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Review Article

Marine fouling: Factors affecting biofouling and future perspectives

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Abstract

Biofouling of the hulls of ships and vessels, caused by the colonization of animals and plants, is an ongoing problem for the shipping industry. Biofouling evokes surface roughness, which results in higher fuel consumption, emissions, and operating costs. Mitigation of biofouling is a complex problem and the effectiveness of any given approach depends on many factors. Compared to complex anti-fouling technologies, the use of anti-fouling coatings presents the most viable solution, both in terms of cost and efficiency. Nevertheless, due to the modest performance of most modern antifouling hull coatings, frequent maintenance, and dry-docking intervals are still required. In addition, application costs are often not negligible. New antifouling technologies, such as low-drag antifouling paints with broad spectrum activity are urgently required in order to promote smoothness of the surface as well as provide adequate protection against biofilm formation. The development of innovative nanocomposite coating structures which combine low-drag film surfaces with antimicrobial components within water-soluble matrices may be a drastic solution to the above problem. Moreover, applying such structures directly on the hulls of ships and marine vessels without the use of primers is a long-awaited possibility, which could have a tremendous impact on reducing application costs.

Introduction

Hull fouling is one of the biggest issues the shipping industry is currently facing. Shortly after their contact with water, the metal parts of a ship or vessel are colonized by living or dead animal and plant organisms. This process is known as bio-fouling [1]. There are four stages (Figure 1) describing the above colonization [2,3].

Stage 1

As soon as a ship is submerged in water, organic matter, and molecules already present in the water, such as polysaccharides and proteins, begin to accumulate on the ship's hulls. The organic particles' inherent ability to stick together results in the formation of a continuous film of chemical compounds. This stage, called primary colonization, occurs shortly after immersion and stabilizes within a short period of time. It also sets the surface up for succeeding stages of colonization by raising its free energy and making it wettable to the organic microfouling components.

Stage 2

Microscopic organisms, primarily diatoms, and bacteria, adsorb on the surface and excrete organic materials, primarily polysaccharides, forming a sticky layer (biofilm). Gravity, electrostatic interactions, water movement, van der Waals forces, and Brownian motion all contribute to the plasmonic cells' instantaneous attraction to the metal surface.

Stage 3

Other, more complex organisms like fungi and protozoa are more easily attached due to the biofilm's sticky texture and the surface's roughness brought on by the presence of the microbial community. Secondary colonization takes place during the transition of the biofilm to a more intricate bio-community that includes primary producers (plant organisms), consumers, predators, and decomposers. Microorganisms form dense epiphytes that are attracted by their phlegmatic secretions. Diatoms slide to their preferred growth sites after passively adhering to the surface.

