

The size of macroalgal spores varies among algal species and for diatoms among genera, the commonly used *Ulva* sp spores and benthic diatom *Navicula* sp are however about 10 microns in size (see refs Callow et al).

In diatom populations dominated by *Amphora*, *Navicula* and *Synedra* in static immersion, only *Amphora* was found on Fouling Release coating after dynamic immersion (Cassé and Swain, 2006). In contrary to static exposure, the diversity appeared to be significantly reduced on FRC coatings. The most common diatom genera found at *in service* ship hull where genera *Achnanthes, Amphora* and *Navicula* - both on copper-SPC and silicone FR coating (Hunsucker et al 2014) and diatom richness was greater on the ship with the FR coating. The diatoms are like bacteria embedded in Extra Polymeric Substances (see fig 1.2) and forces, shear stress in the range of 25-275 Pa, required for an 80% removal (references in Oliveira and Granhag 2016). Algal spores from *Ulva* sp will, upon initial attachment with a surface, release a pad of glue (with approximately the same forces needed for removal as diatoms) and when growing into adult it starts to produce specific holdfast structures.

Larval stages from biofouling invertebrate (focus on world-wide worst animal biofouling barnacles)

The size of larvae from biofouling species varies widely, where the typical size of some common species are: 150 micron (tubeworm, *Ficopomatus enigmaticus*), 300 micron (blue mussel, *Mytilus edulis*), 700 micron (ascidian, *Ciona intestinalis*), 1 000 microns (barnacle, *Amphibalanus improvisus*). Barnacles use a multi-protein “cement” for adhesion. The attachment strength in barnacles varies among species and is dependent on test conditions, but on silicone FR paint found to be around 0.2 MPa while on epoxy up to 2 MPa (review in Oliveira and Granhag 2016). Also “artificial barnacles” can be used and glued onto surfaces to simulate realistic roughness in flow channel experiments (for example 3D printed in Demirel et al 2017). These barnacle replicas are believed to serve well for the purpose of creating realistic hard fouling roughness to use further in resistance modelling (see more in Chapter 4.3). It should however be noted that the attachment of barnacles in nature most often take place within the actual animal (instead of between the animal and surface) leaving the barnacle baseplate on the surface creating a calcarious white ‘scar’.

Calcarious tubeworms, a globally problematic biofouling group, adhere in a similar way as barnacles while mussels instead use specific structures (byssus threads) for their adhesion. The number of the byssus threads produced by the mussels was seen to decrease with increasing Cu_2O content of the antifouling paint (Kojima et al 2016). In a field study testing “superhydrophobic” coatings on yachts, Bae et al (2022) found a decrease in cover of the common soft large fouling ascidians (*Ascidiella aspersa* and *Ciona robusta*) and branching bryozoans (*Bugula neritina*).

2.2.2 Motility

Diatoms and macroalgal spores

Even if some diatoms can create slow gliding movement along a surface through secretion of mucilage by a specific structure (raphe), they lack structures for propelling themselves through the water. Spores from macroalgae with the similar size as diatoms are also mainly dispersed as passive particles with sinking speeds between 0.01 and 0.1 mm/s (Coon et al. 1970, Vogel 1994). However, some brown and green algae have motile spores with maximum swimming speeds of 0.08 to 0.3 mm/s (Norton 1992). The swimming speed of the green alga *Ulva* sp is estimated to 0.2 mm/s (Granhag et al 2007).

Motile larval stages

Swimming speed of barnacle cypris larve has been estimated to 18 mm/s (Larson et al 2016) and larvae of blue mussels 7 mm/s (Fuchs et al 2011). Larvae are also seen to respond to hydrodynamic cues and can adopt different modes like sinking, hovering or swimming (for blue mussels see Fuchs et al 2011). To put the swimming speeds of marine larvae into context, some figures of expected flow velocities in the marine environment will be given. To start there will be a gradient of decreasing flow velocity close to any surface which is known as the *boundary layer* (Schlichting 1979). Within this approximately 1 to 10 mm thick boundary layer, water velocities are reduced. Further down, very close to a solid surface in a 10 to 150 µm thin layer called the viscous sub- layer, water velocities are estimated to range from 1 to 10 mm/s (Denny 1988). To keep in mind when continuing to next chapter is that the larvae might need the turbulent conditions to reach the surface (as passive sinking is to slow).

3 The ship and hydrodynamic conditions outside the hull

3.1 Flow regime

When a ship moves through water, the friction of the water acting over the ship's wetted surface area (WSA) causes a net force opposing the ship's motion. The frictional resistance is a function of the WSA of hull, speed, surface roughness, water density and water viscosity. The fouling is part of the surface roughness together with roughness created by paint damage or failure. To reduce the effects of viscous resistance, it is important to keep the hull clean from fouling (i.e., keep the roughness as low as possible).

Adjacent to a wall or a ship hull, where water is affected by the ship passing through, a boundary layer will be created, with a velocity gradient of decreasing velocities when getting closer to the hull surface (see Figure 3.1). This velocity profile is created by the *"no-slip condition"* i.e., that the velocity in the water layer most close to a surface is zero relative to the surface.

In the boundary layer, there can be two types of flow: laminar and turbulent flow. To predict the type of flow, the Reynolds number (Re) is used, where laminar flow has low Re, and turbulent high Re.

