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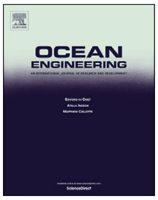

En-route operated hydroblasting system for counteracting biofouling on ship hull

Jian Hua [*], Yin-Sen Chiu, Chin-Yang Tsai

Department of Marine Engineering, National Taiwan Ocean University, Taiwan

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ABSTRACT

Improvement in the management of biofouling on ship hull can help to enhance the operational performance of ships and reduce cost of shipping. It can also effectively minimize the environmental impact e.g. spread of invasive aquatic species of international shipping. The operation of the newly developed hydroblasting cleanup system indicates that angles and types of nozzles have apparent effects on the effectiveness of biofouling removal. With a distance of 6 mm from nozzle tip to specimen surface, the biofouling removal rates were 41%, 59%, and 71% for 25° flat, 65° flat, and rotating jet, respectively. The results obtained in the study demonstrate that the growth of biofilms can be interrupted effectively by using the developed system. We determined the extent to which the proposed technology can be used to prevent the buildup of biofouling on international vessels, to reduce the global transfer of nonindigenous species, and to contribute to the future development of useful solutions. We suggest that future studies use this cleaning system periodically while monitoring the status of biofouling to determine the effectiveness of the interference. The results can also be used to establish parameters (e.g., cleaning cycle duration) for a strategic plan.

1. Introduction

1.1. Biofouling of ship hull

Accumulations of aquatic organisms are commonly found on the submerged hull surfaces of ships (Davidson et al., 2009). The process of biological fouling (biofouling) on a ship hullmay begin with biofilm within a few hours of a ship being placed in water (Characklis et al., 1984; Chambers et al., 2006; Edyvean, 2010; Davidson et al., 2008; Floerl et al., 2005). Once formed on a surface, the biofilms might develop rapidly into a macrofouling system (Floerl et al., 2008; Gunasekera et al., 2008; Guo et al., 2012; Legg et al., 2015).

Macrofouling can substantially increase friction on ship hulls and result in a substantial economic cost for the shipping industry (Guo et al., 2012; Townsin, 2003). For instance, heavy calcareous fouling can increase required shaft power by as much as 86% under cruising conditions (Schultz et al., 2011). In addition, the operational efficiency, maneuverability, and thus safety of ships can be compromised by biofouling (Edyvean, 2010; Logan, 2012; Schultz et al., 2011; Woods Hole Oceanographic Institution (WHOI), 1952). The management of hull fouling and resistance thus plays a crucial role in helping to reduce operating and capital expenses of shipping. Most cargo ships undergo coating renewal every 3–5 years in general.

1.2. Fouling removal

Biofouling develops between dry-docking while in service for most ships even if antifouling systems are applied (Thomason, 2010). As a ship's antifouling coating ages, calcareous forms of biofouling begin to spread over all areas of the ship's hull that are below the waterline. Whereas ships with longer stationary times (e.g., military vessels) and slow turnaround times (e.g., cargo ships) favor tubeworm and barnacle growth, ships with short stationary periods (e.g., passenger liners, large crude carriers, and container ships) favor algal fouling (Almeida et al., 2007).

The most commonly used methods for biofouling removal are high-pressure abrasives in dry dock (ANZECC, 1997; Chambers et al., 2006; Debus et al., 1994). The hull is first treated with either abrasive blasting or ultra-high-pressure water in a dry-dock to remove biofouling along with coating. Plant fouling, including algal slimes and seaweed, can be effectively removed by high-pressure jet water washing (Guo et al., 2012). Most adhering biofouling, scale, rust, and old paint coatings may be removed together from a ship's hull by sand blasting, scraping, and wire brushing (Debus et al., 1994). Shell fouling (e.g., acorn barnacles

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[*] Corresponding author.
E-mail address: huajian@ntou.edu.tw (J. Hua).

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and tubeworms) can be effectively dislodged by scraping (Hopkins et al., 2008). However, mismanagement of these systems will result in increased hull roughness, fouling, fuel consumption, exhaust emissions, costs and the transport of invasive species (Swain, 2010). Cleaning forces should be minimized based on the adhesion strength of biofouling on ship hull because cleaning practices can result in decreased lifetime of coating (Oliveira and Granhag, 2016). Swain and Schultz (1996) have evaluated the biofouling communities, the measurement of biofouling adhesion using a calibrated water jet and the measurement of barnacle adhesion in shear.

Tribou and Swain (2015) developed grooming method which was frequently and gently applied on ship hull to prevent biofouling. The method was tested on large steel plate in Florida, with results indicated that frequent grooming could reduce the fouling rating of ships coated with various fouling-release coatings (Tribou and Swain, 2010, 2015; Hearin et al., 2016; Hearin et al., 2016). The grooming tool can effectively remove even most hard fouling (Tribou and Swain, 2015).

Health and environmental issues are related to antifouling paint renewal for ships (Woods et al., 2012). They include AF paint residue, blasting dust, waste water, and nonindigenous species (Floerl et al., 2008). In addition to dry-docking, in-water cleaning has also been used to clean ship hulls during mooring periods. This method uses rotating brushes or water jets to remove fouling (Hopkins et al., 2008). Divers adhere cleaning machines to the hull, either with suction created using a rotating-brush impeller or with vortex action. This process can remove biofouling together with AF paint effectively (Yebra and Kiil, 2004).

