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New Horizons in Marine Coatings

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Abstract

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 and transportation of harmful non-indigenous species. Marine coatings are prevalently used to mitigate biofouling and smooth the surfaces of hulls. This paper aims at introducing new horizons and novel approaches in marine antifouling coatings. Firstly, marine biofouling and fouling prevention methods are briefly introduced. Afterwards, latest research in coating/fouling hydrodynamics is presented. Biomimetic approach to antifouling technology, bio-inspired antifouling strategies and the challenges in designing bio-inspired antifouling coatings are then discussed in detail. It is believed that, the on-going research in marine coatings will lead to an effective mitigation of marine biofouling while maintaining the harmony between man-made structures and marine life.

Keywords: Marine Coatings, Coating/Fouling Hydrodynamics, Biomimetics

1. Introduction

Fouling is an unwanted phenomenon for 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.

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 (IMO, 2009). The air emissions, due to the increasing fuel consumption by shipping, is expected to increase between 38% and 72% by 2020, unless corrective measures is taken or new technologies are introduced (IMO, 2009). 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.

Antifouling coatings are the primary protective measure to mitigate marine biofouling and surface roughness on ship's hulls. It is estimated that $60 billion of fuel saving, 384 million tonnes of reduction in carbon dioxide and 3.6 million tonnes of reduction in sulphur dioxide emissions can be achieved by using of antifouling coatings (IMO, 2009).

There have been many types of antifouling coatings which mitigate the settlement and growth of the marine species on hulls by means of either releasing biocides or its own surface properties. The antifouling paints containing TBT had been highly preferred for years since they had low initial roughness and perfect antifouling properties. Nevertheless, the research demonstrated that TBT has many negative effects on marine environment, such as toxicity to marine lives, persistence in the aquatic environment. For these reasons, IMO banned the applications of TBT containing coatings. Therefore, the research on environmentally friendly antifouling coating has been accelerated since 2000's. Nonetheless, the desired antifouling coating has not been developed yet.

This paper presents new horizons in marine coatings and is organised as follows: Marine biofouling and the effects of fouling were briefly presented in Section 2, while the current fouling prevention methods were discussed in Section 3. In Section 4, the latest research of the author in coating/fouling hydrodynamics was presented together with research carried out within the EU funded FOUL-X-SPEL Project. In Section 5, new methods in marine coatings addressing biomimetics and bio-inspired antifouling technology were presented. Finally, the results of the study are discussed in Section 6, along with recommendations for future avenues of research.

2. Marine Biofouling

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

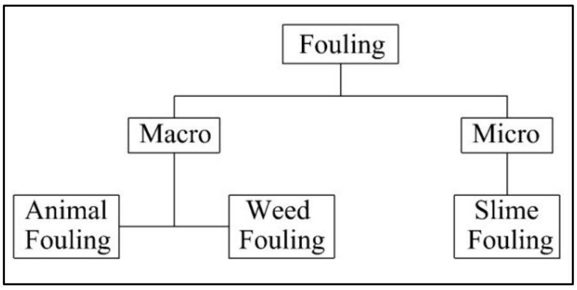

Fig. 1. Fouling organisms, adapted from Taylan (2010).

A detailed classification of marine foulers is demonstrated in Figure 2 (Atlar, 2008).

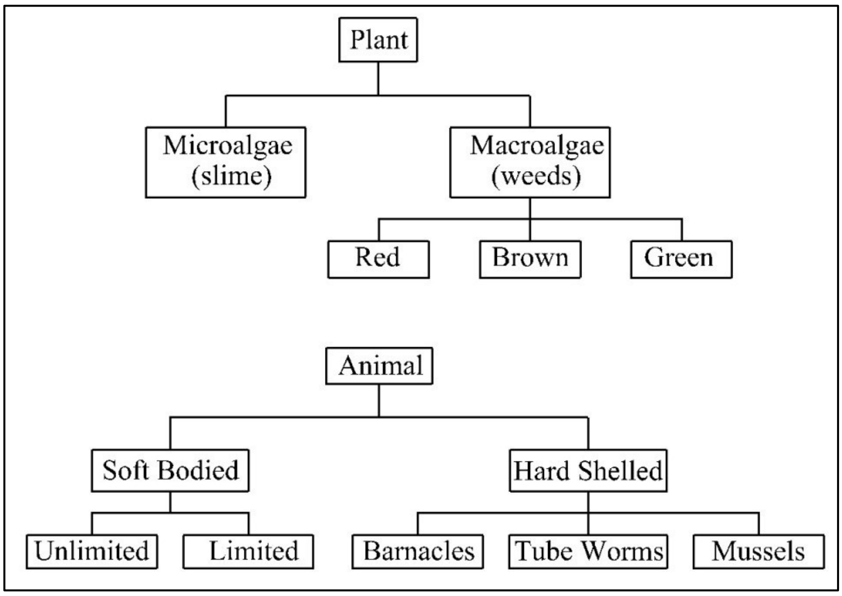

Fig. 2. Classification of marine foulers, adapted from Atlar (2008).

Fouling begins to occur immediately after a ship is immersed in water, and will continue to occur throughout a ship's life at sea until a cleaning process is performed. Fouling is particularly likely to occur when a ship is stationary, such as when it is in a port. Fouling builds up more quickly in tropical waters and it also varies depending on a ship's operational geographical area (Candries et al., 2003). The level of fouling depends on several factors, including the length of time spent at sea, the water temperature, the geographical location of the ship, surface conditions and the salinity of the sea. The longer the ship's immersion time, the greater the level of fouling. Such fouling is responsible for a dramatic increase in a ship's frictional resistance (Demirel et al. 2014).