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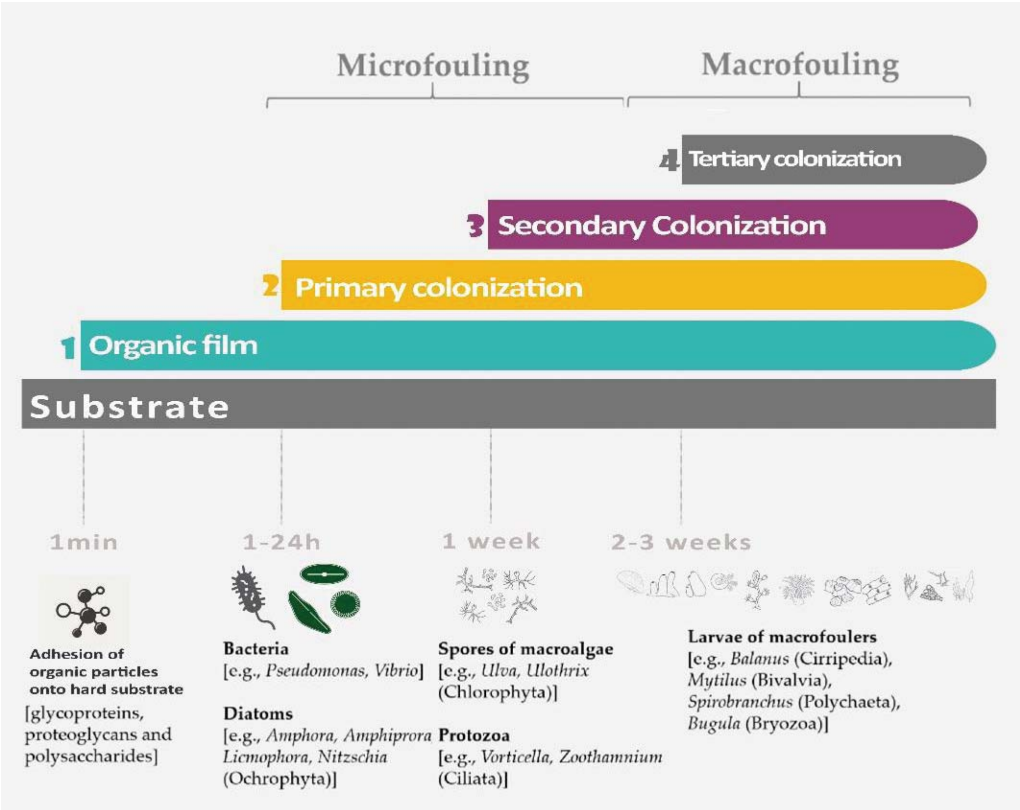

Figure 1: Stages of marine fouling.

Stage 4

Tertiary colonization is characterized by the coexistence of crustaceans (mussels, polychaetes, etc.) and macrophytes, or multicellular plant organisms (chlorophytes, for example, Enteromorpha), as well as phaeophytes, for example, Ectocarpus.

Fouling reduces the ship's cruising speed, exacerbates erosion near the hull, and significantly raises fuel consumption [4]. A ship without biological pollution protection is predicted to accumulate a mass of 150 kg/m^2 of organisms in less than six months at sea. The fouled surface cannot fully regain its original roughness, so even after cleaning and repainting with suitable hull paints, the cruising speed is reduced by 7% – 14% of the original speed [5]. In addition, heating, cooling, and condensing systems using seawater are often contaminated, which reduces the effective cross-section of the suction pipes and increases the amount of energy required to operate the supported units [6].

Factors affecting biofouling

The hydrodynamic theory states that the component force acting on a solid body when it moves through a homogeneous fluid with zero viscosity, such as air or water, is zero because the flow lines pass through the body and return to an undisturbed state away from it. According to Bernoulli's theorem, the flow lines' deflection raises the particle velocities, thus creating a surface pressure drop. As a result, even though forces of different strengths and directions may be applied to the body as a whole, they balance out and there is no drag. This situation, though, is ideal and does not hold in truly coherent, non-zero-density fluids. In reality, pressure changes on a solid body's free surface appear as ripples on the water's surface. These disturbances to the pressure equilibrium cause the appearance of drag forces, which work against the movement of the body in the fluid.

The components of the drag forces applied to the wetted surface of the solid body [7], when it comes into contact with the metallic, watertight hollow section of a ship, are as follows:

- The wave-making resistance
- The skin frictional resistance
- The viscous pressure resistance
- The appendage resistance

Consequently, resistances related to cohesive effects (frictional resistance and the resistance due to changes in the pressure field at the ship's hull) and the interaction of the hull with the free surface of the fluid make a significant contribution to the total resistance (marine vessel drag) [8].

The composition of the distribution of the tangential and vertical elemental forces at the vessel's hulls below the waterline affects how the ship propels itself. Slow ships require a small wetted surface; in this case, friction is the limiting factor. On the other hand, ships that are moving quickly have a high rate of wave resistance [9]. For example, an oil tanker

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traveling at design speed burns a high percentage of its fuel to overcome frictional resistance. For high-speed vessels, wave resistance plays a bigger role [10].

