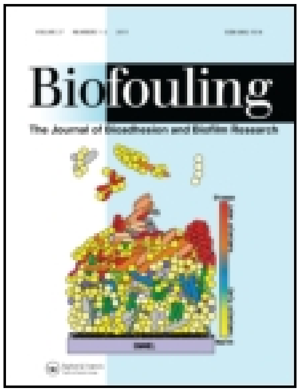

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Fouling by biofilms significantly increases frictional drag on ships' hulls. A device, the friction disk machine, designed to measure torque on rotating disks, was used to examine differences among experimental fouling-release coatings in the drag penalty due to accumulated biofilms. Penalties were measured as the percentage change in the frictional resistance coefficient C_f. Drag penalties due to microfouling ranged from 9% to 29%, comparable to previously reported values. An antifouling control coating showed a smaller drag penalty than the fouling-release coatings. There were also significant differences among the fouling-release coatings in drag due to biofilm formation. These results indicate that the friction disk machine may serve as a valuable tool for investigating the effects of experimental coatings, both antifouling and fouling-release, on microfouling and associated drag penalties.

Keywords: drag; biofilm; fouling-release; silicone surfaces

INTRODUCTION

The accumulation of fouling on a ship's hull degrades performance by increasing frictional drag (WHOI, 1952; Abbott *et al*., 2000; Townsin, 2003). Application of an effective antifouling coating to the hull can substantially improve operating efficiency. Milne (quoted in Townsin, 2003) estimated an annual savings in fuel costs, due to the salutary effects of antifouling coatings on frictional resistance or drag, of approximately $720M.

For more than 20 years, coatings containing organotin have served as the standard treatment for control of fouling on vessel hulls. In practice, these coatings can inhibit fouling for up to 5 years (Townsin, 2003). The success of organotin-containing antifouling coatings, however, has been accompanied by significant detrimental effects on the environment (see Champ, 2000; Evans *et al*., 2000; for reviews). The International Maritime Organization has begun an effort to ban hull paints containing organotin by 2008, with earlier restrictions on application.

With the impending ban of organotin-containing hull paints, research and development has shifted to coatings employing copper and organic 'booster' biocides to prevent buildup of fouling, and to non-biocidal, fouling-release coatings that allow fouling to occur, but prevent it from attaching firmly to the painted surface. A transition in coating technologies is likely to benefit the environment by reducing the input of highly toxic organotin compounds, but potential indirect effects of new coatings on the environment are not well understood and could be important. For example, if new coatings are less effective in controlling the accumulation of fouling, frictional drag on ship hulls will increase, leading to greater fuel consumption and exhaust emissions. As new technologies are introduced, their effectiveness against the accumulation of fouling organisms, and the resulting consequences of that accumulation on frictional drag, must be evaluated.

Standard methods, currently in use for evaluation of new antifouling and fouling-release coatings, focus either on the ability of these materials to prevent accumulation of macrofouling (for example, ASTM D 3623-78a (1993), ASTM D 5479-94 (1994) ASTM D 4939-89 (1996)), or on the ease of removal of macrofouling from the coating surface (ASTM D 5618-94 (1994)). None of these methods provide any specific information on the effects of the coating on

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frictional drag. Macrofouling has long been recognized to contribute significantly to drag penalties suffered by vessels, so to the extent that the evaluation methods demonstrate an effect on the accumulation of macrofouling, they will suggest a corresponding effect on the drag penalty. Frictional drag, however, is also increased by the presence of biofilms, or microfouling, on the hull. The contribution to overall ship drag by microfouling is largely unknown, but available published reports demonstrate penalties ranging from 5% to 25% (for review, see Townsin, 2003). Schultz and Swain (1999; 2000) observed penalties in local skin-friction coefficient of from 33% to 187% on flat plates fouled with biofilms. The amount of increase depended on the thickness and community structure of the biofilm (Schultz & Swain, 1999; 2000). The corresponding increase in overall drag of a ship covered with these biofilms would depend largely on the length, speed, and hull shape of the ship. Standard methods are needed to determine if different types of hull coatings affect the drag penalty due to accumulation of biofilms. Approaches utilizing rotating disks (for example, Loeb *et al.*, 1984), rotating drums (for example, Candries *et al.*, 2003; Weinell *et al.*, 2003), or flow tunnels (for example, Schultz & Swain, 1999; 2000), may provide convenient means by which drag due to biofilms can be estimated for experimental coatings.

