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On the importance of antifouling coatings regarding ship resistance and powering

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Abstract

This paper aims to introduce one of the latest investigations on development of marine antifouling coatings and also to demonstrate the importance of the type of antifouling coatings on fouling accumulation and ship resistance/powering. First, marine biofouling and fouling prevention methods are reviewed. A recent research study (EU FP7 FOUL-X-SPEL Project) concerning a novel and environmentally friendly antifouling coating is presented and discussed. Next, a case study is carried out to assess the effect of fouling on ship resistance and powering. A vessel is selected and the roughness on the hull surface induced by different level of fouling is considered. The increase in frictional resistance and effective power is evaluated for each particular case by using boundary layer similarity law analysis and experimental data. The results emphasise that the type of antifouling coatings has a great importance on the amount of fouling accumulation, hence on ship performance especially in low speeds.

Keywords: Antifouling; coatings; roughness; friction; resistance; effective power

1. Introduction

It is predicted that approximately 300 million tonnes of fuel are consumed per year by waterborne transportation thereby there is an increasing focus on environmental footprint of shipping (FOUL-X-SPEL, 2013). International Maritime Organization (IMO) estimates that the air emissions, due to the increasing fuel consumption by shipping, may increase between 38% and 72% by 2020, unless corrective measures are taken or new technologies are introduced (FOUL-X-SPEL, 2013). Therefore environmental issues lead universities, research organisations and shipping companies to focus on energy saving, greenhouse gas (GHG) emission reduction and other measures to achieve more environmentally friendly transportation.

Fouling is an unwanted phenomenon in marine transportation because ships consume less fuel when their hulls are smooth and clean, *viz.* free from fouling. This is the reason why people have been trying to avoid or to mitigate fouling using various antifouling technologies since the very first days of shipping history.

Antifouling coatings are the primary protective measure to mitigate marine biofouling and surface roughness on ship's hulls. $60 billion of fuel saving, 384 million tonnes reduction in carbon dioxide and 3.6 million tonnes reduction in sulphur dioxide emissions are estimated to be provided by the use of antifouling coatings (FOUL-X-SPEL, 2013).

There have been many types of antifouling coatings which prevent the settlement and growth of the marine species on hulls by means of releasing biocides or surface properties. TBT antifouling paints had been highly preferred for years since they had low initial roughness and perfect antifouling ability, besides the ships coated with TBT did not need frequent drydocking. Nevertheless, it is proved that TBT has many negative effects on marine environment, such as toxicity to marine lives, persistence in

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the aquatic environment. As a consequence, IMO banned the applications of TBT coatings. Therefore, the research on development of an environmentally friendly antifouling coating has been accelerated since 2000's and some alternatives started to be developed. Nonetheless, the desired antifouling coating has not been developed yet.

Following a brief introduction, marine biofouling phenomenon and the effects of fouling on ship performance are presented. The history of fouling prevention methods is covered and the current antifouling technologies are presented in a comparative manner in the third section. Subsequently, EU FP7 FOUL-X-SPEL Project is presented covering the expected impacts and aims of the research while the key parameters affecting the development of antifouling coatings and the desired properties of the antifouling coatings are addressed clearly in section four.

Finally a case study is carried out to demonstrate the impact of fouling on ship performance. An LNG Carrier is selected and the increase in frictional resistance and effective power is predicted for severe fouling conditions on the hull.

2. Marine biofouling

The bio-accumulation of marine organisms on the surfaces of submerged or semi-submerged, natural or artificial objects is called marine biofouling (Lewis, 1998). This infestation is inevitable because the marine environment has a unique bio-diversity. It is estimated that the number of the type of marine organisms may exceed 2500 (Anderson et al., 2003). Some species have tendency to attach on surfaces, settle and grow on them. These marine organisms are named marine foulers and may mainly be classified into micro and macro foulers as shown in Figure 1 (Taylan, 2010).