Fouling causes surface roughness, resulting in an increase in a ship's frictional resistance and fuel consumption (Kempf, 1937). Milne (1990) stated that the fuel consumption may increase by up to 40%, unless any precautions are taken to prevent fouling. According to Taylan (2010), the increase in resistance due to microorganism fouling is around 1-2%, whereas an accumulation of hard shelled organisms may cause an increase in resistance of up to 40%. Schultz (2007) investigated the effect of fouling on the required shaft power for a frigate at a speed of 15 knots. He found that the presence of slime alone caused a 21% increase in shaft power, compared to an otherwise identical slime-free frigate, whereas heavy calcareous fouling led to an 86% increase in shaft power requirements. Demirel et al. (2017) recently carried out experimental and numerical studies and predicted a 66% increase in total resistance of a containership for a 20% coverage of barnacles each 5 mm in height.

3. Fouling Prevention Methods

Fouling mitigation is very desirable from a practical point of view. Fouling has been a challenging problem to solve for many years and efforts to find an effective protection method began long ago. The conventional antifouling method involves the application of antifouling paints, which contain toxic chemicals, on ships' hulls. These toxic chemicals, which are termed biocides, are gradually released into seawater due to exposure to water, and consequently a toxic layer is formed around the hull. This layer prevents fouling species from attaching to the hull. Several different methods have been trialled; it even seems that the toxic antifouling principle was in use as early as the 5th century BC. An Aramaic papyrus details 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 also suffered from fouling problems, with his fouling prevention method as follows (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 changed over time due to new technologies and legislations. The historical development of antifouling strategies is detailed in Table 1 (Dafforn et al., 2011).

The most remarkable success against marine biofouling can be attributed to tributyltin (TBT) based antifouling paints. Self-polishing copolymer (SPC) TBT systems had been widely used from the 1960's until the 2000's due to their unbeatable antifouling ability. Unfortunately, research demonstrated that TBT exposure causes the malformation of oyster shells (Alzieu et al., 1986) and imposex of gastropod molluscs (Gibbs and Bryan, 1986). Moreover, TBT compounds persist in water, show toxic effects to marine organisms even with a low concentration, and they may accumulate in marine organisms and hence enter the food chain (Okay, 2004). As a consequence, IMO banned the application of antifouling coatings which contain TBT in 2003, and banned the operation of ships coated with TBT paints in 2008 (IMO (2001), Champ (2003)). Due to this 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.

Table 1. Historical development of antifouling strategies, adapted from Dafforn et al. (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 Organization (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" comes into force

Today, several types of coatings are used to mitigate fouling. 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.

CDPs use a hydration process and release biocides into the marine environment. They are used for vessels which have short drydock intervals and are preferred for ships operating in low fouling regions (Atlar, 2008). Their effectiveness is said to be up to 3 years (Van Rompay, 2012). Self-Polishing Copolymers (SPC) have good initial hydrodynamic performance owing to their smooth surfaces and have better antifouling abilities due to controlled release of the biocide via hydrolysis. They are preferred for vessels which have longer drydock intervals (Taylan, 2010). SPCs can remain effective for up to 5 years (Van Rompay, 2012). Hybrid SPCs' biocide release method may be regarded as a hybrid of hydrolysis and hydration. The life span of Hybrid SPCs is between 3 and 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 still be banned in the near future.

Foul release (FR) coatings, on the other hand, prevent the attachment of marine species on hulls owing to their physical surface properties (Wahl, 1989), which act like a non-stick coating and prevent the build-up of fouling organisms. The term foul release is in fact misleading because FR coatings cannot release all of the slime on a hull. Additionally, they are only effective above a certain speed, since the release mechanism works by the creation of a shear force to detach the marine organisms. Because of this, FR coatings are not appropriate for slow ships and for ships spending a long time in ports (Candries et al., 2003). Also, they are very expensive compared to other types of coatings and may be damaged easily by hard shelled fouling organisms or any mechanical effects such as cleaning. Due to these limitations, a great deal of effort is being devoted towards developing a novel and environmentally friendly antifouling solution that can eliminate all of the drawbacks of the current antifouling coatings.

4. Latest Research in Coating/Fouling Hydrodynamics

Several different aspects need to be considered when designing a new antifouling system. These aspects concern the environment, the coating and the substrate. Details of the main aspects are given in Figure 3 (Chambers et al., 2006). The main difficulty during the development of a novel antifouling system is to find a compromise among different and conflicting parameters. The requirements for an optimal antifouling coating are described in detail by Chambers et al. (2006) in Table 2.

One of the recent antifouling projects is the EU funded FP7 Project FOUL-X-SPEL (Environmentally Friendly Antifouling Technology to Optimise the Energy Efficiency of Ships, Project number 285552, FP7-SST-2011-RTD-1). *"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, 2011).

Besides the direct impacts and product(s) of this FOUL-X-SPEL project, it has led to extensive research and has developed an increased understanding on the subject of fouling, antifouling technologies and fouling effects on ship resistance, fuel consumption and GHG emissions. It is believed that it will be a leap forward towards environmentally friendly antifouling systems. It is of note that the research presented in this paper was partially generated as part of this FOUL-X-SPEL project. Examples of other recent EU funded research projects are AMBIO (2005), LEAF (2012), BYEFOULING (2013) and SEAFRONT (2014).