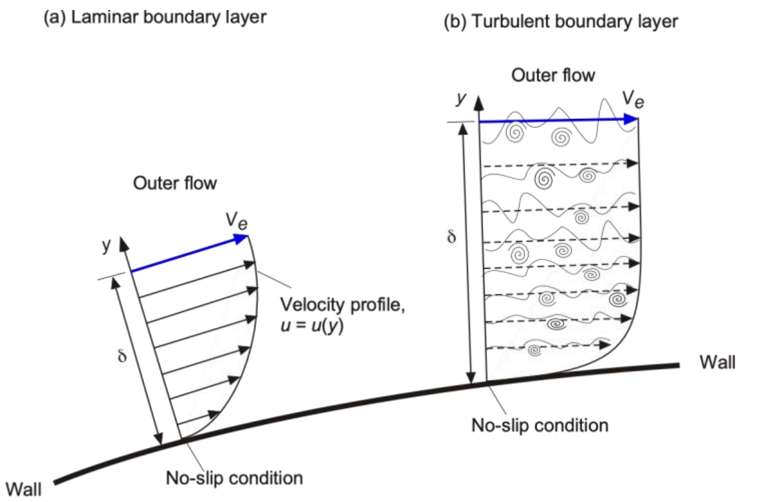


Figure 3.1: Velocity profiles of laminar and turbulent boundary layers (adapted from Leishman, 2023)

The flow outside the ship hull will be turbulent for almost the entire length of the hull as the Re for full-scale ships is typically very high. This will give a turbulent boundary layer except in a short area at the bow (forward-part) of the ship (see Figure 3.2).

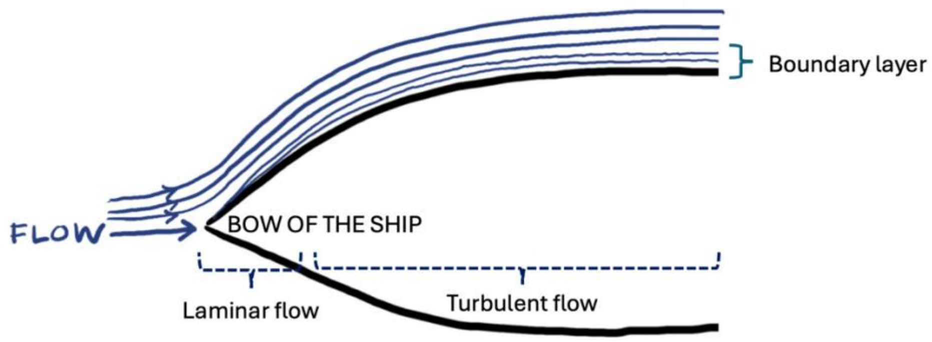


Figure 3.2: A ship moving through water with laminar flow in the bow which transits into turbulent flow after a short distance. (modified from Schultz et al 2000)

3.2 Slow flow close to the surface (viscous sublayer) and biofouling settlement

Picture a barnacle larvae moving towards the ship hull, it will when getting very close to the hull surface, reach a very thin layer (only 10-150 microns in height) dominated by laminar flow, this is called the viscous sublayer. The ability for the larvae to adhere will be dependent on its swimming capability and time for release of adhesive, the "settling window" ie long enough time with low enough forces (Larsson et al 2016).

Figure 3.3: Barnacle larvae in settling stage (cyprid-stage), making contact with the substrate (from Larsson et al 2016, photo credit Kent Berntsson)

At the same time as the turbulence is important for bringing larvae into the viscous sublayer, sweeps of turbulence can also remove larvae out of this layer (Larsson et al 2016).

In the viscous sublayer it is possible for a smaller organism (like the spore of the green alga *Ulva* see Figure 3.3) or a layer of tiny organisms 'slime' to stay attached. In this layer, a small-sized algal spore (≤10 µm in diameter) can be protected from hydrodynamic forces (Charters et al. 1970). This is possible for the motile spores of the globally problematic fouling alga *Ulva* sp (see Figure 3.4).

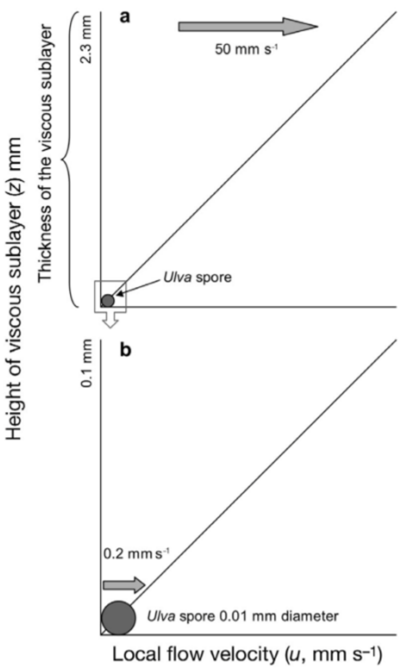


Figure 3.4: A free-stream velocity of 50 mm s–1 gives a (a) viscous sublayer thickness of 2.3 mm and (b) maximum flow speed of 0.2 mm s–1 at a spore height of 10 µm (0.01 mm) Diagonal line is the increase in local flow velocity with increasing height of the viscous sublayer (from Granhag et al 2007)

The so called "slime" is a layer consisting of for example bacteria, diatoms, other microalgae and smaller stages (larval or juvenile stages) of larger organisms. Surfaces in marine environment are never ´empty´ or clean besides a very short time period just after getting submerged.