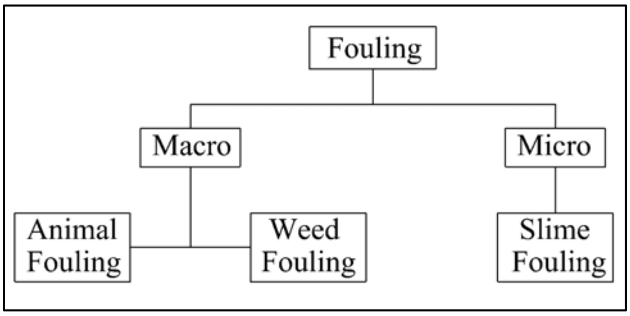

Figure 1. Fouling organisms, adapted from Taylan (2010).

The bio-accumulation begins immediately after the immersion of a ship and continues on the seaway. Firstly, the dissolved organic materials start to accumulate on ships' hulls (Egan, 1987). This may be considered as the first phase of fouling. At the second phase, bacteria and unicellulars accumulate on surfaces as a microbial film. This form is defined as slime and slime generates some chemical secretions and surface roughness, which are encouraging for macrofouling. The accumulation of more complex organisms such as multicellular primary procuders, grazers and decomposers are regarded as the third stage (Bertram, 2000). The fourth and the final phase is the settlement and growth of macro-algal and animal fouling. Figure 2 is the detailed classification of marine foulers (Atlar, 2008).

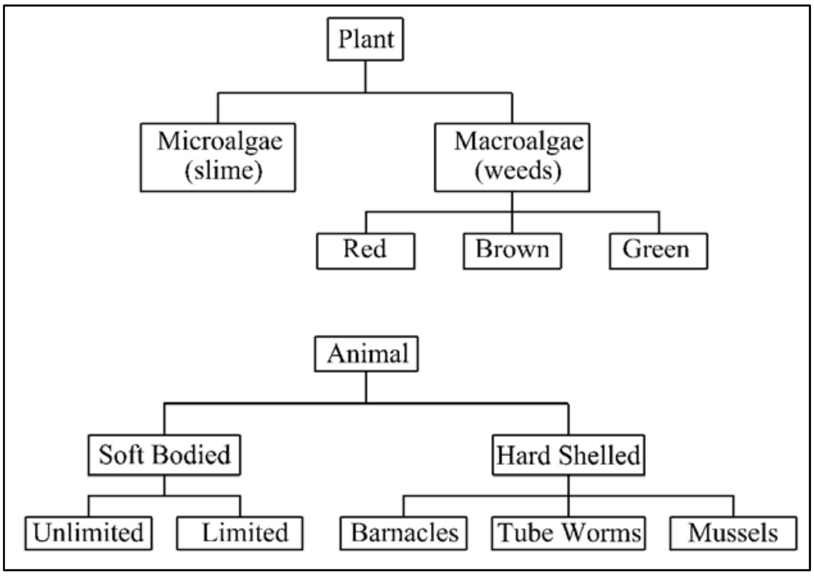

Figure 2. The classification of marine foulers, adapted from Atlar (2008).

Fouling occurs especially when a ship is stationary such as being in port. Fouling emerges more effectively in tropical waters and it varies depending on the geographical area (Stevens, 1937).

Marine biofouling is an increasing problem from both economic and environmental points of view in terms of increased resistance, increased fuel consumption, increased GHG emissions, transportation of harmful non-indigenous species (NIS), etc… It should be kept in mind that a small amount of fouling may lead to a significant increase in fuel consumption. Especially, hard shelled fouling can cause a considerable rise in ship frictional resistance, hence fuel consumption. Hard shelled barnacles can also deteriorate the paint and cause other problems such as corrosion. Fouling accumulation and biocorrosion due to fouling can be seen in Figure 3. It should be noted that the impact of fouling on ship performance is greatly dependent on the type and coverage of fouling (Schultz, 2007).

Figure 3. Biofouling and biocorrosion on ship hulls. (Photograph: Estaleiros Navais de Peniche, S.A.)

Transportation of invasive aquatic species is another important problem which occurs due to fouling. Some fouling species remain alive for a long time; thereby, they may be transferred to another ecosystem. These invasive species can be very harmful in terms of ecological and economic aspects. They may cause extinction of some species and may harm biodiversity and/or transport and dissipate various diseases (Okay, 2004).

3. Fouling prevention methods

Fouling mitigation is very desirable from a practical view point. Fouling has been an insurmountable problem to solve since earliest times and the effort to find an effective protection method started long time ago.

