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An experimental study on the effect of Cu$_2$O particle size on antifouling roughness characteristics and their subsequent effect on frictional drag by using a turbulent flow channel

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Abstract

As typical biocides in marine antifouling (AF), copper and copper compounds are used to prevent the biofouling organisms that naturally grow on artificial surfaces exposed to seawater. Copper oxide, one of the most commonly used copper-based compounds, can provide an efficient mechanism for keeping surfaces free of fouling, and subsequently reducing fuel consumption and emissions of Greenhouse Gases (GHG). Commercially, before being formulated into AF paint, copper oxide is manufactured with different particle sizes, but the roughness effect of the various sizes of copper oxide particles on the drag performance of AF, and hence on the ship hull drag, has not been systematically studied in the past. Hence, in order 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 2µm to 250µm, were applied on Newcastle University’s (UNEW) standard acrylic flat test panels, 642×282×30 mm (L×W×H). Their surface roughness characteristics were analysed by using an optical surface profilometer. The macrostructure and microstructure observations of the coatings were achieved using topography mapping and Scanning Electron Microscopy (SEM). Concurrently, laboratory experimental streamwise pressure drop measurements were conducted within the Reynolds number (based on bulk mean velocity and channel height) range from $3 \times 10^4$ to $1.6 \times 10^5$. The frictional drag penalties were estimated from the coated plates compared to the uncoated acrylic control panels. Analyses indicated that, compared to the uncoated cast acrylic smooth surface, the specimens with particle sizes 12µm and 17µm kept an average low drag increase, between 17% and 26%. Specimens with particle size 250µm resulted in the highest drag penalty increase of about 160%. Interestingly, due to particle agglomeration and surface finish conditions, those panels coated with particle sizes < 12µm were found to have higher roughness and drag characteristics than expected.

1. Introduction

Copper and copper compounds have been used as effective antifouling (AF) agents for centuries. During the Age of Sail (1571-1862), it was known that copper sheathing could provide an efficient mechanism of protecting the under-water hull of a ship or boat from continuously being attacked by shipworm and other fouling organisms. Ship hull surfaces
coated with copper compounds are protected by copper being released into the water gradually in the form of copper ions, i.e. \( \text{Cu}^{2+} \) or \( \text{Cu}^+ \). Under natural conditions, \( \text{Cu}^+ \) ions will be oxidised immediately into \( \text{Cu}^{2+} \) ions, their main biocidal form, which is more stable [1].

For in-service ship performance, keeping the hull surface free of fouling free is vital due to the drag penalties caused by micro-fouling conditions, which can range from 5% to 25% [2] [3] [4]. Friction drag can account for as much as 90% of total drag even without fouling occurring [5]. As copper-based AF are commonly used on ships’ hulls, many research interests have focused on surface roughness and drag penalties, either from laboratory-scale tests or from the results of full-scale ships coated with AF coatings.

Haslbeck and Bohlander [6] and Holm, Schultz [4] did exposure tests and drag measurements of rotating disks that were coated with copper-component ablative AF coatings. They found that the frictional resistance coefficient increased due to the development of micro-biofouling. However, without surface roughness measurements it was not possible to evaluate drag changes based on the surface roughness. The ablative coating matrix was changing by reaction with the seawater at the same time as fouling structure was developing. Rotating drum experiments were carried by Candries, Atlar [7], comparing the drag characteristics of two AF technologies, Foul-Release (FR) and copper-based acrylic copolymer (SPC copper). Frictional drag results showed that, compared with FR surfaces, the SPC copper could result in a higher frictional drag coefficient. Towing tank measurements were carried out on flat plates to compare the frictional drag of Tin-free AF with that from FR coatings [8-10]. 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, Atlar [7], who found that the roughness amplitudes and frictional resistance of SPC copper was higher than that of the FR scheme, when both were applied with 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 [11]. A 22 month full-scale trial with a ship hull covered with ablative copper oxide AF was recorded [6]. Comparing before and after biofilm removal, there was a significant power difference, with only slightly changes of roughness characteristics. Even though the impact of biofilm should be taken into consideration, the initial surface condition and power requirements must also be studied.