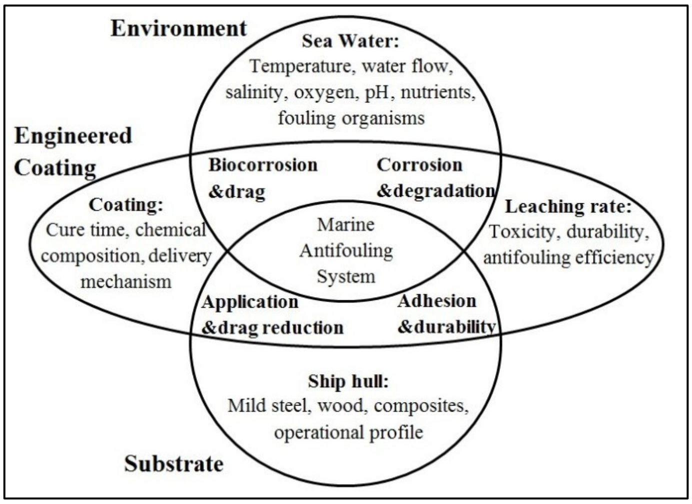

Fig. 3. Key parameters for antifouling systems, adapted from Chambers et al. (2006).

Table 2. 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	

5.1. Experimental Studies

Demirel et al. (2015, 2017b) carried out a series of towing tests using flat plates coated with different marine coatings and covered with artificial barnacles. The tests were designed to allow the examination of the as applied drag performances of several paints and the effects of the barnacle height and percentage coverage on the resistance and effective power of ships. The drag coefficients and roughness function values were evaluated for the flat plates. Roughness effects of the fouling conditions on the ship frictional resistances were predicted. Added resistance diagrams were then plotted using these predictions, and powering penalties for these ships were calculated using the generated diagrams. The results indicate that the effect of barnacle size is significant, since a 10% coverage of barnacles each 5mm in height causes a similar level of added power requirements to a 50% coverage of barnacles each 1.25 mm in height.

Figure 4 illustrates the frictional resistance coefficients, C_F, of all of the test surfaces coated with different paints together with their added resistance coefficient, C_R, values. It is clearly seen that the newly developed F0034 showed the best frictional resistance performance among all of the antifouling coatings, with an average decrease of 0.79% with respect to the Reference Plate (Demirel et al., 2015).

Figure 5 shows the added resistance diagram for 230 m containership with different fouling conditions whereas Figure 6 demonstrates the increases in the frictional and total resistance and hence in the effective power of the containership at a design speed of 24 knots.

The increase in the C_F and P_E values of the containership due to S-type barnacle accumulation at a ship speed of 24 knots was predicted to be 27%, 17.5% for 10% coverage, 42%, 27% for 20% coverage, 66%, 42% for 40% coverage and 69.5%, 44.6% for 50% coverage. These values changed to 49%, 31% for 10% coverage, 67%, 43% for 20% coverage, 97%, 63% for 40% coverage and 103%, 66% for 50% coverage when it comes to M-type barnacle accumulation. The increases in C_F and P_E were predicted to be 72%, 46% for 10% coverage and 103%, 66% for 20% coverage for B-type surface condition. The effect of size of barnacle on added resistance is significant as 10% coverage of B-type surface causes same level of added power requirements as 50% coverage of S-type surface (Demirel et al., 2017b).

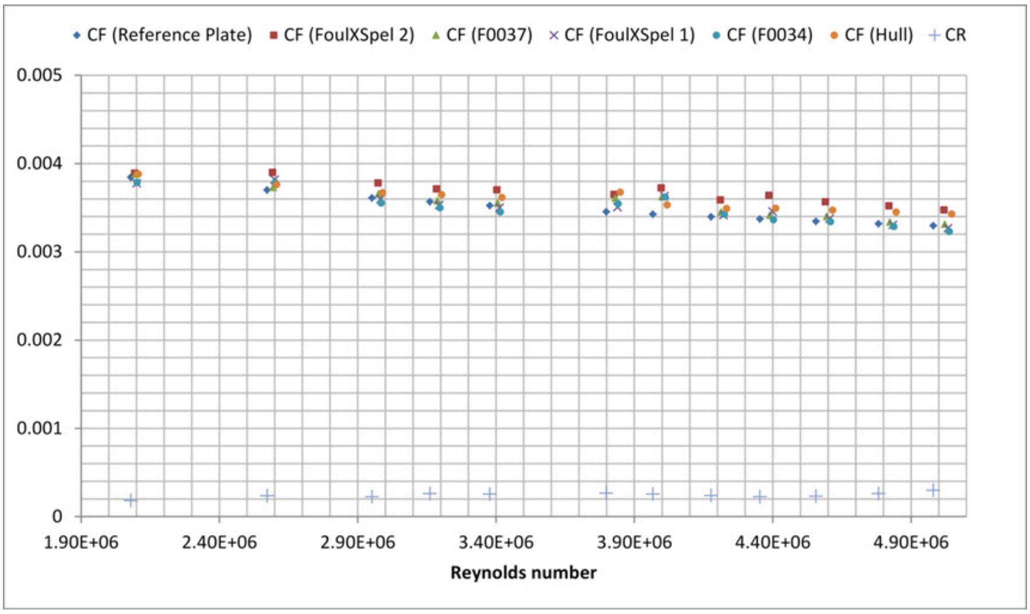

Fig. 4. Frictional resistance coefficients of all test surfaces together with C_R values (Demirel et al., 2015).