In the present study, a device, the friction disk machine, designed to measure torque on rotating disks (Loeb *et al.*, 1984), was used to examine differences among experimental fouling-release coatings in the drag penalty due to accumulated biofilms. The Paints and Processes (Code 641) laboratory at the Carderock Division of the Naval Surface Warfare Center has developed and used this device, in this role, for over 20 years (for example, Belt & Smith, 1979; Loeb, 1981; Loeb *et al.*, 1984). Schultz and Myers (2003) recently used the same device to quantify roughness functions for experimental surfaces. The 'disk drag test,' using the friction disk machine, discriminated between types of coatings (antifouling *vs* fouling-release), and among coating formulations, in terms of their effects on drag due to biofilms. The disk drag test can serve as a convenient standard method, during the research and development process, to examine the drag consequences of microfouling on experimental coatings or formulation variations.

MATERIALS AND METHODS

The disk drag test employs coated disks (22.86 cm diameter by 0.3 cm thick), mounted to a variable speed electric motor equipped with a torque sensor, to measure drag on the coated surface under varying conditions of fouling and angular velocity.

Measurement of Drag Using Rotating Disk Method and Friction Disk Machine

The drag on the painted disks was measured using the friction disk machine (FDM, Figure 1). The FDM consists of a variable speed, direct current motor (Baldor Model 3445) that drives a shaft onto which the disks are mounted. A sensor (Lebow Model 1104-50 slip-ring type torque sensor) installed on the shaft measures the torque produced when the disk rotates. Drag may be calculated from this torque. Disks were mounted on the shaft of the FDM and then immersed in a cylindrical test chamber (25 cm height × 33 cm diameter) filled with tap water. Torque on the motor shaft was recorded, along with water temperature, as the disks were spun at increasing angular velocities from 700 rpm to 1500 rpm and back to 700 rpm (in increments and decrements of 200 rpm), followed by a final measurement at 1500 rpm to complete the cycle.

The precision and bias of the FDM's tachometer is approximately 1% of the reading, that of the torque sensor is approximately ± 0.05% of full scale, and the thermocouple produces water temperature readings with an error of ± 0.05°C (Schultz & Myers, 2003). Taking into account these errors, the 95% confidence

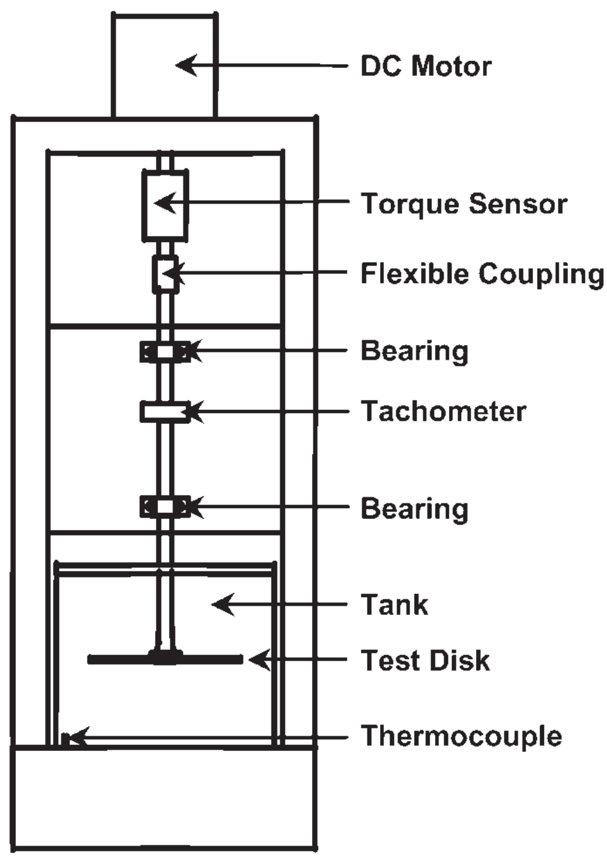

FIGURE 1 The Friction Disk Machine (FDM). The diagram is Figure 2 from Schultz and Myers (2003), and is provided courtesy of the publisher, © Springer-Verlag GmbH & Company KG.

interval for the estimated torque or moment coefficient C_m (see below) is approximately ± 2%.

