Ocean Engineering 159 (2018) 481–495

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

An experimental investigation into the effect of Cu_2O particle size on antifouling roughness and hydrodynamic characteristics by using a turbulent flow channel

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ARTICLE INFO

Keywords:
Copper oxide
Antifouling
Roughness characteristic
Frictional drag
Pressure drop measurement
Roughness function

ABSTRACT

Copper and copper compounds are commonly used as biocides against biofouling on surfaces exposed to seawater. Copper oxide, one of the most commonly used forms of copper biocide, can provide an efficient mechanism for fouling-free surfaces, resulting in substantial fuel savings and reduction of Greenhouse Gases (GHG) emissions. However, copper oxide is commercially formulated with different particle sizes, which can consequently lead to surfaces with different roughness conditions. The roughness effect of various sizes of copper oxide particles on the drag performance of antifouling coatings, and hence on the ship hull drag, has not been systematically studied in the past. Therefore, to investigate the effect of particle sizes on antifouling roughness and hydrodynamic characteristics, a number of different sized cuprous oxide pigments (with median size ranging from 2 μm to 250 μm) were applied on Newcastle University's (UNEW) standard acrylic flat test panels. Roughness characteristics were analysed by using an optical surface profilometer. Moreover, the microstructure observations of all test specimens were carried out using Scanning Electron Microscopy (SEM). Subsequently, a laboratory experiment of streamwise pressure drop measurements was conducted on all coated plates and compared to uncoated acrylic control panels. The Reynolds number for the experiment, based on bulk mean velocity and channel height, ranged from 3×10^4 to 1.6×10^5. Analysis indicated that for the panels coated with particle sizes $\geq 12\mu m$, the roughness characteristics and frictional drag increased as particle size increased. Interestingly, due to particle agglomeration and surface finish condition, those panels coated with particle sizes $< 12\mu m$ were found not to follow this trend and had higher roughness and drag characteristics than expected.

1. Introduction

At present, 95% of global bulk trade involves transport by sea with significant fuel consumption and corresponding exhaust emissions. According to the reports from the Third International Maritime Organization (IMO) GHG Study (Smith et al., 2014) over the period of 2007–2012 international shipping was estimated to have produced an average of 846 million tonnes of CO_2, which is equivalent to 2.7% of global CO_2 emissions. Smith et al. (2014) estimated that the annual global CO_2 emissions of 2012 were dominated by three ship types: oil tankers (124 million tonnes), bulk carriers (166 million tonnes) and container ships (205 million tonnes).

Marine fouling can increase ship hull surface roughness and result in ship efficiency loss. Biofilm (slime) is the primary stage of biofouling and can be formed within hours of a ship or other marine structures being immersed in seawater (Candries et al., 2003a). Biofilm is believed to cause frictional drag increase of up to 10% on full-scale ships (Watanabe et al., 1969). Controlling biofouling by applying antifouling (AF) paints can reduce the frictional drag and subsequently the fuel consumption as well as the GHG emissions. In a recent investigation on the effect of biofilms on ship hull resistance Yeginbayeva (2017) presented perhaps the most comprehensive and systematic study exploring the effect of slime on Foul-Release (FR) type coating performance by using naturally and dynamically grown biofilms in the sea environment, as well as artificially cultivated slime in a laboratory environment. This study also recommended a procedure to estimate the effect of biofilm on ship hull resistance based on Granville's procedure (Granville, 1987) by using the experimentally determined database for roughness functions of surfaces

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https://doi.org/10.1016/j.oceaneng.2018.01.042
Received 31 May 2017; Received in revised form 13 December 2017; Accepted 8 January 2018
Available online 20 January 2018
0029-8018/

Nomenclature

h, b	Inner dimension size of the channel height and beam
B	Smooth wall log-law intercept = 5.0
f	Fanning Friction Factor
C_f	Skin friction coefficient
D	Hydraulic Diameter
D_{10}	Particle diameter at 10% in the cumulative distribution
D_{50}	Particle diameter at 50% in the cumulative distribution
D_{90}	Particle diameter at 90% in the cumulative distribution
D_Z	The number of zero crossing with the mean line
g	Gravitational acceleration
H	Channel height
k	Roughness length scale
k^+	Roughness Reynolds number
ΔP	Pressure drop values
Re_D	Reynolds number based on duct hydraulic diameter
R_a	Arithmetic average height
R_q	Root Mean Square (RMS) Roughness height
R_t	Peak to trough roughness height
R_{sk}	Skewness
R_{ku}	Kurtosis
S_m	Defined as the mean spacing between profile peaks at the mean line, measured over the assessment length
$\overline{U}$	Bulk mean velocity
ΔU^+	Roughness Function
u_τ	Friction velocity
Δ_a	Mean slope of the profile
Δx	Streamwise pressure dropping distance
λ_a	Average wavelength
κ	Von Karman constant = 0.41
ν	Kinematic Viscosity
ρ	Density
τ_w	Wall shear stress

Superscript

$+$	Inner variable (normalized with U_τ or U_τ/ν)

Subscript

max	Maximum value
min	Minimum value
R	Rough surface
S	Smooth surface

with biofilms.