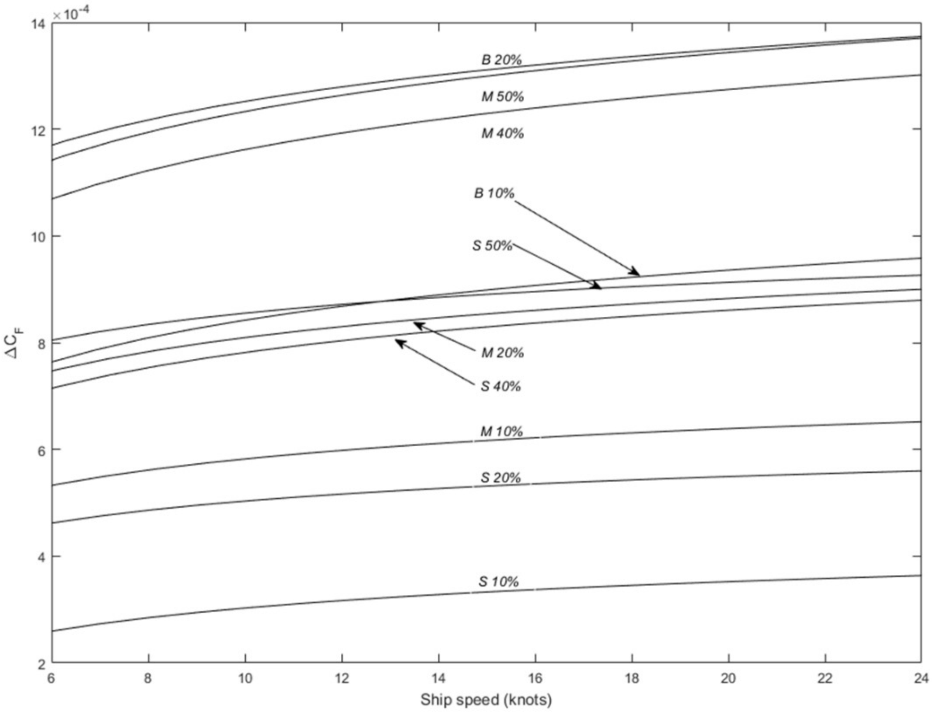

Fig. 5. Added resistance diagram for a 230 m container ship with different barnacle fouling conditions (Demirel et al., 2017b).

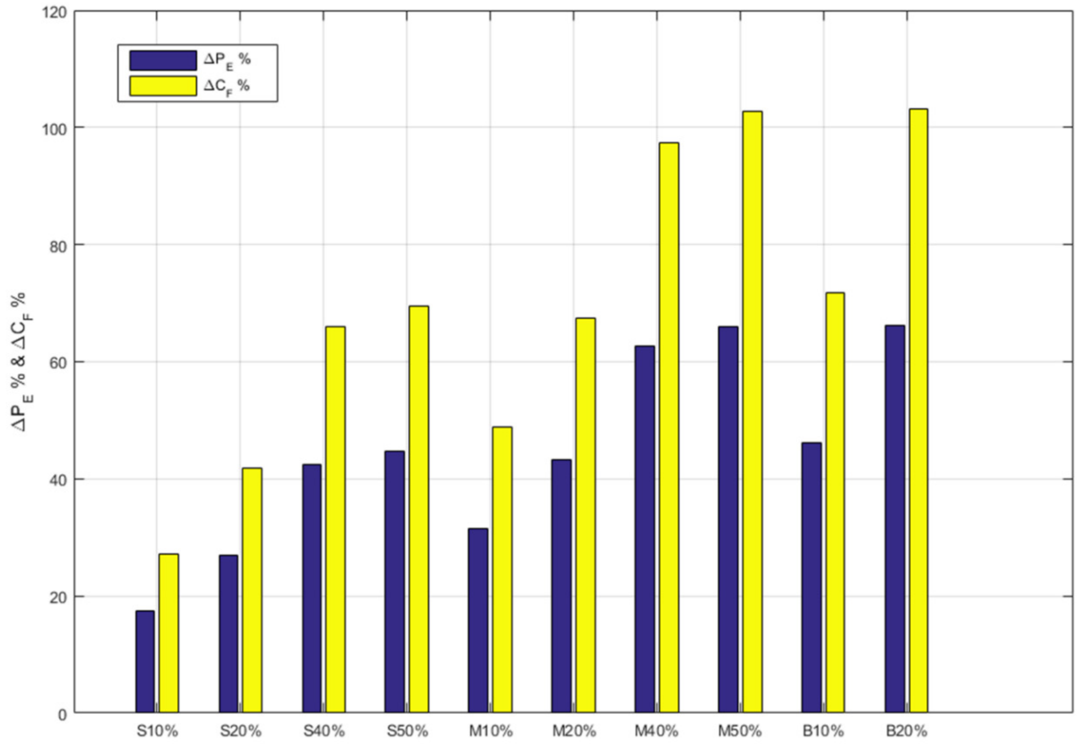

Fig. 6. Percentage increases in C_F and P_E values of a 230 m container ship with respect to the smooth hull condition (Demirel et al., 2017b).

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5.2. Numerical Studies

Demirel et al. (2014, 2017a) proposed Computational Fluid Dynamics (CFD) based unsteady RANS models which enable the prediction of the effect of marine coatings and biofouling on ship resistance. Demirel et al. (2017a) presented CFD simulations of the roughness effects on the resistance and effective power of the full-scale 3D KRISO Container Ship (KCS) hull. This can be considered as an alternative method to traditional similarity law scaling procedure, which uses the flat plate approach. Initially, a roughness function model representing a typical coating and different fouling conditions was developed by using the roughness functions given in the literature. This model then was employed in the wall-function of the CFD software and the effects of a typical as applied coating and different fouling conditions on the frictional resistance of flat plates representing the KCS were predicted for a design speed of 24 knots and a slow steaming speed of 19 knots using the proposed CFD model. The roughness effects of such conditions on the resistance components and effective power of the full-scale 3D KCS model were then predicted at the same speeds. The resulting frictional resistance values of the present study were then compared with each other and with results obtained using the similarity law analysis. The increase in the effective power of the full-scale KCS hull was predicted to be 18.1% for a deteriorated coating or light slime whereas that due to heavy slime was predicted to be 38% at a ship speed of 24 knots. In addition, it was observed that the wave resistance and wave systems are significantly affected by the hull roughness and hence viscosity.