For any coated surface, understanding the impact of natural irregular particles on microstructure and surface roughness are essential. One of the challenges is to evaluate a three-dimensional irregular shaped particle, for example a sand grain or a pigment, with a unique number [12]. 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, Heaney [13] studied the surface roughness effect of different sized glass-sphere particles. They found roughness increases with particle size. Instead of irregularly shaped particles, only the artificial regularly shaped particles were tested during the work. Kong, Carroll [14] carried out studies of average powder effect on surface roughness and powder deposition efficiency with different sized Nickel alloys. They found that the highest powder
deposition efficiency did not result from either the largest or the smallest particle size powder. According to the discussion from Rawle [12] and Kong, Carroll [14], the phenomena of agglomeration and aggregation can occur for those minuscule particles, and this results in higher surface roughness. However, further research focusing on micro-scale particles from different materials is lacking.

Moreover, the interaction between surface roughness and particle size may also be affected by other factors. From the investigation of Irzaman, Darmasetiawan [15], a strong correlation indicated that the surface roughness and grain size would be decreased while increasing the annealing temperature. A few studies (Melo, Vaz [16]; Xin, Xiao-Hui [17] pointed out that the coated layer thickness increases with grain size and this can lead to higher surface roughness. The surface roughness changes from elastic and plastic deformations were evaluated by [18]. The test demonstrated that roughness insignificantly increased during the elastic deformation but that it changed rapidly within the plastic domain. This research studied temperature, layer thickness and deformation aspects of nanometre-scale particles, but the results for larger scale grain sizes were not very clear.

According to the literature research, there is a gap in the existing literature on AF coatings performance using different sizes of cuprous oxide particles. In order to make a contribution in the above field, the present paper is to investigate surface roughness effects of different sizes of cuprous oxide particles on the drag performance of antifouling coatings by using a pressure drop method. To have a better insight of the coatings, the microstructures were represented with SEM images and the macrostructures evaluated with topography mappings. The statistical roughness characteristics of the UNEW’s test panels were analysed using an optical surface profilometer. The frictional resistance coefficient of the test surfaces were measured using a turbulent flow channel. This paper discusses the results in relation to the coating microstructure and macrostructure, using the roughness and drag characteristics of the UNEW’s flat test panels.

2. Experimental Set-up

2.1. Powder Preparation and Application

For initially investigating the effects of various sized particles and surface roughness characteristics, eight sizes of cuprous oxide powder were manufactured by American Chemet Corporation. As shown in Table 1, the size of Cu$_2$O powder can be described with $D$ values such as $D_{10}$ (10%), $D_{50}$ (50%) and $D_{90}$ (90%) which respectively stands for 10%, 50% and 90% in the cumulative distribution. The weight content (%) of each type of Cu$_2$O powder has been included as well. In this paper, each size of Cu$_2$O powder is labelled with their rounded up value of $D_{50}$, which also represents the median diameter of each group.

Regarding the coating compositions, these were made with 75% (by weight) of cuprous oxide particles and 25% of VC17M Extra-Part B, and applied on Newcastle University’s (UNEW) standard acrylic flat testing panels by air-assisted spray application. The UNEW standard testing panel, as shown in Figure 1, has dimensions of 642×282×30mm (L×W×H). In the centre area of the test panel, a prominent area with 598×218mm (L×W) needs to be coated. The
VC17M Extra-Part B uses a volatile solvent as a carrier, leaving a majority of cuprous oxide particles in the coating matrix dry film. As the dry coating contains > 90% cuprous oxide, it can be considered a hypothetical surface of pure cuprous oxide [19]. The thickness measurements indicated that the finished dry film, on average, varied between 20~150µm. Moreover, the strength and insolubility of the matrix enabled the performance of the coating to be tested in the Flow Channel.