The conventional antifouling method is the application of antifouling paints, which contain toxic chemicals, on ships' hulls. These toxic chemicals, which are called biocide, are released to the seawater eventually with water exposure and consequently a toxic layer is fromed around the hull. This layer prevents the foulers to attach the hull.

Several different methods have been tried; nevertheless, it seems that the antifouling principle was based on toxic contents even in the 5th century BC. An Aramaic papyrus left us the message about the antifouling strategy of those days (ABS, 2011):

> *"…the arsenic and sulfur have been well mixed with the Chian oil that you brought back on your last voyage, and the mixture evenly applied to the vessel's sides, that she may speed through the blue waters freely and without impediment.''*

Christopher Columbus was also suffering from fouling problem, and gave the details of their fouling prevention method (ABS, 2011):

> *"All ships' bottoms were covered with a mixture of tallow and pitch in the hope of discouraging barnacles and teredos, and every few months a vessel had to be hove-down and graved on some convenient beach. This was done by careening her alternately on each side, cleaning off the marine growth, re-pitching the bottom and paying the seams."*

Antifouling strategies have been changed due to the new technologies and legislations. The historical development of antifouling strategies are shown in Table 1 (Dafforn, Lewis and Johnston, 2011).

Table 1. Historical development of the antifouling strategies, adapted from Dafforn, Lewis and Johnston (2011).

Timeline	Major events
1500-300 BC	Use of lead and copper sheets on wooden vessels
1800-1900s	Heavy metals (copper, arsenic, mercury) incorporated into coatings
1800s-present	Continued use of copper in AF coatings
1960s	Development of TBT conventional coatings
1974	Oyster farmers report abnormal shell growth
1977	First foul release AF patent
1980s	Development of TBT SPC coatings allowed control of biocide release rates
1980s	TBT linked to shell abnormalities in oysters (Crassostrea gigas) and imposex in dogwhelks (Nucella lapillus)
1987-90	TBT coatings prohibited on vessels <25 m in France, UK, USA, Canada, Australia, EU, NZ and Japan
1990s–present	Copper release rate restrictions introduced in Denmark and considered elsewhere e.g. California, USA
2000s	Research into environmentally friendly AF alternatives increases
2001	International Maritime Organisation (IMO) adopts ''AFS Convention'' to eliminate TBT from AF coatings from vessels through: 2003 – prohibition of further application of TBT 2008 – prohibition of active TBT presence
2008	IMO ''AFS Convention'' entered-into-force

The most remarkable success against marine biofouling can be ascribed to TBT antifouling paints. Self-polishing copolymer (SPC) TBT systems had been widely used since 1960's until 2000's due to its perfect antifouling ability. Nevertheless, research activities demonstrated that TBT exposure causes shell malformation of oysters (Alzieu et al., 1986) and imposex of gastropod molluscs (Gibbs & Bryan, 1986). Moreover, TBT compounds persist in the water, show toxic effects to marine organisms even with a low concentration; also it may accumulate in marine organisms and hence enter the food chain

(Okay, 2004). As a consequence, IMO banned the applications of antifouling coatings which contain TBT in 2003 and the operations of ships coated with TBT paints in 2008. Due to the ban, TBT has been replaced with other toxic biocides. These chemical systems release toxic compounds to the marine environment just like TBT whereas they are not as effective as TBT.

Today, there are several types of coatings to mitigate fouling and they can be classified into two main categories based on their compositions; namely, biocidal and non-biocidal coatings. Biocidal coatings can be listed as Controlled Depletion Polymer (CDP), Self-Polishing Copolymer (SPC) and Hybrid SPC. Non-biocidal coatings are foul-release coatings (FR), which are also called non-stick coatings (Taylan, 2010). CDPs use hydration process and release biocides into the marine environment. They are used for vessels which have short drydock intervals and also they are mainly preferred for the ships operating in low fouling regions (Atlar, 2008). Their effectiveness are said to be up to 3 years (Rompay, 2012). Self-Polishing Copolymers (SPC) have good initial hydrodynamic performance owing to their smooth surfaces and have better antifouling ability. They are preferred for vessels which have longer drydock intervals (Taylan, 2010). SPCs can remain effective up to 5 years (Rompay, 2012). Hybrid SPCs' biocide releasing method may be regarded as hybrid, between hydrolysis and hydration. The life span of Hybrid SPCs is between 3 to 5 years (Taylan, 2010). However, all biocidal antifouling coatings are under scrutiny regarding their toxic effects; hence, they all are affected by legislative issues and may be banned.