The increase in the frictional resistance of the KCS due to different surface conditions with respect to those of a hydraulically smooth, predicted using the different techniques, are demonstrated in Figure 7.

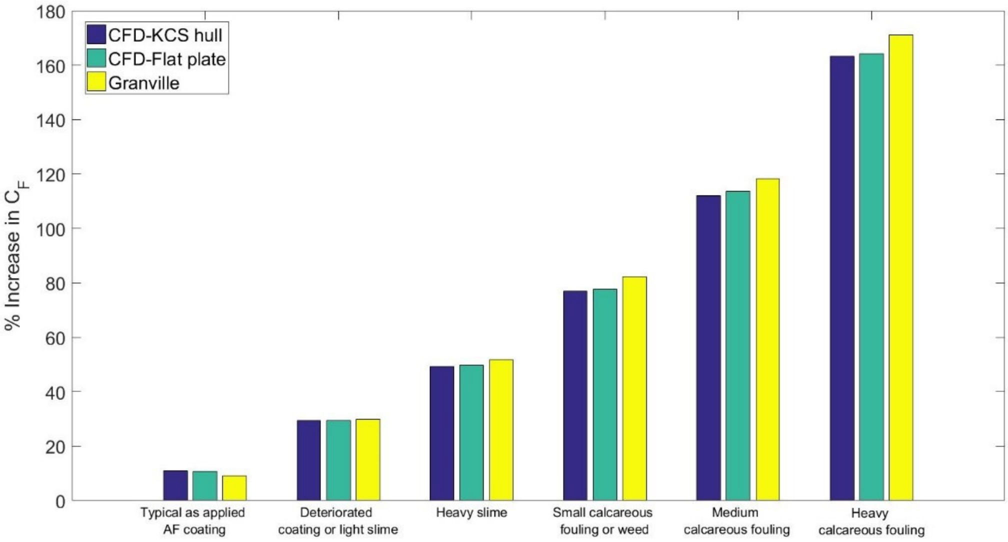

Fig. 7: Estimation of the percentage increase in the frictional resistance of the KCS due to different surface conditions at 24 knots (Re=2.89 x 10^9) (Demirel et al., 2017a).

The results obtained using "CFD-KCS hull" method presented in Figure 7 indicate that the increase in C_F due to the hull roughness of a typical antifouling (AF) coating is 10.9% at 24 knots and 7.4% at 19 knots, whereas the increase in C_F due to biofouling is predicted to be dramatic, which would lead to a drastic increase in the fuel consumption and hence CO_2 emissions. The increase in the frictional resistance of the KCS due to a deteriorated coating or light slime surface condition was predicted to be 29.4% at a ship speed of 24 knots and to be 26.3% at a ship speed of 19 knots. These values became 49.2% and 45.6% when calculating the increase in C_F due to a heavy slime condition. Calcareous fouling causes significant increase in C_F values, ranging from ~77% to ~163% at 24 knots and ~73% to ~157% at 19 knots, depending on the type of calcareous fouling and ship speed.

Figure 8 compares the global wave patterns around the hull surface of the KCS in smooth and heavy calcareous fouling conditions at 24 knots, while Figure 9 shows the wave profile along a line with constant y = 0.1509.

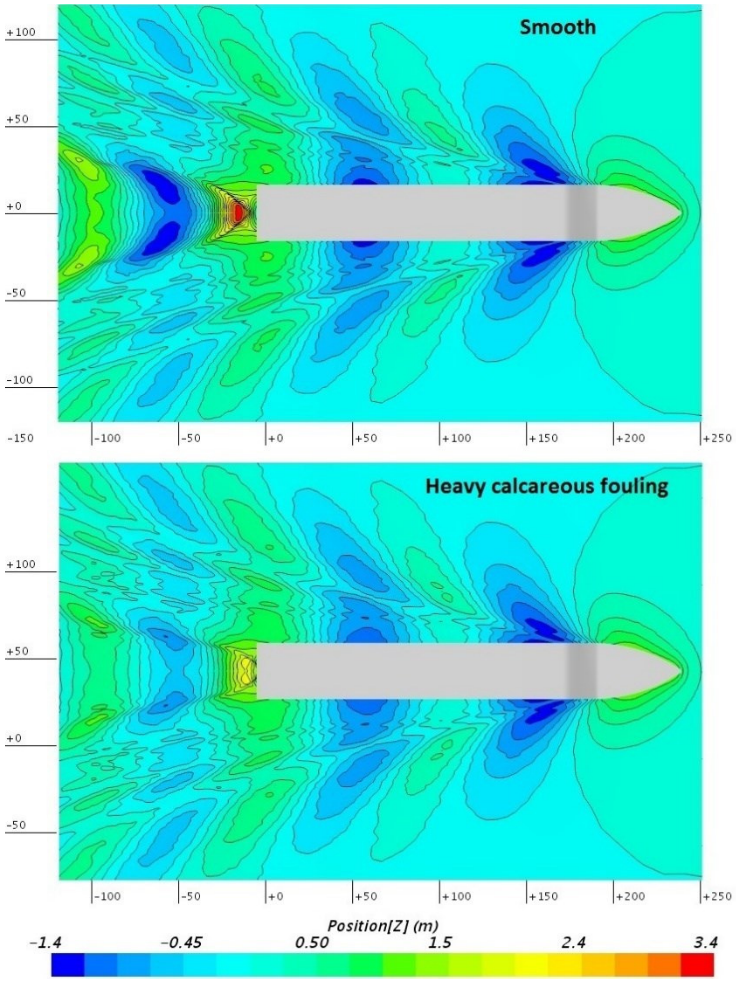

Fig. 8. Wave pattern around the KCS for smooth and heavy calcareous fouling conditions (V=24 knots) (Demirel et al., 2017a).