Bacteria and other microorganisms like marine fungi will due to their small size form thin microbial films and therefor during the first time be sheltered in the viscous sublayer (with slow water movement and low forces). However, when bacteria grow the thickness of this film increase be reached by higher shear forces and parts of the film will be removed (peel off).

4 Static and Dynamic testing rigs and setups

4.1 Static and Dynamic panel immersion test

There are several immersion test platforms where panels are submerged in the ocean, for example Harsh Lab and The Poseidon Dynamic Test System https://poseidonsciences.com/testing-services/dynamic-immersion/. At those facilities relatively small panels are attached to test antifouling coatings ability to deter fouling from settling on the surface. Alternatively, the biofouling adhesion strength to the surface can be tested by exposing them to shear stress through water movement. Dynamic testing, i.e., where the samples endure a simulated shear stress by for instance a rotating drum, is as pointed out above scarcer (however see Table 1.1:). At the testing facility 'Harsh lab´ the Dynamic Antifouling Test (DANTE) is performed with speeds up to 15 knots and max capacity of 120 samples. In the Poseidon Systems panels rotate horizontallt with speed 15-25 knots.

Figure 4.1: Harsh Lab facility for testing marine antifouling coatings to biofouling and fluid shear forces in natural seawater

State of topic: In general, for static testing it's assessed that sufficient facilities of acceptable quality exist. However, dynamic test facilities are not that frequent, and as fouling speed is affected by shear stress, more dynamic testing facilities using similar standardized testing would be useful. Another issue is size of samples from the static and dynamic test facilities. To test how much more skin friction a fouled surface generates, larger samples are necessary.

4.2 Surface condition and measurement of surface roughness

In the maritime sector, hull roughness has large influence on the friction/drag and ship performance (Schultz et al., 2011). Typically, the hull roughness is measured at intervals between in-docking and out-docking of a ship, using a device called hull roughness gauge. This device has a pressure-sensitive probe and measures the maximum peak-to-valley height over a 50 mm length of the hull surface (Rt50). Several values over 50 mm will be combined to give a mean hull roughness (MHR) at a location and the average of all (approximately 100) location readings will give the Average Hull Roughness (AHR). For practical estimation, data of Average Hull Roughness linked with visual inspections can be translated into skin friction. From measured Average Hull Roughness, the skin friction can be traditionally estimated using the ITTC-1978 correlation allowance formula (Townsin's formula). Alternatively, for more detailed comparisons regarding specific surface conditions, databases such as the SSPA's Skin Friction Database (https://sfd.sspa.se) can be used.

This method (as used by inspectors/classification companies during dry dockings) is sufficient to evaluate roughness of the ship hull surfaces. The hull roughness probe works on solid material and can measure a 2D profile of, for example, paint wear and chipping of paint, while it has limitations regarding measurements on soft biofilms and hard biofouling.

Figure 4.2: Hull roughness Analyzer used to measure roughness of hull surface

For more accurate approaches and to be able to model a surface with biofouling methods like for example Computational Fluid Dynamics (CFD) or 3D stereography needs to be used.

State of topic: Methods for surface topology measurements are much more time consuming and expensive than direct measurements on the hull and usually only very small samples can be measured. Therefore, development of such methods and/or link between the advanced methods and the simpler measurements with a hull roughness gauge would be beneficial.

4.3 Artificial surface or user input

For lab test of skin friction on rough surfaces, a general problem is that it's difficult or time consuming to replicate surfaces found in the marine industry. Many types of rough surfaces exist, which are quite different topology wise. The most common types are: newly applied coatings, biofilms, biofouling, damaged and/or aged coatings and combinations thereof. Under real conditions this is even more complex as on a vessel, the severity and type of roughness is not uniformly distributed but instead for instance often more damaged coating found along the flat of side of a vessel (due to docking operations), and more algal fouling where sunlight more easily reaches the surface.

In order to test and build up a database describing these surfaces in terms of the effect on skin friction, the surfaces need to be tested in a lab, in for example a cavitation tunnel or a towing tank. Then the issue becomes how to replicate these surface topologies on the test surface in the device used for testing in the lab. To achieve results from natural biofouling is fairly simple if the test plate can be submerged in the ocean and tested for skin friction afterwards, however controlling the degree of fouling and what fouling attaches to the surface is difficult (see Chapter 2 on biofouling)

Figure 4.3: Fouling plate in the ocean

Figure 4.4: Simulated aged and damaged coating

4.4 Towing tank tests

State of topic: In reality, it is difficult to replicate surfaces which are common on vessel surfaces. The problem is not that the industry does not know the state of the surface condition, but that replicating large samples and transferring them to lab measurement equipment is difficult.

Two possible solutions have been proposed. The first is applying sheets to the vessel surface over months or years that can be transferred to measurement equipment. The second is scanning the surface and subsequent fabrication for lab testing (3D printing). Recent studies have successfully utilized 3D printing to replicate hard fouling, such as barnacles to determine added resistance (Uzun et al., 2017; Gowing et al., 2018).

However, while 3D printing is effective for rigid roughness elements, it faces challenges in replicating soft fouling or biofilms. Consequently, neither solution is fully established as a standard procedure at present, due to these technical limitations and the high cost of experiments.