Foul release (FR) coatings, on the other hand, prevent the attachment of marine species on hull owing to surface properties. Nevertheless, the term foul releasing is misleading because FR coatings could not release all of the slime and they are effective only above a certain speed since the releasing mechanism works by means of a particular amount of shear force to detach the marine organisms. Because of this, they are not appropriate for slow ships and for the ships spending long time in ports. Also, they are very expensive compared to the other types of coatings and may be damaged easily due to hard shelled fouling organisms or any mechanic effects such as cleaning. Some of the important properties of the existing coating systems are shown in Table 2 (Rompay, 2012). Because of these reasons, a great deal of effort is being devoted to develop a novel and environmentally friendly antifouling solution that can eliminate all of the drawbacks of the current antifouling coatings.

Table 2. Properties of the existing hull coatings, adapted from Rompay (2012).

	Protection and longevity	**Fuel saving properties and conditions**	**Need to drydock for repainting**	**Environmental concerns**
Typical antifouling coatings (SPC)	Soft coating. Fairly easily damaged. 3-5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2-4% fuel penalty. Usually, sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties. Coating degradation increases fuel penalty over time.	5 - 8 drydockings required for paint alone during ship's service life including 1-3 full blasting and repainting. Multiple coats and length curing times can mean 2-3 weeks in drydock for a full repaint.	Contaminates marine environment with toxic biocides, harming marine life, the food chain and humans. Pulse release of biocides if cleaned in-water. High VOC content when applied. Limits fuel consumption and GHG emissions from effects of heavy fouling. Prevent some NIS but further others.
Typical FR coating system	Soft coating. Easily damaged. 3-5 years before FR coat needs repair/reapplication. Full recoating required 1-3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups. Coating degradation increases fuel penalty over time.	5 - 8 drydockings required for paint alone during ship's service life including 1-3 full blasting and repainting. Multiple coats and length curing times can mean as much as 2 – 3 weeks in drydock for a full repaint.	Does not contain biocides but leaches potentially harmful oils, alters enzymes in barnacle glue; some silicones catalyzed by highly toxic dibutyltin dilaurate. Medium VOC. Some reduction in fuel consumption/GHG. Can help limit spread of NIS.

4. Recent research

The recent research in the field of development of a novel and environmentally friendly antifouling coating is believed to be successful to enhance the performance of shipping as well as to eliminate the negative effects of the existing solutions. There are different aspects considering the design of a new antifouling system. These key parameters are associated to environment, coating and substrate. The details of the main aspects are given in Figure 4 (Chambers et al., 2006).

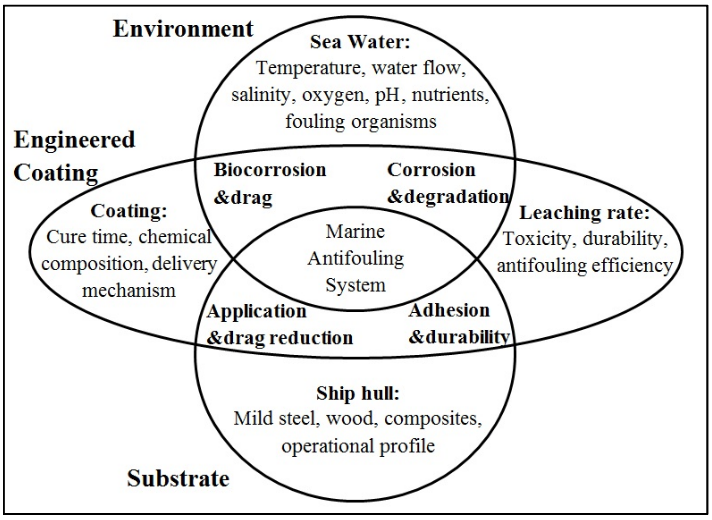

Figure 4. Key parameters for antifouling systems, adapted from Chambers et al. (2006).

The main difficulty of the development of a novel antifouling system is to compromise among different and conflicting parameters. The requirements for an optimal antifouling coating are described in details by Chambers et al. (2006) in Table 3.