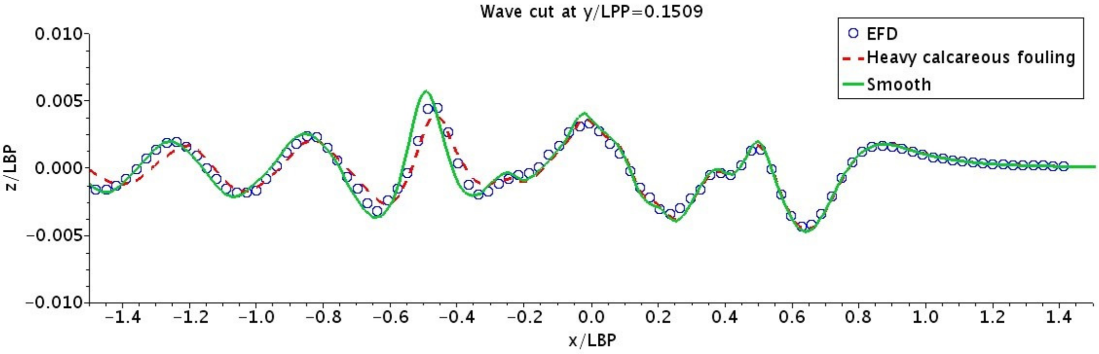

Fig. 9. Wave profiles at y = 0.1509 (V=24 knots) (Demirel et al., 2017a).

It is seen from the comparison in Figure 8 and Figure 9 that wave amplitudes appear to be reduced by roughness effects. This is an indication of the effect of viscosity on the wave systems. The resulting free surface elevation around the KCS hull was recorded to range from -1.406m to 3.357m for smooth condition, and -1.345m to 2.266 for heavy calcareous fouling condition (Figure 9).

Figure 10 demonstrates the increase in the total resistance and hence in the effective power of the KCS due to different surface conditions with respect to the smooth condition at a design speed of 24 knots and at a slow steaming speed of 19 knots, respectively.

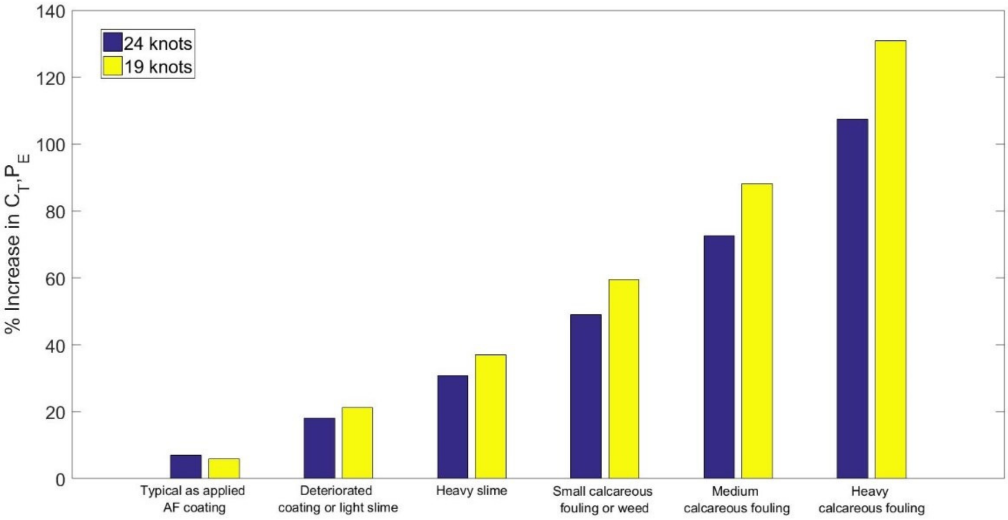

Fig. 10. Estimation of the percentage increase in the resistance and effective power of the KCS due to different surface conditions (Demirel et al., 2017a).

The results presented in Figure 10 indicate that the increase in the C_T and P_E of the KCS due to a typical, as applied antifouling (AF) coating were predicted to be 7.1% and 5.9% whereas those due to a deteriorated coating or light slime may increase to 18.1% and 21.2% at ship speeds of 24 knots and 19 knots, respectively. The effect of heavy slime on the KCS hull was calculated to cause an increase in the C_T and P_E of 30.8% at 24 knots and 37% at 19 knots. The calcareous fouling would increase P_E by up to 107.5% at 24 knots and 130.9% at 19 knots.

An interesting point to note is that the effect of a particular fouling condition on the effective power of the KCS is more dominant at lower speeds. This can be attributed to the fact that the contribution of the frictional resistance becomes more important than residuary resistance at lower speeds. In other words, at higher speeds, the wave-making resistance becomes dominant due to wave generation. Therefore, the effect of a given fouling condition on the total resistance of a ship is greater at low to moderate speeds than at higher speeds (Schultz, 2007).