In general, however, frictional resistance is the dominating form of marine drag. This is significantly influenced by the roughness of the surface in contact with the water flow [11]. The generated counter-current and the altered wave shape also have an impact on the overall ship frictional resistance in shallower areas. Furthermore, mechanical detachments or structural flaws often increase the surface roughness of hulls. Improper surface preparation and/or insufficient coating applications can also promote surface roughness due to the formation of revetments, which may lead to an increment in fuel consumption of 3% - 4% [12].

Biofouling may also raise frictional resistance. According to estimates for light displacement ships a light slime coating covering the entire surface of the hulls, can increase the total drag by 7% - 9%, while a heavy coating can do so by 15% - 18%. Seaweed and small shellfish boost resistance by another 20% – 30% [13]. The intensity of the biofouling effect is influenced by the hydrodynamic effects of sailing speed and the presence of shear stresses in the ship's waterline. More specifically, since the rate of heat exchange rises under low-pressure conditions, fouling phenomena become constrained at higher cruising speeds. In addition, the functionality of an antifouling hull paint is enhanced at uniform flow and constant cruising speed. Finally, high shear stresses may facilitate the removal of deposits from the hull's surface [8,9].

A direct correlation exists between the ship's hulls' roughness and fouling. According to calculations, the frictional resistance for ships traveling at high speeds increases by 5% for every 10 – 20 μm increase in hull roughness. Moreover, the fluid flow and cruising speed impact on the ship's hydrodynamic behavior may be evaluated by dimensionless numbers. It is known for example, that the ratio of inertial to viscous forces is expressed by the Reynolds number, which quantifies the relative effect of these two types of forces at specific flow conditions [11,14]. A laminar flow (smooth, continuous fluid motion) has a low Reynolds number, characterized by viscous forces, whereas a turbulent flow has a high Reynolds number, characterized by inertial forces, which tend to create chaotic vortices [15].

Fouling of ships' hulls causes a reduction in speed of up to 40% and increases fuel consumption. Therefore, the challenge is to develop antifouling technologies, such as low-drag antifouling paints, which are robust and lightweight in order to promote smoothness of the surface as well as provide effective antifouling performance.

The cost of increased fuel consumption as a result of biofouling's increased friction is thought to be much higher than the cost of cleaning the hulls and propellers, as well as the cost of using and maintaining the hull paint, according to the American Bureau of Shipping (ABS). As a result, these procedures are economically advantageous to ship owners and also lessen the spread of bio-invasive organisms into the marine environment and the emission of hazardous air pollutants.

It should be also noted that the adhesion and attachment abilities of microorganisms are influenced by seawater parameters in addition to surface roughness. When developing an effective hull paint, temperature, and pH variations are essential control parameters. The behavior of hull coatings has been observed to change slightly with small changes in the alkaline behavior of seawater, either due to hydrosulfide production (decrease in pH) or due to a decrease in CO_2 (increase in pH) attributed to the presence of algae. These changes affect the solubilization of biocides as well as the rate at which the coating corrodes [16].

The type of growing microorganisms, the order in which they are deposited on the ships' hulls, and the extent of the biofouling phenomenon are all significantly influenced by annual temperature variations and seasonal temperature changes [17]. The gradual stages of cell growth, the rate of corrosion of the sub-sail area, and the activity of the antifouling paint are all increased at high temperatures due to the speedy chemical and enzymatic reactions [18-21]. Although the rate of reactions is slow at low temperatures, the biological deposits of microorganisms solidify, making it challenging to prevent biofouling with conventional antifouling paints [22].

The rate of photosynthesis and the conditions for different microorganisms to survive are both affected by sunlight [21,23]. Diatoms, the primary component of marine food, are unable to grow and survive in the dark. Reproductive cycles are also impacted by seawater turbidity and salinity, as well as various environmental factors [24,25]. Certain species of microorganisms exist at comparable latitudes and in regions with comparable climates, though their proportions change and fluctuate seasonally [26,27].