Table 3. Requirements for an optimal antifouling coating, adapted from Chambers et al. (2006).

Must be	Must not be
Anticorrosive	Toxic to the environment
Antifouling	Persistent in the environment
Environmentally acceptable	Expensive
Economically viable	Chemically unstable
Long life	A target for non-specific species
Compatible with underlying system	
Resistant to abrasion/ biodegradation/erosion	
Capable of protecting regardless of operational profile	
Smooth	

There have been several attempts to develop the optimum antifouling coating for a long time. An alternative strategy, which is worth highlighting, is using an antifouling polymeric coating where a biocide is attached, in order to kill the fouler microorganisms attaching on the coated hull, without releasing the biocide (Charnley, Textor and Acikgoz, 2011). These systems are called bioactive polymers.

One of the most recent projects is the EU FP7 Project entitled “Environmentally Friendly Antifouling Technology to Optimise the Energy Efficiency of Ships” (FOUL-X-SPEL). “The basic idea concerns the modification of usual hulls by providing a new antifouling coating, by fixing bioactive molecules, which can provide biocide activity, in order to avoid leaching and to promote a long-term effect of surface protection" (FOUL-X-SPEL, 2013).

The detailed objectives of the project can be listed as below:

- To reduce the emissions and optimize energy efficiency of existing ships through improved hull-propulsion interactions by means of low friction antifouling coatings
- To enhance antifouling physical properties, avoiding the adhesion of fouling to reduce fuel consumption of the ships and improving hull-propulsion interaction, which will maintain its biocide activity over the medium to long term
- To assure enough resistance to impact, wear, corrosion and their interaction to increase the lifetime of the paint and controlling deterioration and toxic emissions to improve environmental impact and minimize the footprint of the existing ships
- To provide environmental friendly novel coating materials and surface
- To develop and validate on-field innovative new coating finishing and protection longer cycles in compliance with owner demands and technical, safety and environmental IMO Rules and EU and International Regulations
- To develop accurate assessment tools (mathematical models) for the determination of the environmental, energy and operational benefits, including energy saving of retrofitting solutions (hull-propulsion interaction) taking into account the remaining life cycle
- To provide more economical alternative ship management
- To provide coating guidelines to be applied in shipyards, ship life (inspections), repair and maintenance scheduling

The main impacts of the innovative coating are:

- Propulsion improvement due to average drag reduction
- Validation of low environmental antifouling coating impact and valorization
- Energy saving and reduction of fuel costs
- Improvement of ship management and overall costs
- Immobilization period reduction in drydocks for hull repaints
- Contribution to environmental regulations

Besides the direct impacts and product(s) of the project, it leads and fosters an extensive research and understanding on the subject of fouling, antifouling technologies and fouling effect on ship resistance, fuel consumption and GHG emissions.

A wide range of activities are performed within the project. Short term sea exposure tests are to be conducted using the new coating and conventional coatings in order to assess the time dependent drag performance of the new coating as well as to compare the new coating's antifouling and hydrodynamic properties against the conventional solutions. The resistance tests are to be conducted in order to assess the hydrodynamic performance of these paints with and without sea exposure. Moreover, long term full scale field tests will be carried to monitor the real performance of the new coating under realistic speed-activity conditions. Following the results of these tests, the roughness variation of the new coating in time is to be obtained and also energy efficiency of the ships and savings due to the use of new coating will be investigated. In addition, the environmental impact of the new coating is to be determined from a life cycle assessment (LCA) point of view. Above all, a new model is to be developed to determine the efficiency of the new coating addressing the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Index (EEOI). The optimum compromise among antifouling ability, safety, environmental issues, ecotox issues and the IMO and EU Regulations is expected to be achieved (FOUL-X-SPEL, 2013). It is believed that it will be a leap forward towards environmentally friendly antifouling systems.

5. Case study

The importance of a new and novel antifouling coating may be stressed by showing the effect of the coating type on fouling accumulation and ultimately on ship resistance and powering which can be translated into fuel consumption. An LNG carrier of 270m length at the speed of 12.5 knots is selected as the test vessel. The increase in frictional resistance and effective power due to the different levels of fouling is evaluated. Three different antifouling types are selected, namely SPC TBT, Ablative Copper and SPC Copper. The effect of the coating types on fouling accumulation and hence indirectly impact on ship resistance and powering due to fouling in time, in other words time dependent drag performance of the ship coatings, is investigated.