Prior to and following the spinning of each set of disks, a standard disk was run to ensure stable operation of the FDM and to correct for bearing drag. The standard disk was made of a titanium 6Al-4V alloy with a known roughness.

Exposure of Coated Disks and Testing in the Fouled Condition

For exposure to fouling organisms, disks were mounted vertically on a pipe (protected with zinc anodes) that passed through a 3.8 cm diameter hole in the centre of the disk. One disk of each coating treatment was attached to each pipe. Pipes (5) supporting the test disks were immersed horizontally in estuarine—brackish waters (salinity = 8 – 10‰) from a floating dock located at the Small Craft Test Facility, Naval Air Station Patuxent River, on the Chesapeake Bay. Disks remained exposed under static conditions for approximately 3 weeks, at which point they were retrieved and evaluated on the FDM for drag in the fouled (with a biofilm) condition. Any barnacles or other large, 'hard' fouling organisms found on the coating surface were removed by hand before testing, since the FDM is not capable of accurately measuring the contribution to drag by large macrofouling organisms.

Each fouled disk was spun through two cycles on the FDM. Measurements from the second cycle were used to perform the calculation of drag, as this cycle represented the steady-state condition after loosely adhered biofilms had been shed from the coated surface during spinning. After evaluation in the fouled condition, a rubber squeegee was used to gently remove any remaining biofilm, and the drag was again measured. This cleaning was an attempt to simulate underwater hull cleaning and to determine whether or not a cleaned coating exhibited similar drag to the unexposed condition.

Coating Systems Evaluated

Three elastomeric fouling-release coating systems were evaluated, along with a control antifouling treatment, International BRA 640, an ablative coating employing copper as a biocide. BRA 640 is on the US Navy MIL-PRF-24647B qualified products list, and is one of the hull coatings routinely used to protect Navy vessels from accumulation of fouling. The three fouling-release systems (FR-1 to FR-3), were provided by Kansai Paint Company Ltd, and represent formulations developed either to shed fouling at very low speeds (FR-1), or to shed fouling at higher speeds while displaying improved resistance to mechanical damage (FR-2, FR-3). These coatings were multilayered systems consisting of an anticorrosive paint, a sealer, and finally the fouling-release topcoat (Table I). For FR-1, the topcoat was BIOX M 100-2; for FR-2, BIOX M 110-2; and for FR-3, BIOX M 120-2. Coating FR-1 was very slick with an oily surface; the surface of FR-2 was less noticeably oily, while FR-3 did not feel oily to the touch.

Coatings were applied to five replicate steel disks. Surfaces were prepared prior to coating application by abrasive blasting with 90 mesh aluminum oxide grit (50 – 75 μm profile). The disks were then coated with the candidate fouling control systems, either by the manufacturer (fouling-release coatings) or in the paint laboratory at the Naval Surface Warfare Center, Carderock Division.

Calculations and Statistical Analysis

Granville (1978, 1982) developed the analytical tools necessary to characterize the roughness and drag of rotating disks, and convert them to ship scale. The approach employs similarity-law characterization methods to generate descriptors of roughness (ΔB = similarity-law roughness function, and k^* = roughness Reynolds number) at the disk edge, which can then be used to predict the skin friction for a flat plate with similar surface properties, at lengths representative of ships (see Granville, 1978, 1982; Loeb *et al*., 1984; Schultz & Myers, 2003; for details). The torques generated during spinning of the disks were used to calculate moment coefficients C_m

$$C_m = \frac{2Q}{\rho \omega^2 r^5 \phi^2} \quad (1)$$

where Q is the measured torque, ρ is the density of water, ω is the angular velocity, and r the radius of the disk. The confinement of the disk by the FDM tank sets up a flow that reduces the observed angular velocity of the disk by a 'swirl' factor ϕ (Granville, 1978; 1982). Loeb *et al*. (1984) calculated $\phi = 0.854$ for the FDM. The rotational Reynolds Number for each moment coefficient was calculated from

$$Re_r = \frac{r^2 \omega \phi}{\nu} \quad (2)$$

where ν is the kinematic viscosity. Values for kinematic viscosity, and density of the water in the test chamber, were interpolated from data of Saun-

TABLE I Composition of the fouling-release coating systems tested

	FR-1	FR-2	FR-3
Anti-Corrosive Coat	Nu Forte M	Nu Forte M	Nu Forte M
Sealer	Biox M Sealer	Biox M Sealer	Biox M Sealer
Top Coat	Biox M 100-2	Biox M 110-2	Biox M 120-2