Recently, Owen et al. (2018) investigated the effect of biofouling on propeller characteristics of Potsdam Propeller Test Case (PPTC) propeller using CFD. The effect proved to be drastic with the most severe fouling condition resulting in a 11.94% efficiency loss at J=0.6 ranging to an alarming 30.33% loss at J=1.2 compared to the smooth condition. Figure 11 is useful in showcasing all three open water characteristics in one plot allowing the variation in each to be demonstrated. J = 1.2 was chosen as the clearest difference between fouling conditions occurs here.

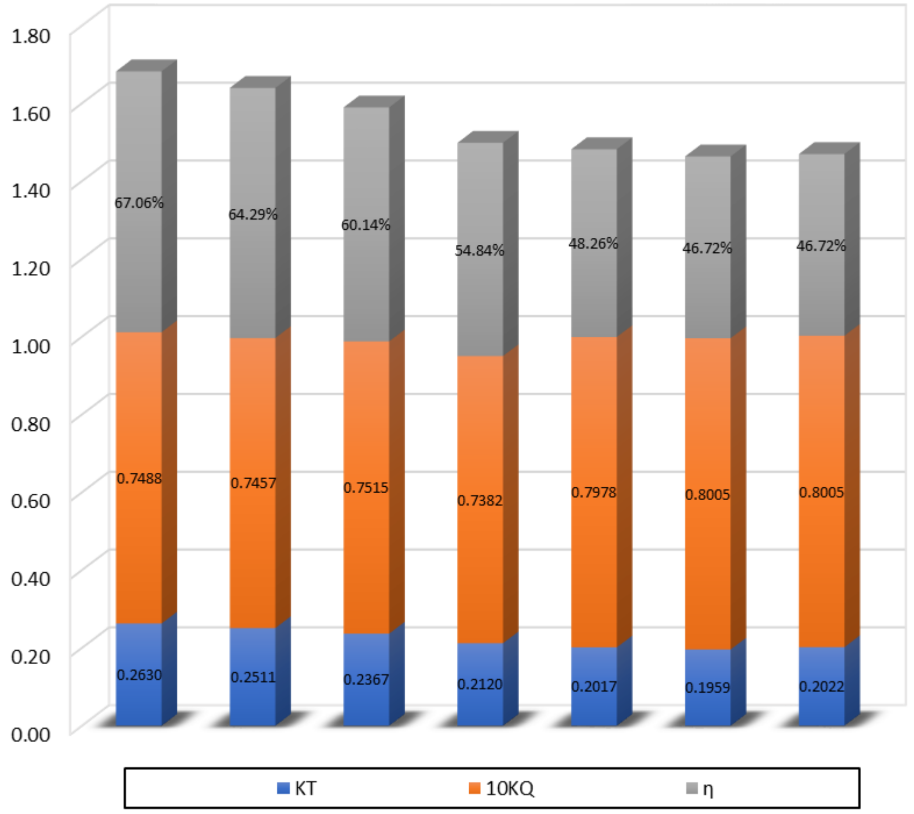

Fig. 11. Open water characteristics for different surface conditions at J=1.2 (Owen et al., 2018).

Results showed that with increasing propeller surface fouling, the magnitude of the propeller thrust coefficient decreases while the magnitude of the torque coefficient increases. This results in a net decrease in open water efficiency of up to 30% at the highest simulated fouling level.

The decreases in the efficiency of the propeller were predicted to be 1.40% at J=0.6 and 4.12% at J=1.2 for a typical as applied antifouling (AF) coating, 3.88% at J=0.6 and 10.31% at J=1.2 for a light slime condition and 11.94% at J=0.6 and 30.33% at J=1.2 for a heavy calcareous fouling condition. These values altered to 6.38%, 11.11% and 11.94% at J=0.6 and 18.22%, 28.03% and 30.33% at J=1.2 for heavy slime, small calcareous fouling or weed and medium calcareous fouling, respectively.

5. Biomimetics

The study of natural systems and copying their functions by means of reverse engineering is called biomimetics. Antifouling strategies are one of the most remarkable features of marine creatures to mimick. Many antifouling strategies have been evolved by marine creatures to keep their surface clean and free from other marine organisms. Ironically, the most nuisance foulers generally have a good antifouling surface topography to avoid the other foulers to attach on themselves (Salta et al., 2012).

5.1. Natural Antifouling Strategies

Many organisms in the nature use various types of antifouling strategies and also combination of them. Some examples of the organisms that use antifouling methods can be expanded from human red blood cell to shark, lotus and birds. This study is focused on the antifouling strategies of marine creatures since the scope of the study covers marine antifouling coatings. In general 3 types of antifouling strategies are used by marine creatures:

- Chemical
- Physical
- Stimuli-Responsive

Many types of chemical secretions are produced by marine creatures to avoid fouling. Some examples of the producers of natural chemical antifouling secretions can be listed as parazoa, algae, bryozoans, cnidarian and mollusca (Chambers et al., 2006). Some tunicate species have acidic pH body fluids at body surface (Ralston and Swain, 2009).

The surface topography and texture are widely used and may be called physical strategies. Physical strategies consist of low drag, low adhesion, wettability and microtexture (Bixler and Bhushan, 2012). Shark skin has inspirational antifouling surface strategies and it also generates low drag and fast swimming properties due to its riblet microtexture and flexion of scales (Bixler and Bhushan, 2012). These scales are longitudinal along the body and they affect the flow properties, such as shear stress, which is the source of frictional resistance (Bixler and Bhushan (2012), Bechert et al. (2000)). Moreover, micro-organisms cannot attach and accumulate on shark skin due to these mechanisms (Kesel and Liedert, 2007). The shark skin demonstration is given in Figure 12 (Bixler and Bhushan, 2012).