The number of larvae in the water, their rate of growth, their attainment of reproductive potential, as well as the average size of the developing organisms, and their susceptibility to adsorption all play a significant role in determining the intensity of biofouling [28]. Depending on environmental factors, the size of different species varies. Individual organisms typically grow slowly as they expand in size [29]. Eusocial microorganisms, in conjunction with food and space limitations, control the majority of biofouling.

Discussion and innovative perspectives

Unambiguously, the mitigation of biofouling presents a multifaceted challenge, with the efficacy of each approach contingent upon numerous variables. When considering various anti-fouling technologies, such as seawater electrolysis or robotic hull cleaning, it becomes evident that the utilization of anti-fouling coatings remains the most practical and effective solution, primarily due to its favorable cost-effectiveness ratio. However, the need for regular maintenance and dry-docking intervals is still essential, primarily due to the limited effectiveness of contemporary antifouling hull coatings. Furthermore, it is worth noting that application costs are frequently significant and should not be overlooked.

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One potential solution involves the implementation of anti-fouling coatings that effectively disrupt the colonization process, even during its initial phases [30]. BFP's research group is working on the above field by developing core-shell antifouling nanostructures consisting of modified carbon allotropes and organofunctional silanes. These are able to disperse hull surface charges directly into the matrix of the antifouling paint, thus preventing electrostatic interactions with the externally charged membrane of marine organisms. By doing so, we aim to prevent the early formation of biofilms, which serve as a foundation for macrofouling [31].

The above mechanism of action is based on the intrinsic properties of the components used, e.g., high conductivity and photocatalytic activity. However, given the variability of biofouling from site to site and between static and dynamic conditions, it is necessary to devise strategies that possess a wide-ranging efficacy. Modern antifouling paints usually do not meet this need, e.g., an anti-fouling paint that is functional in the Mediterranean Sea is usually not equally functional in the Singapore zone, and vice versa. At the moment, the development of one-fits-all antifouling formulas with exceptional longevity seems to be rather unlikely.

Furthermore, it should be noted that the primary cause of marine drag is frictional resistance, which, to a large extent, is influenced by surface roughness. Surface roughness, in turn, is primarily caused by the presence of foul ants. Therefore, an effective solution may be achieved indirectly by combining low-drag surfaces with antimicrobial components embedded in water-soluble matrices. Through the utilization of this methodology, it is conceivable to potentially fabricate nanocomposite coating architectures that exhibit exceptional efficacy across various environmental circumstances.

A final aspect of designing cost-effective and efficient antifouling coatings is application costs. The latter is significantly influenced by the number of layers, i.e., primer coat, tie coat, and top coat, required to develop an adherent antifouling coating system. Among them, surface priming is perhaps the most important process, since it provides the fundamental foundation on which the coating adheres and also protects the substrate against corrosion. However, it is also the most time-consuming and labor-intensive process. Anticorrosive primer-free coating systems for metal substrates are a long-awaited possibility. The application of such systems directly on the hulls of ships and marine vessels within a single application step could have a tremendous impact on reducing the overall cost of antifouling paints.

Conclusion

Colonization of the hulls of ships and boats from animal and plant organisms poses an ongoing threat to the shipping industry. Marine vessels accumulate organic matter and molecules on their hulls, creating a strongly adherent and structured microbial community. The biofouling effect is directly related to the roughness of the ship's hull, with an increase in surface roughness resulting in higher fuel consumption and increased friction. New antifouling technologies, such as primers and/or low drag antifouling paints with broad spectrum activity are urgently required in order to promote smoothness of the surface as well as provide adequate protection against early biofilm formation. Proper surface preparation and hull paint selection are crucial for reducing the cost of biofouling and reducing the emission of harmful air pollutants and transport costs.

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