5 Hydrodynamic performance modelling

5.1 Empirical method, International Towing Tank Conference (ITTC)

The general procedures used in towing tank facilities for predicting full scale performance of a vessel based on experimental measurements and CFD methods are described in the ITTC method (International Towing Tank Conference). These methods describe how to separate and scale gravitational and viscous effects affecting the resistance of the vessel, propulsion and residual resistance etc. Towing tank facilities adopt these methods to be able to provide the best possible full-scale speed/power prediction and the best possible design of the vessel.

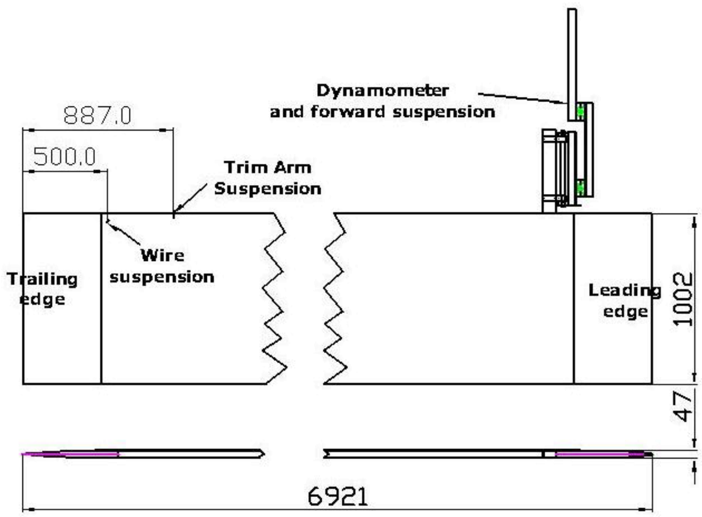
Included in the ITTC method is the Correlation Allowance, ks, (often based on Bowden-Davison correlation allowance), to increase the skin friction resistance of the full-scale vessel. This allowance is usually set to a standard value for all vessels at newly built surface condition (ks=150 microns). As the ship ages, the surface condition deteriorates, and the equivalent sand grain roughness parameter (ks) cannot in reality be directly linked to a certain roughness topology for the vessel.

State of Topic: This issue is under continuing investigation at towing tank facilities using various approaches. It is unlikely that linking ks used in the ITTC method to laboratory tests of rough surfaces is sufficient, as rough surfaces on vessels do not only affect skin friction resistance, but also the wake fraction (inflow to propeller) and therefore also propulsive efficiency.

5.2 Towing tank tests

Once the issues regarding surface replication have been solved, the next part is to predict the performance effect of roughness better. By far, using a flat plate in a towing tank is widely recognized as the most accurate way to measure the effect of a rough surface on skin friction (Demirel et al., 2017).

There are several reasons for this. First, tests can be conducted at towing tank facilities operating under ITTC guidelines, ensuring standardized and quality measurements. The Reynolds number (Re) is quite high for the tests, typically about half full-scale ship speed is used and the test plates are long (at SSPA Maritime Center, the plate is 7 meters long). Re is used as a predictor of the flow regime (laminar low Re, turbulent high Re) and in towing tanks you can get a higher Re than any other types of skin friction measurement (i.e., you will have a turbulent flow representative for ship conditions). The long length of the plate also mitigates issues of turbulent transition and step change in roughness. The test device (the plate) can be moved to do for example fouling in the ocean.



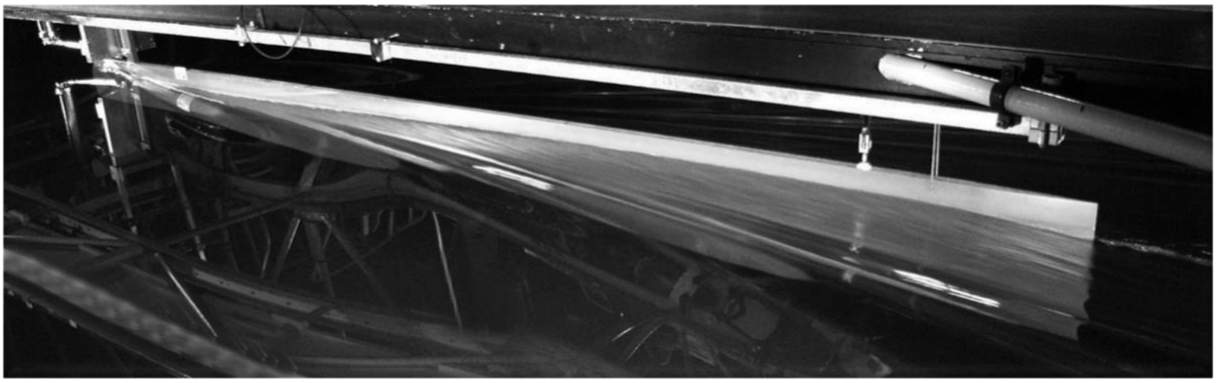


Figure 5.1: Flat plate in towing tank at SSPA Maritime center

State of topic: For the reason that a high Re can be achieved, the skin friction measurement on a flat plate in a towing tank is considered the best option, but it comes at a price of quite high cost per test as it's a large area (14 m^2) that needs to be covered with the rough surface to be tested, and the towing tank facility is expensive to use. In terms of necessary technical developments for flat plate testing in towing tanks, methodology is well-established and highly reliable. However, research on scaling laws, such as Granville scaling, or correcting for differences with actual hulls where pressure gradients exist, is still ongoing.