1.3. *Objective*

The main objective of this study is to experimentally test an alternative biofouling cleaning system designed for operation by crews on board ships that are en route of cruising. To the best of the authors' knowledge, this is the first proposed antifouling practice for ships. Instead of thoroughly removing biofouling from a ship hull, the aim of this new method is to interrupt the development of biofouling. The duration between dry-dock or in-harbor underwater cleaning can be extended, and the operational and maintenance costs are expected to be significantly reduced.

To the best of our knowledge, few studies have addressed the effects of cleaning on biofouling in different types of operations. In this experiment, we tested the effectiveness of the proposed method and various practical considerations, such as the integration of pump with nozzle arm, and the availability and operational requirements for applying the system on a ship. This paper presents the results of our experiment for answering primary questions such as how effective with which various nozzle jets remove biofouling. We also discuss the potential of this system as a vital approach to be integrated into a complete antifouling strategy.

2. Method and procedure

The experimental study simulated the process of in-water biofouling cleaning system sliding on a ship hull and hydroblasting the hull simultaneously. We conducted experiments in both field and laboratory conditions. In the field, we established time series for the development of biofouling on ship hull surfaces in a coastal environment. In the laboratory, we primarily tested the effectiveness of the cleaning system with a number of combinations of design parameters.

2.1. *Observation of biofouling development*

2.1.1. *Specimen preparation*

The field investigation simulated the progress of biofouling on the surfaces of a ship hull submerged in water. The specimens for biofouling experiment were PVCsheets (400 × 200 × 3 mm ± 1%) coated with one layer of commercial marine primer followed by one layer of oleoresin based inorganic marine paint (SP-255) marine paint. The marine primers include formulations based on specific materials (e.g., vinyl, chlorinated rubber, epoxy, and epoxy-coal tar). We prepared two sets of specimens, all of which were weighed on an electronic scale (Precision APTP456B 3 kg × 0.01 g) before field incubation. All specimens were prepared in triplicate.

To our knowledge, the performance of any paint coating is directly dependent upon the correct and thorough preparation of the surface prior to coating. We prepared each biofouling specimen by pickling it in a solution of hydrochloric acid with an inhibitor according to the C3.5 designation of ASTM G 1-90 (ASTM, 2003). The specimens were rinsed with deionized water, and were then air-dried and weighed before testing. We prepared the specimens to ensure a surface profile allowing satisfactory adhesion of the coating to be applied. The most expensive and technologically advanced coating system will fail if the surface preparation is incomplete.

2.1.2. *Field incubation*

We arranged a series of specimens vertically on a steel rack set which was contained in a chamber. We then sank the entire experimental system in water (1.8 m in depth) near the shore at Keelung Port, Taiwan (121°46′31″E, 25°09′06″N). Fig. 1 shows the experimental system in coastal water. The chamber was a rectangular plastic tank, constructed from heavy gauge, chemical- and water-resistant, opaque orange cross-linked polyethylene. The bottom of the tank was removed to make it ready to sink to the seabed.

We used a measuring system with a miniaturized sensor for in-situ water quality monitoring (Simbeye and Yang, 2014). The sensor system featured low energy consumption and automatic measurement and logging. The data presented in this paper were taken during the entire testing period.

Data were collected on temperature, salinity, concentration of chlorophyll a (Chl a), nitrate (NO_3), and phosphate (PO_4). The physical environmental parameters, including salinity and temperature, were recorded 0.5 m below the surface by using a SYA 2-2 salinometer and thermometer. Levels of nitrates in the form of soluble reactive phosphorus were determined using the molybdenum blue method immediately after sampling (Parsons et al., 1984). The detection limits of NO_3 and PO_4 were 0.02 and 0.03 mmol L1, respectively. The mean Chl a concentration was then determined fluorometrically (Turner Designs 10AU fluorometer) before and after acidification.

2.1.3. *Determining biofouling growth*

We tested the biofouling growth 2, 4, 8, 12, 16, 20, 24, 48, 96, 144, 192, and 240 days after the specimens were set in the coastal water. The incubation specimens were collected from the field periodically for measuring biofouling growth. We calculated the rate of biofouling growth (g/m^2-day) as:

$$\frac{W_f - W_s}{A \times D}$$

where

W_f = weight of specimen after D days of incubation in water, g
W_s = weight of specimen on previous sampling day, g
A = surface area of specimen, m^2

2.2. *Simulating ship hull cleaning during navigation*

2.2.1. *Determining cleaning effectiveness, E_c*

We constructed an experimental system (Fig. 2) to simulate the operation of the cleaning system proposed in this study. The system mainly consisted of a specimen holder, which was a 90-cm-diameter FRP ring, and a hydraulic cleaning device submerged in a circular 120-cm-diameter FRP water tank. The cleaning device was a series of interchangeable jet nozzles. The water pressure was adjusted by controlling