The coatings were prepared by Kansai Paint Company Ltd; the anticorrosive layer consisted of two coats, each with a target dry film thickness of 150 μm; the target thickness for the sealer coat was 75 μm; the fouling-release topcoat comprised two layers of the designated paint, each with a target thickness of 75 μm ders (1957) and Weast (1959), respectively. The calculation of the roughness functions (ΔB *vs* k^*) and conversion to frictional resistance coefficients C_f at the appropriate Reynolds number for a flat plate, is an iterative process based on the concept of boundary layer similarity for rough and smooth walls. The details of these calculation methods can be found in Granville (1982) and Granville (1978), respectively. A plate length of 100 m, which is representative of the length of a ship, was used for the conversion to frictional drag coefficient in the present study.

The absolute value of the drag experienced by a spinning disk is potentially confounded with the type of coating applied to the disk surface (Candries *et al.*, 2003). The drag on a clean or fouled disk is a function of the roughness of the disk surface, which may be a fundamental characteristic of the coating or a result of preparation of the disk surface before painting and the care taken during paint application (Candries *et al.*, 2003; Weinell *et al.*, 2003). Thus, the differential effects of test coatings on the accumulation or adhesion of biofilms, and the impact of those biofilms on drag, cannot be estimated using the measured absolute values of drag. Instead, only changes in drag, relative to the drag experienced by the surfaces before they were immersed, can be compared among coatings. Change in drag, for disks in the fouled and cleaned condition, were calculated by dividing the drag experienced by fouled or cleaned disks by the drag experienced by the disks before exposure. Calculations were carried out at a fixed value of $\log(Re) = 9.2$ (equivalent to a ship speed of about 42.6 km h^{-1} or 23 knots). The percentage change in drag due to fouling and after cleaning was calculated for each replicate disk, and used in statistical comparisons among the coatings tested.

For each statistical test, values for the percentage change in drag were first subjected to the angular transformation (Sokal & Rohlf, 1981), then to Levene's Test for homogeneity of variance. If variances were homogeneous, analysis of variance (ANOVA) was used to test for significant differences among the various coatings, and, where appropriate, *post-hoc* comparisons between the coating treatments were conducted using Tukey's Studentized Range test. All statistical tests were carried out in SAS (SAS Institute, 1989).

RESULTS

The coated disks were exposed, in five blocks, between 14 August and 13 September 2000. Each block comprised one replicate of each of the four coating treatments. The distribution of the coated disks into blocks allowed the investigators to control for any variation in drag that might have been due to spatial or temporal variation in the development of biofilms on the surface of the disks. Block 1 was retrieved after 24 d exposure, blocks 2, 3 and 5 after 22 d exposure, and block 4 after 21 d exposure. All disks supported a biofilm; typically the fouling-release coatings also supported several small colonies of encrusting bryozoans and scattered, small, barnacles, covering at most approximately 5% of the coating surface. In all cases the remainder of the disk surface was fouled by a biofilm. The barnacles and bryozoans were removed by hand before testing.

Drag (as measured by the frictional resistance coefficient C_f) increased on all the coated disks with the development of a fouling biofilm (Figures 2 – 5). Increases in drag appeared to be larger for the fouling-release coatings (Figures 3 – 5) than for the antifouling coating (Figure 2). There was also some variation in the change in drag among replicate coatings. This variation may have been due to multiple causes (individually or in combination), including i) differences among replicate disks in the properties that affect accumulation of biofilms, ii) differences in the roughness of the painted surfaces before immersion, perhaps arising during preparation of the disks (Weinell *et al.*, 2003), and iii) block effects (see above).

The change in drag, experienced by the disks after the accumulation of biofilms, varied significantly among the test coatings (Figure 6; one-way ANOVA; $F = 43.25$; df = 3, 16; $P < 0.0001$). The ablative antifouling coating showed the smallest change in drag; accumulation of biofilms increased drag on these disks by approximately 9% (n = 5, SD = 2.5). Increases in drag on the fouling-release coatings were approximately 17% (SD = 4.6) for FR-1, 27% (SD = 2.2) for FR-2, and 29% (SD = 2.2) for FR-3 (n = 5 in all cases). The change in drag for coating FR-1 was significantly greater than that for the antifouling coating, but significantly smaller than the increases observed for FR-2 and FR-3 (Figure 6, Tukey's Studentized Range test). In no case did exposure and fouling of a disk lead to a decrease in drag.