5.3 Cavitation tunnel test or fully turbulent flow channel

Although the flat plate in a towing tank is the most accurate and versatile method, alternative devices exist for specific applications.

Below following alternative devices for measuring skin friction are described:

1. Cavitation tunnel
2. Flow channel
3. Couette cell (rotating cylinder)
4. Rotating discs (flat plates horizontal)

Cavitation tunnel

A cavitation tunnel is a facility many towing tank facilities has access to. It is mainly used for propeller testing by circulating water, usually at a low pressure around a closed loop. However, it can also be used for testing skin friction on rough surface, by adding a plate in the roof or bottom of the cavitation tunnel where the forces (mainly forces in the streamwise direction) can be measured. Applying the rough surface to this plate, the effect on skin friction can be extracted using the measured force. Alternatively, the boundary layer can be measured over the test section using LDV (Laser Doppler Velocimetry), and the velocity shift can be extracted from which the skin friction coefficient can be calculated.

Figure 5.2: Cavitation tunnel at SSPA Maritime Center

State of device: A cavitation tunnel is as the towing tank expensive to use but doesn't offer the same advantages as the flat plate in the towing tank. The sample size is much smaller which requires more extrapolation, and more importantly the step change in roughness from the surface before the sample is difficult to take into account. LDV measurements are even more expensive and time consuming, and as such this device is rarely used for skin friction measurements.

Flow channel

A flow channel is a channel where flow is generated by a pump, much like a cavitation tunnel, with the difference that free surface is exposed to the environment, i.e., it's not closed on the top as a cavitation tunnel. It is therefore a middle ground between towing tank (free surface with moving plate) and cavitation tunnel (closed surface and stationary plate).

A flow channel is usually a much smaller facility than both a cavitation tunnel and a towing tank, for which reason the Reynolds number is also smaller, leading to less accuracy than the other two devices.

Figure 5.3: Example of flow channel

State of device: As the accuracy and sample size is much smaller, these are usually used for dynamic testing for example fouling attachment over time. They are however much cheaper to use than larger facilities, and as such could be used for skin friction measurement on smaller budget.

Couette cell

A Couette cell is a device consisting of two cylinders, where either the inner or outer cylinder is rotating, creating a boundary layer flow between the cylinders. Measuring the rpm and torque, it is possible extract the skin friction coefficient of the surface, which can be for example a marine coating.

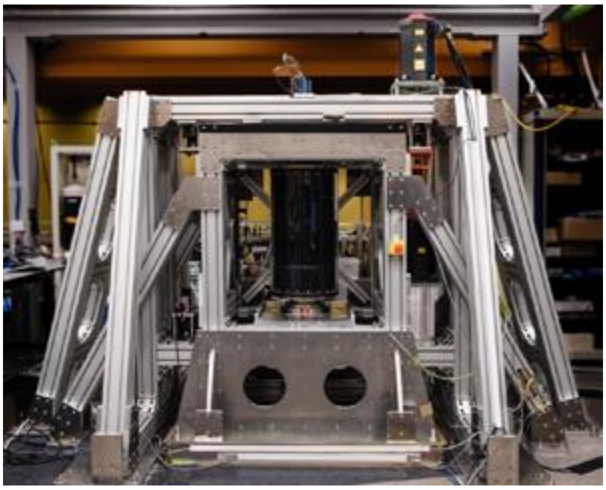


Figure 5.4: Example of Couette cell

State of device: Although being a relatively cheap option for measuring skin friction on rough surfaces, it does come with some complications. The flow inside is a Couette cell is quite complicated by the formation of Taylor vortices, which create a flow which is anything but uniform in the axial direction of the cell, making it very difficult to translate rpm and torque to skin friction with confidence. The device is however quite useful for self-polishing of coating or aging of coatings as having the device active for long durations is not too expensive. Couette cell flow is quite well understood and needs no further research.

Rotating Discs

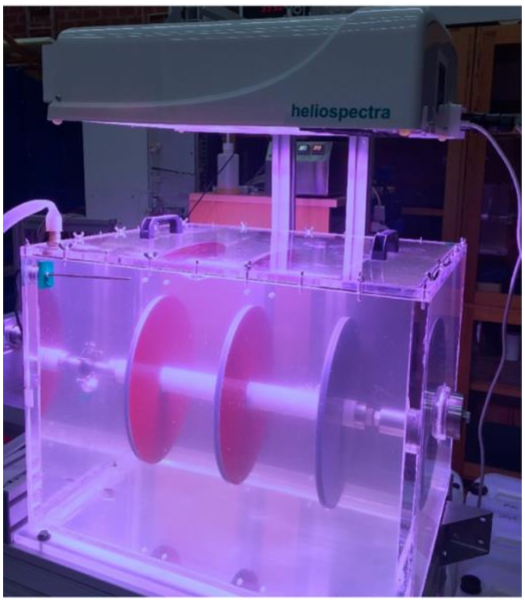


Figure 5.5: Lab set up with Rotating discs (fromYeginbayeva et al 2019)

Rotating discs involve spinning a coated disc in a fluid to generate shear stress. The setup allows for high-speed testing and is relatively compact.

State of device: While it is useful for accelerated testing, the shear stress varies along the radius of the disc, which makes it difficult to define a single roughness Re for the entire sample.