SPC TBT had been standing for the best antifouling solution for decades; however it is not possible to use it as a biocide due to the ban. Currently other biocides, such as copper, are used prevalently. It may be meaningful to compare copper coatings with the banned SPC TBT in order to demonstrate the importance of the efforts to develop an effective antifouling coating. Because, the antifouling ability of SPC TBT is by far better than what has been achieved by other solutions so far. The procedure of this case study is divided into two parts, (1) Prediction of the increase in ship frictional resistance coefficient (ΔC_F) due to fouling, (2) Prediction of ship total resistance coefficient through model tests and taking ΔC_F into account. The details of these two procedures are given in the following.

5.1 Frictional resistance increase due to fouling

Once, frictional resistance coefficients, C_F, roughness functions, ΔU^+, and roughness Reynolds numbers, k^+, of a flat plate covered with a particular roughness, e.g. fouling, are obtained, it is possible to predict the frictional resistance coefficient of a ship covered with the same roughness, using Granville's (1958) boundary layer similarity law analysis (Schultz, 2007).

The experimental data of Schultz (2004) was utilized to predict the increase in frictional resistance coefficient of the selected ship due to three different levels of fouling. Schultz (2004) conducted flat plate sea exposure tests and the plates were towed before and after sea exposure in order to obtain the frictional resistance coefficients of the plates. The plates were coated with five different types of coatings and have been exposed to water for 287 days. Fouling coverage on the selected plates after exposure is shown in Table 4. Roughness function values of each plate after exposure is shown in Figure 5 (Schultz, 2004). Further details of the experiments and evaluation of the quantities are given in Schultz's (2004) paper.

Table 4. Fouling coverage on the plates coated with SPC TBT, Ablative Copper and SPC Copper after 287 days of exposure, adapted from Schultz (2004).

Coating Type	Exposure Time (days)	Total fouling coverage (%)	Slime (%)	Hydroids (%)	Barnacles (%)
SPC TBT	287	70	70	0	0
Ablative Copper	287	76	75	0	1
SPC Copper	287	73	65	3	4

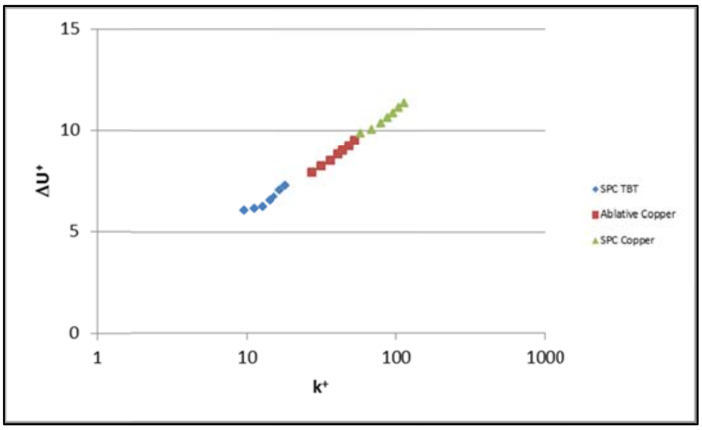

Figure 5. Roughness function *vs.* roughness Reynolds numbers after sea exposure, adapted from Schultz (2004).

Now that, $\Delta U^+ = f(k^+)$ is known for each plate for the same exposure time, it is possible to predict the C_F of the ship for the same surface conditions with the plates. Prediction of the increases in frictional resistance coefficients of the LNG Carrier is made for three different levels fouling coverage given in Table 4. The increase in C_F (ΔC_F) is computed for each case with respect to that obtained by ITTC – 1957 correlation line. The computation is made using a home-made tool based on boundary layer similarity law procedure proposed by Granville (1958) using the roughness functions. The scale up procedure is graphically demonstrated in Figure 6.