For all coatings, removal of the attached biofilm with the squeegee resulted in a decrease in drag over the fouled condition (Figure 6). The measured change in drag over the unexposed condition, however, was still significantly greater than 0% (*t*-test; df = 4, $P < 0.01$ in all cases), suggesting that a simple scraping of the disk did not restore the original drag-inducing properties of the coatings. After cleaning there were no differences among the four test coatings in the change in drag, over the painted, unexposed condition (Figure 6; $F = 1.66$; df = 3, 16; $P < 0.22$).

DISCUSSION

Significant differences among the coating treatments in the drag they experienced after the accumulation

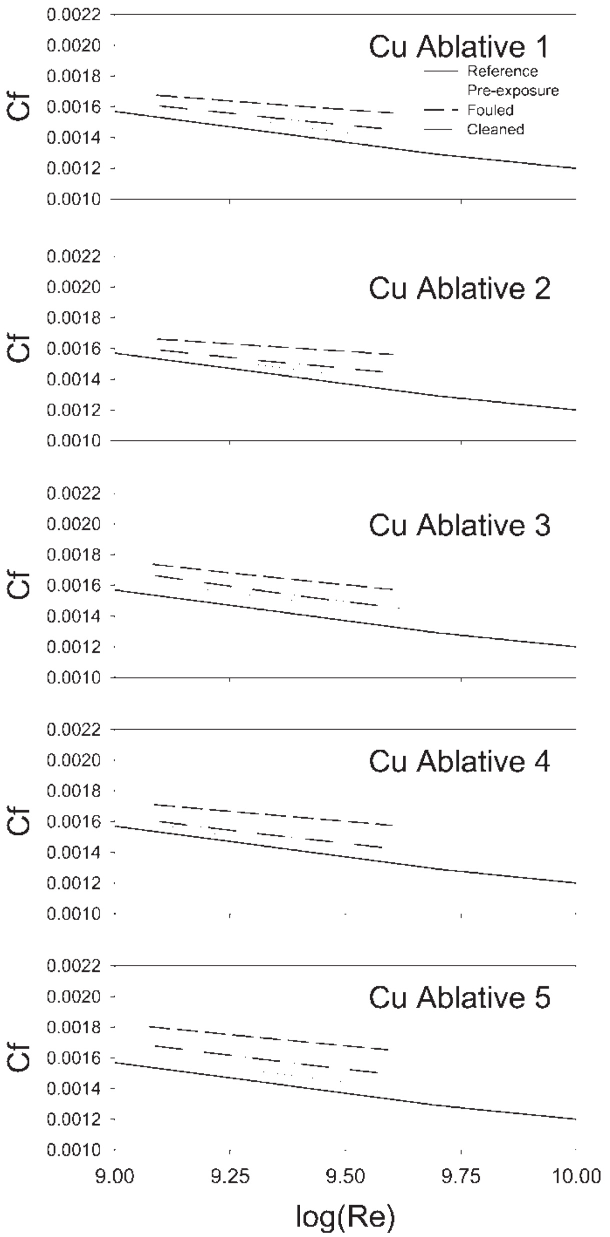

FIGURE 2 Copper ablative surface. Frictional resistance coefficients (C_f, see Materials and Methods section) calculated for five replicate disks at various values of the flat plate Reynolds Number, log(Re). Reference = smooth surface; pre-exposure = painted disk before exposure; fouled = painted disk fouled by biofilms; cleaned = fouled disk after cleaning with squeegee.