Copper and copper compounds have been used since the 16th century as effective antifouling agents. As an AF biocide, copper is known to protect marine immersed surfaces from tube worms, barnacles and most types of algal fouling. For those ship hull surfaces protected with inorganic copper compounds (such as Cu_2O, CuO, Cu_2S, and CuS), copper is released into the water in the form of copper ions Cu^{2+} or Cu^+. Under natural conditions, Cu^+ ions will be oxidised immediately into Cu^{2+} ions, their main biocidal form, which is more stable (Zhao and Wang, 2015).

As AF coatings are commonly used for preventing fouling settlement on ships' hulls, much attention has been paid to evaluating and estimating their antifouling performance and drag penalties, either using experimental models or from results of full-scale ships coated with AF coatings. Research interests have investigated the effects of copper-based AF coatings on surface roughness and drag penalties. Haslbeck and Bohlander (1992) and Holm et al. (2004) performed drag measurements on copper-component ablative AF coatings by using rotating disk apparatus, but without surface roughness evaluations at each experimental stage and fouling condition. Especially for an ablative coating matrix, it would be expected that the surface roughness changes while it is reacting with seawater, and therefore the roughness needs to be observed during the tests. Candries et al. (2003b) used rotating disk drag tests to study Foul-Release (FR) and Self Polishing Co-polymer (copper SPC) AF coatings. Two cylinders were coated with an FR scheme and a copper SPC scheme respectively, by spray application; one other cylinder was coated with an FR scheme by roller application. It was noted that the finished surfaces were expected to be rougher when the coating was applied by a roller in comparison to spray application. It was concluded that roughness comparisons under the same coating application methods are required for more accurate roughness estimation.

Towing tank measurements were carried out on flat plates allowing for the comparison of the frictional drag of Tin-free AF with that from FR coatings (Candries, 2001; Candries et al., 2003a; Schultz, 2004). It was found that SPC copper had the highest roughness amplitudes and frictional force, followed by the ablative copper scheme, whilst the FR scheme exhibited the lowest roughness amplitude and frictional force. The results are in agreement with the work of Candries et al. (2003b), who found the roughness amplitudes and frictional resistance of SPC copper to be higher than that of the FR scheme under the same application procedure. Also, the SPC copper scheme was found to have a higher frictional resistance than the FR scheme according to water tunnel tests carried out by Candries and Atlar (2005).

For any processed surface, understanding the impact of natural irregular particles on coating microstructure and surface roughness is essential. One of the main issues stems from the fact that it is harder to evaluate a three-dimensional irregular shaped particle, for example a sand grain or a pigment, with a unique number (Rawle, 2002). As a result, a body of research focuses on the interaction of surface roughness and particle size due to coating properties, addressing questions such as how particle size can affect viscosity, dispersion stability and surface roughness. Heslin et al. (1974) studied the surface roughness effect of different sized glass-sphere particles. Particle sizes of 10–40 and 40 to 80 μm were tested, and it was established that roughness increases with particle size. However, the limitation of the study is that only artificial regular shaped particles were tested instead of irregularly shaped particles. Kong et al. (2007) carried out studies of average powder effect on surface roughness and powder deposition efficiency. Five groups of different sized Inconel 625 Nickel alloy, ranging from 37 μm to 158 μm, were tested. The study found that the highest powder deposition efficiency did not result from the largest or the smallest particle size powder. Both large and very small particles were associated with high roughness with evident waviness. However, for minuscule particles, only coagulation within the nozzle was discussed by Kong et al. (2007). A discussion from Rawle (2002) indicated that the phenomena of agglomeration and aggregation could occur for very small particles which may cause suspension during the particle powder application. Further research focusing on particles from different materials of the same size ranges is lacking.

Moreover, the interaction between surface roughness and particle size may also be affected by other factors. Irzaman et al. (2011) investigated surface roughness and grain size under annealing temperature effects. They found that with temperature increasing, the RMS roughness and grain size decreased, which showed a strong correlation with annealing temperature. Xin et al. (2010) studied thickness dependence of particle size and surface roughness. Furthermore, there is evidence that thickness increases with grain size, which causes higher surface roughness (Melo et al., 2004; Xin et al., 2010). An investigation of surface roughness with Nano-crystalline Aluminium was conducted by (Perron et al., 2008) using mean grain sizes of 5, 10, 15 and 20 nm. They