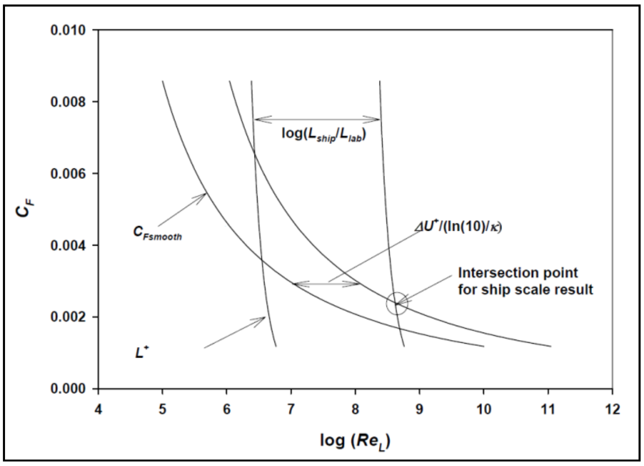

Figure 6. Granville scale-up procedure, adapted from Shapiro (2004).

Further details of the procedure can be found in Granville (1958), Schultz (2007) and Shapiro (2004). It is of note that Schultz (2007) made predictions of powering of a naval ship using this method and an excellent agreement between the predictions and full-scale trials results was recorded. Alternatively, computational fluid dynamics (CFD) software packages can also be used to predict the frictional resistance increase due to the given roughness once $\Delta U^+ = f(k^+)$ is obtained. An example of this approach is given by Demirel et al. (2013) and the results showed a very good agreement with the experimental data.

5.2 Full scale predictions of total resistance

The total resistance and effective power prediction of a ship can be made through model resistance tests using ITTC procedures. The total resistance (R_T) can be calculated as.

$$R_T = \frac{1}{2}\rho S C_T V^2 \tag{1}$$

where ρ is density of water, S is wetted surface area, C_T is total resistance coefficient and V is speed.

The effective power (P_E) is:

$$P_E = R_T V \tag{2}$$

The total resistance coefficient (C_{TS}) of a ship is given as (ITTC, 2011):

$$C_{TS} = (1+k)C_{FS} + \Delta C_F + C_A + C_R + C_{AAS} \tag{3}$$

where k is the form factor, C_{FS} is the smooth frictional resistance coefficient, ΔC_F is the frictional resistance increase due to the roughness, C_R is the residual resistance coefficient, C_A is the correlation allowance and C_{AAS} is the air resistance coefficient in full scale. The air resistance is ignored in this study. C_{FS} is evaluated from the ITTC – 1957 correlation line,

$$C_{FS} = \frac{0.075}{\left(\log_{10} \mathrm{Re} - 2\right)^2} \tag{4}$$

ΔC_F values are obtained using the approach presented in the previous section.

C_R is determined from the total and frictional resistance coefficients of the model in the resistance tests in accordance with the following equation (ITTC, 2011).

$$C_R = C_{TM} - C_{FM}(1+k) \tag{5}$$

where subscript *M* indicates the model terms.

C_A can be derived from the following equation (ITTC, 2011).

$$C_A = (5.68 - 0.6 \log \mathrm{Re}) \times 10^{-3} \tag{6}$$

5.3 Results

The increase in frictional resistance coefficient (ΔC_F) due to fouling at a ship speed of 12.5 knots is shown for each case in Table 5. From this point the terms SPC TBT, Ablative Copper and SPC Copper stand for the fouled surface conditions of the ship after 287 days of exposure, which were coated with SPC TBT, Ablative Copper and SPC Copper before exposure.

Table 5. Frictional resistance coefficients of the fouled ships.

Coating Type	**SPC TBT**	**Ablative Copper**	**SPC Copper**
Sea Exposure Period	287 days	287 days	287 days
ΔC_F	0.0006904	0.0009929	0.0012851

One of the most important indicators which reflect fuel consumption is the effective power. Hence, the effect of fouling on effective power must be investigated. The increase in frictional resistance and effective power compared to the smooth condition is shown in Figure 7.

It is clearly depicted that coating type directly affects the increase in frictional resistance since it closely affects the fouling accumulation amount in time. The increases in R_F of fouled hulls are around 47%, 68% and 88% for SPC TBT, Ablative Copper and SPC Copper coated hulls respectively. It is evidently noted that effective power of a ship may increase dramatically due to fouling and there is a strong link between the fouling amount and the effective power. The increase in effective power of SPC TBT is approximately half of that of SPC Copper, around 30% and 57% respectively, while it is around 44% for Ablative Copper. It should be mentioned that it is an extreme situation for a ship being stationary for 287 days.