5.4 Roughness function (Basis from experiment) and Empirical method (ITTC 2011)

Roughness functions, often implemented via the Correlation Allowance using Bowden-Davison formula, are the simplest method for estimating effects of roughness on skin friction. They usually consist of a single parameter equation (for the roughness, AHR) along with usually the Reynolds number (i.e., speed and length). For the cheap and quick but not very accurate estimation of increase in skin friction, they certainly have their justification, especially for surfaces not very rough, like a newly built ship. However, describing the skin friction by a simple empirical universal relation just using a one parameter function introduces quite large uncertainties.

When the ship ages and the surface deteriorates, more advanced methods can be used for a more accurate estimation. Describing the rough surface not only as a roughness height but linking it to actually measured rough surfaces will allow for a much more accurate prediction. Several researchers (Schultz, 2004; Schultz and Flack, 2007) have done such measurements over the years in the laboratory for surfaces relevant to the maritime industry, but these results are measurements particular for the laboratory and measurement technique used (see Figure 5.6). Compiling the results into a single database is difficult, as a common reference more often than not does not exist. Perhaps the most complete database for rough surfaces and the of skin friction in the maritime industry is the SSPA Skin Friction Database (available on https://sfd.sspa.se), where results are collected and presented in an interactive database (see Figure 5.6).

This collection of results, although quite large (about 20 rough surfaces tested) could benefit for more variety of rough surfaces to be tested.

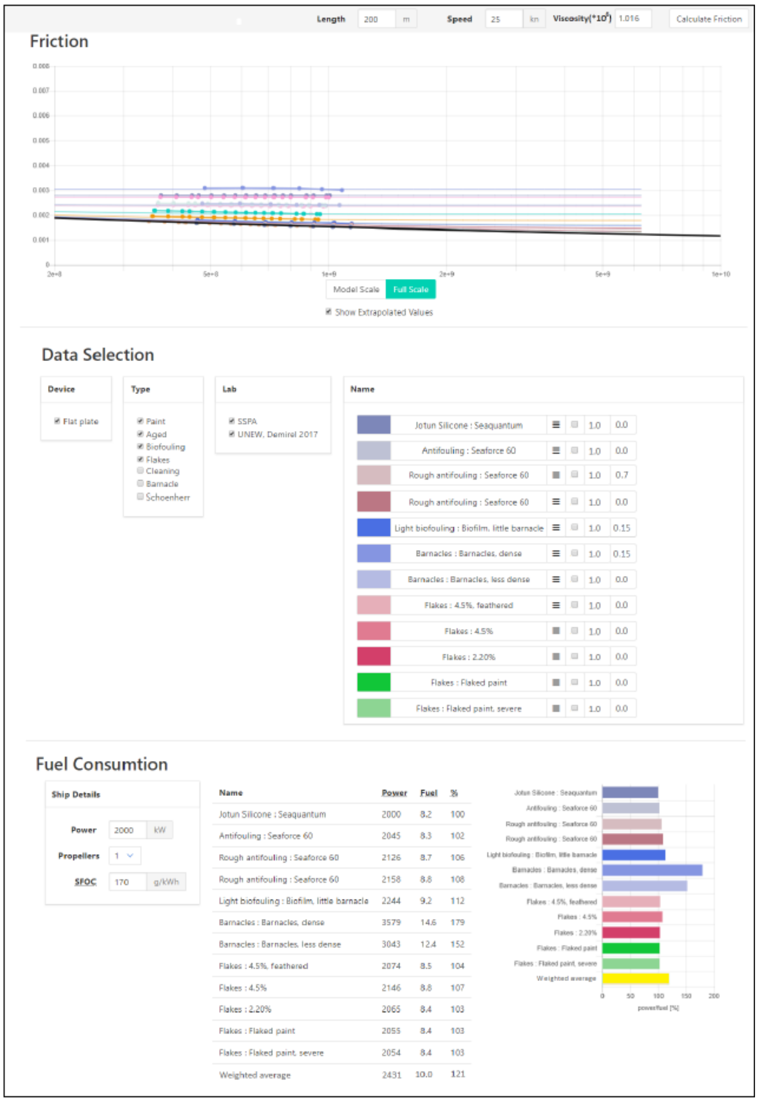


Figure 5.6: Interphase Skin Friction Database

5.5 Roughness function (ΔU^{+})

The roughness function, also referred to as the velocity shift function (ΔU^{+}), is a well-known and understood hydrodynamic phenomenon describing the flow modification in the boundary layer due to surface roughness. As the skin friction increases due to roughness, the velocity gradient in the viscous sublayer also increases, which in turn results in a velocity shift in the log layer region of the boundary layer which can be measured (see Figure 5.7). However, measuring the velocity shift requires quite expensive equipment such as LDV (Laser Doppler Velocimetry) and is very time consuming.

For practical development skin friction database results, it is therefore not considered to be an economically viable method, although both measurement methods and the understanding of physics behind have been developed.