Generally, marine creatures combine these strategies to prevent fouling. For example pilot whale skin uses the combination of chemical and physical strategies (Baum et al., 2002).

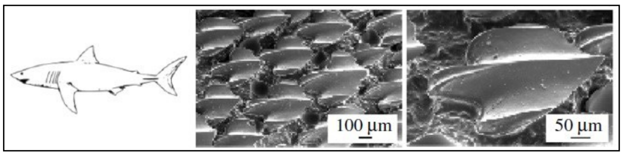

Fig. 12. Shark skin (Bixler and Bhushan, 2012).

The skins of marine mammals and fishes have responsive properties to stimulus such as temperature or pH in the marine environment. The skin of pilot whale, which demonstrates a self-cleaning mechanism by enzymatic digestion (Baum et al., 2002), the denticles of shark skin, which can be bristled actively or passively for drag reduction (Lang et al., 2008) are some examples of surfaces using stimuli responsive strategies.

It is strongly expected that bio-inspired antifouling materials will mimic the physical and chemical activities of the nature to generate the natural defence mechanism against fouling and this principle will play significant role on the development of environmentally friendly antifouling materials/coatings to control and prevent the marine fouling while maintaining an advanced ship performance and hence reduced air emissions.

The use of the antifouling strategies should be associated with operational profile of the vessel and the environmental properties of the region which the vessel in question operates. In other words, the bio-inspired antifouling coating should be a tailored solution, since there are several natural antifouling mechanisms, developed regarding the specific demands of the transportation. The factors affecting the development of bio-inspired antifouling coating are shown in Figure 13. It is clearly seen that biomimetics offers a promising solution and researchers should take the advantage of the natural antifouling strategies to tie them to the marine antifouling coatings.

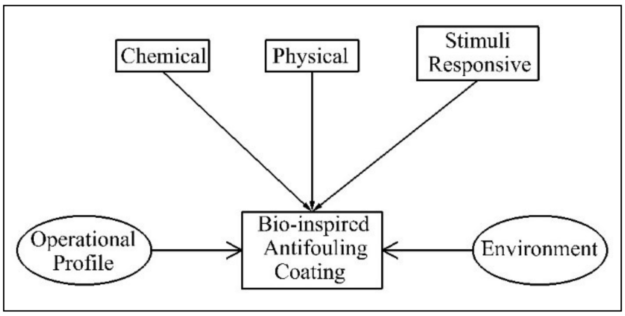

Fig. 13. Development of bio-inspired antifouling coatings.

5.2. Challenges

Although, bio-inspired antifouling technology rises up as one of the best possible solution, there are many challenges and questions far from answered.

One remarkable drawback of the idea of using natural chemicals for antifouling purposes would be their lifespan which last only a few months (de Nys and Steinberg, 2002). It should be taken into consideration that there are many unknowns about these chemicals and the effects of excessive use of these chemicals on marine environment.

Solely physical antifouling methods are effective for a few months and against only specific foulers (Bers and Wahl, 2004). On the other hand, physical strategies are compatible with the existing antifouling coatings and also promising for future studies (Ralston and Swain, 2009).

Because of the fact that natural surfaces and properties are totally distinct from man-made marine structures' surfaces, it is not easy to achieve a harmony. For instance, producibility in large quantities is one of the most important issues. Hitherto, it is not commercially feasible to do.

Marine creatures are generally moving at very low Reynolds number compared to ships. Another challenge is to adapt these antifouling properties to man-made marine vehicles that move in relatively higher Reynolds numbers. The different Reynolds numbers of marine creatures and ships are demonstrated in Figure 14 (Salta et al., 2012). A major problem with biomimicry is to maintain the physical and chemical properties for long time since these properties normally remain on the living things.

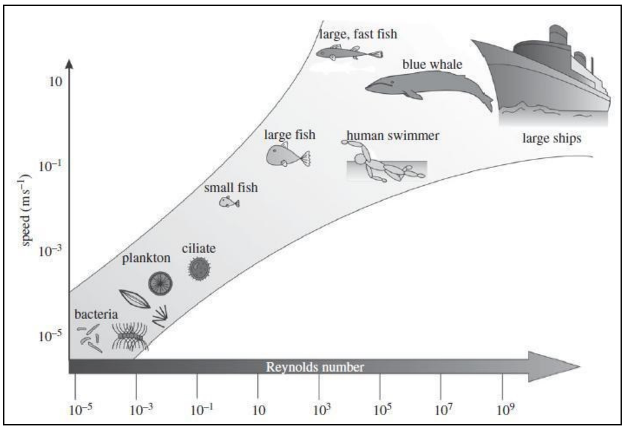

Fig. 14. Reynolds number range of different marine creatures and ships (Salta et al., 2012).

6. Conclusions

New horizons in marine coatings were covered in this study. Marine biofouling problem and the current antifouling methods, the latest research in coating/fouling hydrodynamics and also novel approaches to the solution were presented from a naval architecture point of view. The recent research project FOUL-X-SPEL developed a novel, non-leaching antifouling polymer systems, in which the biocide is fixed in and hence the surface has active antifouling principle in order to avoid fouling while avoiding biocide releasing.

Another novel and pioneering approach is bio-inspired antifouloing technology utilizing biomimetics. Nature has diverse antifouling strategies and nature often uses the combination of them. The tailored combination of these strategies could be used to achieve an effective fouling prevention for both ships and stationary marine structures.

Novel antifouling technologies should be developed concerning the possible direct harmful effects of existing antifouling methods to marine environment and also indirect effects such as increasing emissions. For these reasons, more research effort 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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