As depicted in Figure 8, the relative contribution of added resistance due to fouling to the total resistance is 23% for SPC TBT while this rate is 31% and 36% for Ablative Copper and SPC Copper, respectively.

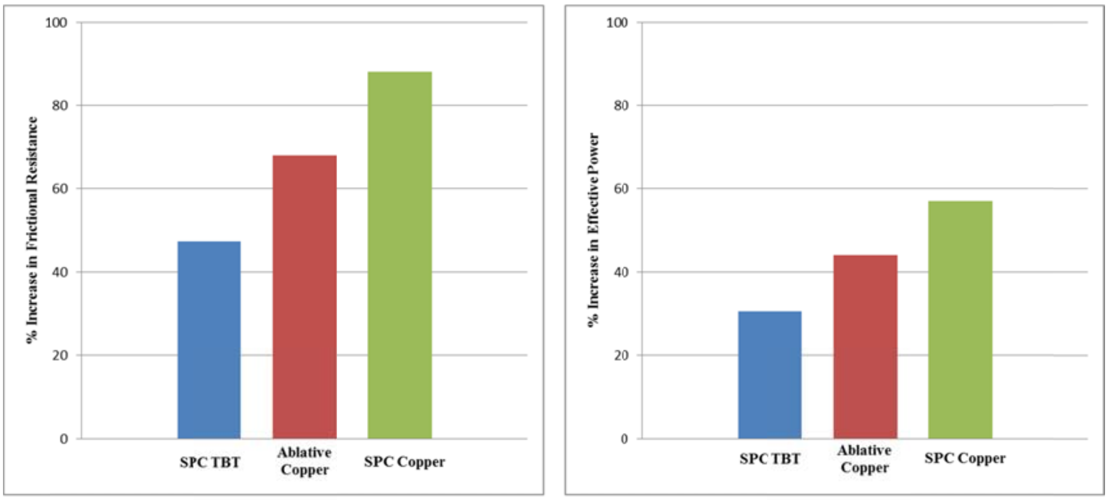

Figure7. Increase (%) in ship frictional resistance and effective power after 287 days of exposure.

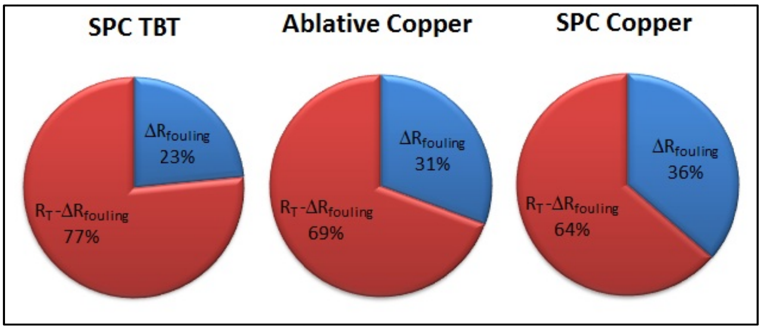

Figure 8. The relative contribution of added resistance due to fouling.

6. Conclusions

The importance of antifouling coatings regarding ship resistance and powering have been highlighted in this study. Marine biofouling problem and the current antifouling methods, also new approaches to the solution have been presented from a naval architecture point of view.

EU FP7 FOUL-X-SPEL Project aims to develop novel, non-leaching antifouling polymer systems, in which the biocide is fixed and hence the surface has active antifouling principle in order to avoid fouling while avoiding biocide releasing.

It is shown that the time dependent drag performance of antifouling coatings is of great importance to ship resistance and powering since it directly affects the amount of fouling accumulation on ship hulls, hence fuel consumption and GHG emissions.

Thereby, novel antifouling technologies should be developed concerning the possible harmful direct effects of existing antifouling methods to marine environment and also indirect effects such as increasing air emissions. For these reasons, more research efforts should be devoted to enhance the marine antifouling coatings/technologies as well as to achieve more environmentally friendly shipping. All in all, it is believed that, the research activities on antifouling coatings will lead to very effective prevention of marine biofouling while maintaining the harmony between man-made structures and marine life.

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