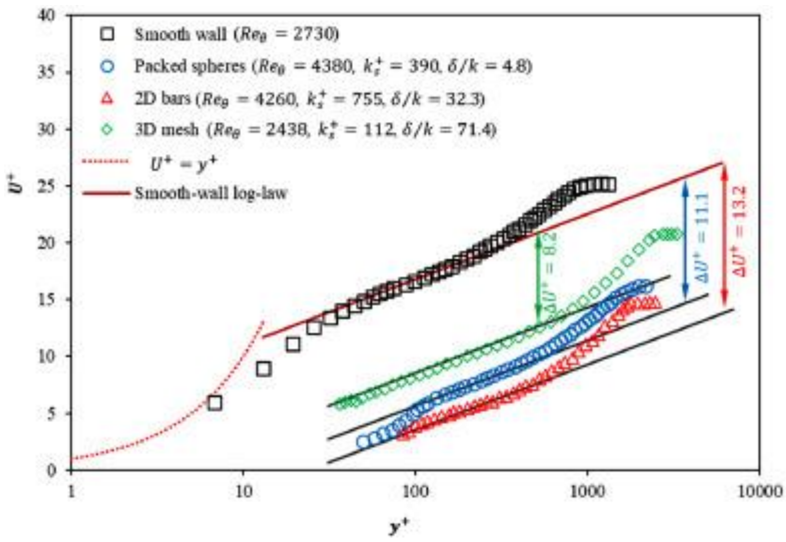


Figure 5.7: Examples of the roughness function (ΔU⁺) in the turbulent boundary layer. The graph shows the downward vertical shift of the mean velocity profiles in the log-law region for various rough surfaces compared to the smooth wall baseline (adapted from Kadivar et al., 2021).

5.6 Computational Fluid Dynamics (CFD) modified wall function

CFD (Computational Fluid Dynamics) has been used for many years for resistance predictions for vessels, and more recently for more accurate resistance predictions with rough surfaces. Many roughness functions in CFD have been suggested in the literature both for fully resolved boundary layer and wall functions. In general, most such functions work quite well and are able to predict the increase in skin friction and even how rough surfaces will affect the flow around the hull influencing not only skin friction but also the wake fraction and propulsive efficiency, to mention a few. Several validation studies and comparisons of roughness function are available in the literature (Demirel et al., 2017; Farkas et al., 2018; Song et al., 2019).

Most CFD roughness functions utilise the parameter ks (equivalent sand-grain roughness), which is a hydraulic parameter that cannot be directly measured such as AHR (Average Hull Roughness). For this reason, it is difficult to inspect a rough hull surface and determine what value of ks to use to simulate that surface. However, if substantial skin friction databases are available, ks for a given surface can be found by reverse engineering the model tests in CFD (i.e., testing several ks for a laboratory measurement until ks reproduces the increase in skin friction). This will improve the accuracy of a relation that already exists (AHR/ks relation) which facilitates the introduction of roughness to CFD. More validation of this relation and validation of CFD skin friction prediction is still needed to increase confidence in these models.

5.7 Summary differences static and dynamic testing

Table 5.1 Summary differences static and dynamic testing

Test type	Facility types	Main purpose	Main characteristics	Measurement/metrics	Test quality (reproducibility/ environment)	Complexity	Pros	Cons
Static Immersion Test	- tank (lab scale) - seawater pool (outdoor) - rack/raft (open sea)	- antifouling performance evaluation at static conditions - long-term durability assessment	- stagnant environments - low flow velocity/shear stress not accounted - prolonged immersion (seawater pool/rack) - natural conditions (if outdoor)	- biofouling attachment - surface roughness - changes in coating surface properties (contact angle, surface energy, etc.)	- tank (very high/low) - seawater pool (medium/medium) - rack (low/very high)	- simple procedure, facility accessible - standardized protocol (ISO 11306) - low-medium complexity	- simple and inexpensive - easy to standardize - strict parameter control (tank) - exposure to natural environment (saltwater pool, outdoor rack) - long-term observation of biofouling communities	- disparity with real environment - stagnant environment - flow rate/shear stress X - limitation in seasonal biodiversity due to lack of flow - environmental variability (outdoor)

Dynamic Immersion Test	- rotating drum - rotating disk - tank+pump (recirculating) - flow channel/Tunnel	- antifouling performance evaluation at specific operating conditions - precise shear stress and hydrodynamic performance - high-fidelity performance validation	- realistic operational environments - varying flow velocity/shear stress - precise rotation/shear stress control	- biofouling attachment - hydrodynamic properties (drag, shear stress) - dynamic contact angle - speed-dependent biocide release rate analysis	- rotating drum (medium/low) - rotating disk (very high/medium) - tank+pump (medium-high/medium-high) - flow channel/tunnel (very high/high)	- require specialized expertise in procedure, facility operation - high-speed cameras/shear force sensors required - medium-high complexity	- realistic operational conditions - evaluate flow rate/shear stress effects - assess long-term durability, and vary flow rate conditions - quantitative analysis of coating-fluid interactions	- high cost and complexity - difficult to standardize - challenge to simulate perfect environment - limited facility accessibility

6 Conclusion and selection of best matching setup based on use

One reason for the relatively few studies on biofouling and antifouling coatings in dynamic conditions can be due to the need for elaborated test setups and specialized equipment to measure hydrodynamic forces.

Within this field there are several reasons and interests for conducting tests, such as:

- Antifouling paint to be both durable and effective in hindering settlement or biofouling.
- Ship performance modelling to describe the roughness part created by biofouling in the search for reducing surface roughness and subsequently reduce friction and fuel penalties.
- Achieve background data for sustainability assessment and regulations to set the frames for environmental impact

Hence a thorough reasoning around the key parameters of importance in the process to be tested is required at design of test.