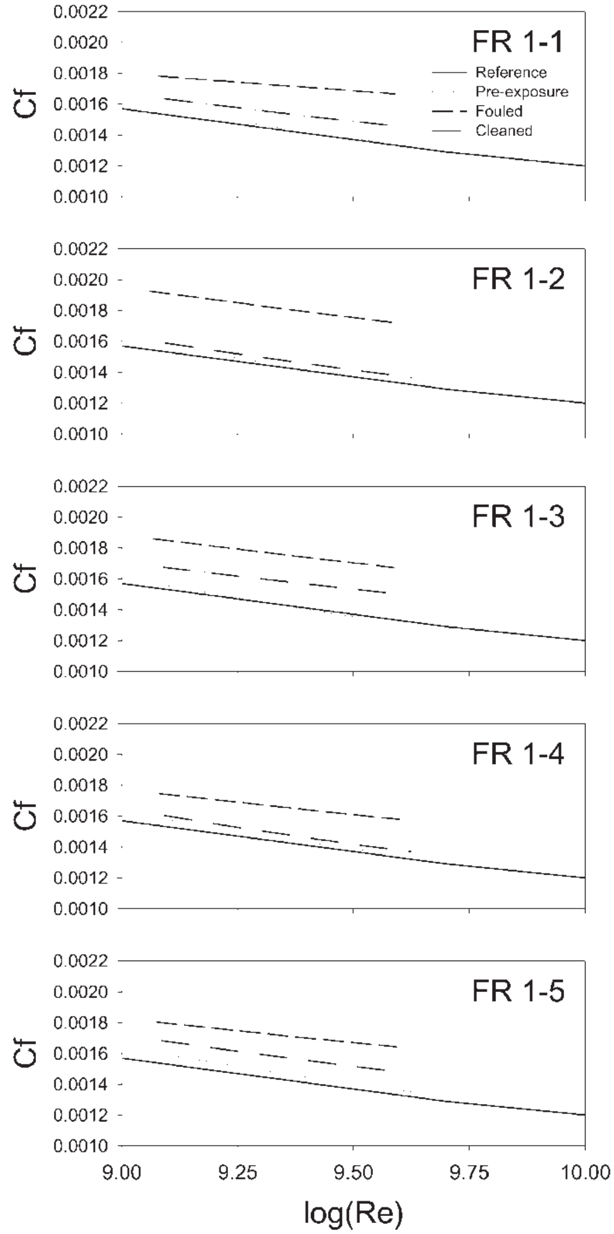

FIGURE 3 Fouling-release Treatment 1. Frictional resistance coefficients (C_f, see Materials and Methods section) calculated for five replicate disks at various values of the flat plate Reynolds Number, log(Re). Reference = smooth surface; pre-exposure = painted disk before exposure; fouled = painted disk fouled by biofilms; cleaned = fouled disk after cleaning with squeegee.

of biofilms were found (Figure 6). Drag penalties ranged from 9% to 29%, depending on the coating. These penalties are comparable to previously reported values (Townsin, 2003).

The additional drag experienced by the fouled coatings is attributed to the presence of biofilms. Increases in roughness of the coatings themselves during the exposure period could, however, also contribute to the observed drag penalty. However, there were no measurements of surface roughness of the materials either before exposure or after cleaning, so the effects of changes in the coating surface itself cannot be estimated. For the ablative coating BRA 640, copper is leached from a resin/rosin matrix, leaving a leached layer that erodes under flow. Depending on the local flow environments and the leaching rate of the copper, the microroughness (Weinell *et al.*, 2003) of BRA 640 could conceivably increase, decrease, or remain the same during exposure. In contrast, changes in the microroughness of the fouling-release coatings should have been minimal. On the other hand, the surface of exposed