As described by Davidsson et al 2020, biofouling accumulation is more likely to occur during stationary periods where the hull is more likely to be colonized than when ship is underway. In the Biology chapter (see Chapter 2) we illustrate the relatively weak swimming abilities of algal spores and invertebrate larvae in comparison to the flow and corresponding forces that organisms encounter in a turbulent flow regime around a hull which also supports this. However, some water movement is needed for the fouling organisms to reach the hull surface.

In the study by Davidsson et al 2020, longer stationary times or "lay-ups" of several weeks were tested, which are quite rare cases for most shipping segments. Today's dynamic test settings include alternating periods between running and still time which is realistic in terms of ship operation profiles. However, the type of boundary layer created in the rotating devices (as explained in Chapter 4) due to their form and size (relatively small cylinders), is not fully representative for the boundary layer created along the long and flat ship hull.

Biofouling revisited

As biofouling consist of many different organisms, with varying body shapes, with and without hard structures, they are difficult to translate into a roughness and further to predict how it will be affected by shear stress. For example, will soft several cm long algal filament streamline along the hull and not impact the ship speed in the same way as a cm high barnacle with hard shell? When zooming into the slime or microbial film including all smaller organisms, it turns out to be complex as well as the Extra Polymeric Substances in this layer can change its biochemical composition and under flow conditions this layer can become tenacious and more difficult to remove.

What type of biofouling organisms that will be able to attach is dependent on the plants and animals present in the water. The strands of bacteria, or species of diatoms, microalgae and larval stages will constitute the "seed pool" in that water area, referred to as the fouling pressure. The fouling pressure varies with geographic location and season. However, as biofouling species are known to be overall present in the ocean there will always be some candidates. Recalling that world-wide biofouling includes more than 4000 marine organisms, it is not a question of if the surface will be fouled but with what type of biofouling. Together with abundance of different organisms, also knowledge of the attachment procedure and attachment strengths of the organisms is needed, together with the forces they are exposed to due to the ship movement. Here also their sensitivity and tolerance to biocides and surface characteristics provided by the antifouling paints is important. In short, the biocides can impact the ability for organisms to attach by disrupting or destroying cells and systems. The physical and chemical surface characteristics will impact the attachment, i.e., weaken the adhesive strength by making the crosslinking between the larvae and surface weaker.

Collaboration and forums within Academia

As shown by the presented literature compilation several different devices are used in the research on dynamic testing. This can often be explained by that collaboration started up with test facility geographically close (at same or nearby Univerist or site). To share information and knowledge within research the formation of networks like the GDR in France is a promising way forward. Collaboration is needed to align testing, agree on characteristics/description to be included with aim to make results from dynamic testing available and comparable.

Testing in Antifouling Paint industry

Antifouling paint producers have been conducting dynamic testing for paint durability, resistance and effectivity over long time (Sanches and Yebra 2009), however without openly available data. Durability and biofouling efficacy testing of coatings are to our knowledge performed under dynamic conditions using varying devices. Antifouling coatings evaluated using ASTM6990 "Standard for Evaluating Biofouling Resistance and Physical Performance of Marine Coating Systems." will be representative for the specific region and time of year in which the panels are immersed. To ensure that antifouling paint products are exposed to challenging conditions the coating companies also use tropical test sites

ASTM Standards

D6990-05 (2020) Standard Practice for Evaluating Biofouling Resistance and Physical Performance of Marine Coating Systems1

D4939 Test Method for Subjecting Marine Antifouling Coating to Biofouling and Fluid Shear Forces in Natural Seawater

D5618 Test Method for Measurement of Barnacle Adhesion Strength in Shear

7 Future outlook

Besides the identified need for characterization and description of the dynamic conditions to be able to make useful comparisons, both between different field tests and in the transfer of results to ship hull conditions, this area also benefits from well elaborated databases and decision support tools. Today this type of service is mainly produced within the coating industry, with few openly available tools (but see for example HullMASTER). It would be beneficial if comprehensive tools for general use in future could be provided (through for example IMO).

As illustrated in this report, the problem of biofouling is complex due to the interaction of several factors like flow, surface characteristics and biofouling type. We therefore believe a multi-disciplinary research approach is needed in future studies combining several scientific fields like marine ecology, ecotoxicology, surface and interphase chemistry and physics and fluid dynamics.

8 Acknowledgement

Many thanks to the antifouling paint industry representatives sharing experiences and through fruitful discussions enabling us to understand more about the ongoing activities on dynamic testing within this industry. As testing of products are directly linked to coating performance internal industry results are not openly available why discussion is taking place on a conceptual level.

The company I-tech for arranging the International Antifouling Conference in Gothenburg 2025 with presentation on updates in the field and for creating a forum for industry (antifouling paint producers PPG, Hempel, Jotun) and academia to meet and discuss the knowledge gaps in the field.

GDR Biofouling and Environment for including Chalmers as a strategic partner in this French initiative which serves as an important platform for future knowledge exchange and collaboration between academia and industry. Webpage (in French) Creation of the Biofouling and Environment Research Group – IUEM

The GDR Biofouling and Environment, directed by Fabienne Faÿ (LBCM) and co-directed by Raphael Lami (Banyuls/Mer Observatory) funded by the French CNRS Institute of Ecology and Environment since January 1, 2025 for a period of 5 years.

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