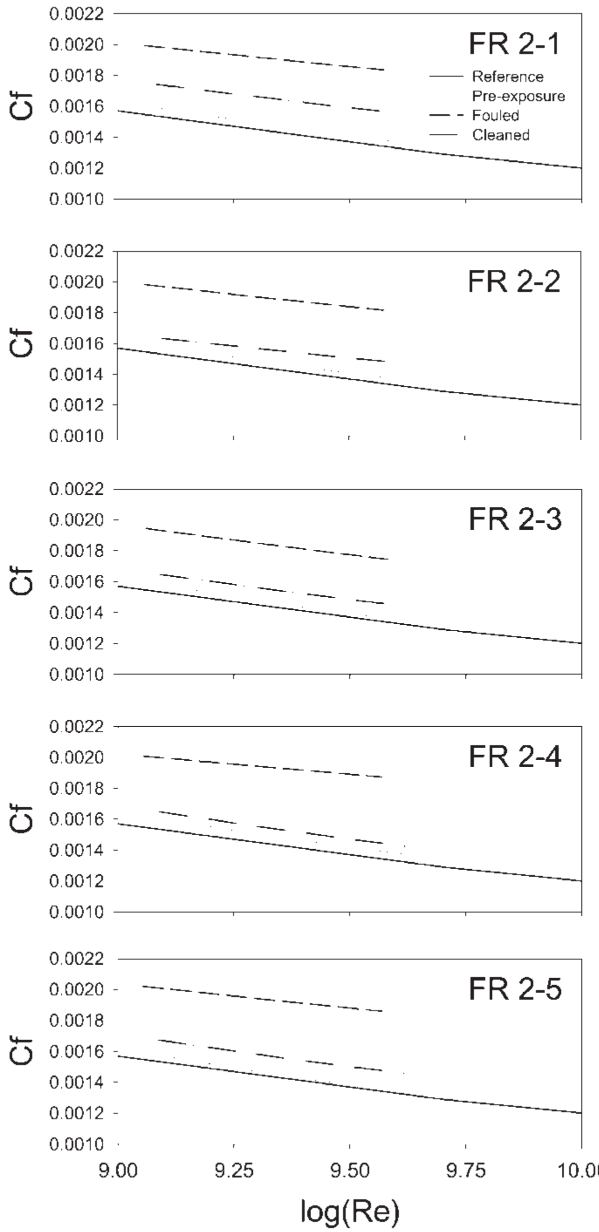

FIGURE 4 Fouling-release Treatment 2. Frictional resistance coefficients (C_f, see Materials and Methods section) calculated for five replicate disks at various values of the flat plate Reynolds Number, log(Re). Reference = smooth surface; pre-exposure = painted disk before exposure; fouled = painted disk fouled by biofilms; cleaned = fouled disk after cleaning with squeegee.

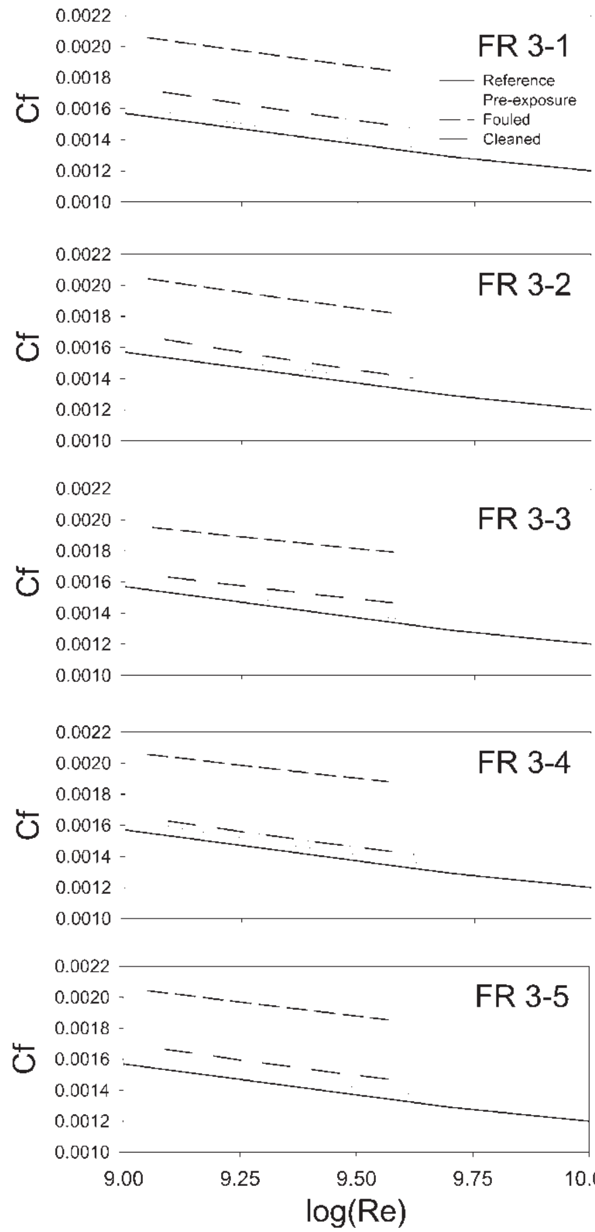

FIGURE 5 Fouling-release Treatment 3. Frictional resistance coefficients (C_f, see Materials and Methods section) calculated for five replicate disks at various values of the flat plate Reynolds Number, log(Re). Reference = smooth surface; pre-exposure = painted disk before exposure; fouled = painted disk fouled by biofilms; cleaned = fouled disk after cleaning with squeegee.

disks routinely suffers some damage during exposure, expressed as small nicks or chips in the coating. These roughness elements are rare, widely scattered, and difficult to measure, yet are likely to have a significant effect on drag (Schultz, 2004). The drag penalty on the cleaned disks probably reflects, to a great extent, the effects of such damage. For the coatings tested, the drag penalty for the fouled disks ranged from 3.3 to 5.8 times greater than the drag penalty on the cleaned disks, suggesting that accumulation of biofilms, as opposed to changes in the roughness of the coating itself, generated a significant proportion of the drag experienced when fouled.

The mechanical and physical properties of biofilms are likely to play a role in determining the magnitude of the drag penalty they generate (Towler *et al.*, 2003). Schultz and Swain (1999; 2000) found that the thickness and community structure of the attached biofilm affected drag on fouled flat plates. To the extent that the biological entities producing the biofilm also determine the mechanical and physical properties of that film, it is proposed that the effects

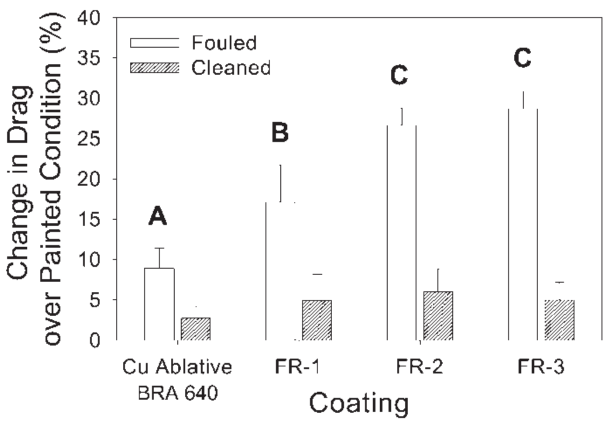

FIGURE 6 Change in frictional drag (as a percentage) over the painted, unexposed condition, for fouled and cleaned disks. Change in drag was calculated at log(Re) = 9.2, approximating a 100 m long flat plate traveling at 42.6 km h^{-1} (23 knots). Treatments with the same letter are not significantly different (Tukey's Studentized Range Test, $\alpha = 0.05$).

observed in the present study were due to differences in the properties of the biofilms accumulating on the various coatings, or to their adhesion to those coatings, arising from the properties of the coatings themselves.

Physical and biological characteristics of biofilms are affected by the substratum with which they are associated. Adhesion or attachment of biofilm-forming bacteria, and the morphology of the attached cells and films, is influenced by the surface energy or wettability of the substratum (for example, Dexter *et al*., 1975; Dexter, 1978; Pringle & Fletcher, 1983; Cunliffe *et al*., 1999; Ista *et al*., 1999; Dalton *et al*., 2000). In addition, the properties of the biofilm matrix can vary significantly in space and time (for example, Michael & Smith, 1995; for reviews see Costerton *et al*., 1995; Allison, 2003), depending in part on aspects of the surrounding environment including the concentration of nutrients and toxic substances (Costerton *et al*., 1995; Allison, 2003). The diversity and abundance of diatoms participating in biofilm formation on painted surfaces is affected by the type of paint. Toxic antifouling paints typically support a lower abundance and diversity of diatoms than non-toxic surfaces or non-toxic paint formulations (Robinson *et al*., 1985; Callow, 1986; Callow *et al*., 1986; French & Evans, 1986; Pyne *et al*., 1986). The ultimate causes for the differences in drag observed in the present study are unclear, but could be associated with differences in biofilms caused by surface energy or other surface properties among the test coatings, or to biocidal activity (particularly due to the copper oxide present in the ablative antifouling paint).

The friction disk machine (FDM) may serve as a valuable tool in coating development. The device can quantify differences among types of coatings, but is also sensitive enough to reveal differences due to designed variations in the formulation of the same basic coating, in their ability to mitigate the effects of drag-inducing biofilms. Although the aim of this study was to compare the performance of a selection of experimental coatings, and not to identify the particular surface physical or chemical properties that caused the coatings' effects on drag, such experiments could be carried out using the FDM. Currently there is no standard method to evaluate the influence of coating formulation on the drag penalty due to fouling biofilms. The disk drag test, employing the FDM, could form the basis for a convenient standard method for such investigations.

Acknowledgments

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