It should be noted that these coatings were purely experimental, and not at all similar to commercially available antifoulings. Commercial antifoulings generally have a cuprous oxide content of < 50% (dry film weight), and are applied by airless spray at film thicknesses well in excess of 100 microns.

| Table 1: Statistical description of Cu₂O powder |
| :------------ | :------------ | :------------ |
| Powder | D₁₀ (µm) | D₅₀ (µm) | D₉₀ (µm) |
| C₂ | 0.7 | 1.4 | 2.5 |
| C₇ | 4 | 7 | 12 |
| C₁₂ | 5 | 12 | 23 |
| C₁₇ | 10 | 17 | 25 |
| C₂₅ | 11 | 25 | 57 |
| C₆₀ | 32 | 61 | 89 |
| C₁₀₀ | 40 | 97 | 170 |
| C₂₅₀ | 190 | 246 | 366 |

2.2. Roughness Measurement

The surface roughness of the test surfaces was measured using Uniscan’s Optical Surface Profiling (OSP) 100A system, which is a non-contact high accuracy topography mapping instrument. As shown in Figure 2, the OSP100A system consists of a precision x-y-z scanner, an operation bench with three adjusting legs, a granite bed, an optical probe, control electronics and computer control software. The laser probe was adjusted on the two-axis traverse with
maximum positioning range of 100mm × 90mm (x × y). The scanning speed can be adjusted from 1mms⁻¹ to 25mms⁻¹. For the present investigation, the scanning area consisted of 90mm × 60mm (x × y), including 120 linear profiles that were measured at a scanning speed of 25mms⁻¹. The statistical analysis of surface roughness was calculated with a 2.5mm cut-off length, which is a commonly used value [20]. The roughness statistics were demonstrated by six roughness amplitude parameters: arithmetic mean height (Ra), root-mean-square deviation (Rq), total height (Rt), skewness (Rsk), kurtosis (Rku) and ten-point roughness of the roughness profile (Rz). The formulae for the six roughness amplitude parameters are as follows:

\[
Ra = \frac{1}{n} \sum_{i=1}^{n} |y_i| \\
Rq = \sqrt{\frac{1}{n} \sum_{i=1}^{n} |y_i^2|} \\
Rt = \max_{i} y_i - \min_{i} y_i \\
Rz = \frac{1}{5} \sum_{i=1}^{5} (\max_{i} y_i - \min_{i} y_i) \\
Rsk = \frac{1}{nRq^3} \sum_{i=1}^{n} y_i^3 \\
Rku = \frac{1}{nRq^4} \sum_{i=1}^{n} y_i^4
\]

**Figure 2: Portable laser profilometer schematic diagram**
where $y_i$ is the vertical distance from the mean line to its profile and $n$ is the number of points on each profile.

2.3. Turbulent Flow Channel

The experiment of pressure drop measurements was performed in the turbulent flow channel at the School of Marine Science and Technology, Newcastle University, United Kingdom, as shown in Figure 3. The test section of the channel is 10 mm in height (H), 180 mm in width (W), and 2.7 m in length (L). [21] postulated the minimum aspect ratio 7:1 to ensure two-dimensional flow in the turbulent channel. [22], [23] both have approved Dean’s conclusion of an aspect ratio (W/H) of 18:1 to be more than sufficient to provide two-dimensional flow along the centerline of the channel.

6000 L of water can be held by the reservoir tank, and the temperature of the water controlled constantly at 20±0.25 °C via a cooling coil fitted in the discharge tank linked to a refrigeration unit. The flow is produced by a 15kW centrifugal pump that can provide flow rates up to 300L/s, computer controlled by separate variable frequency drive units. The pumps operate in parallel and generate a bulk mean velocity of 1.62–8.30 $m s^{-1}$ in the test section. The resulting Reynolds number based on the channel height and bulk mean velocity ($R_{em}$) ranges from $3\times10^4$ to $1.6\times10^5$.

A stainless honeycomb flow straightener with 5 mm diameter cells, and 100 mm in length is fitted in the settling chamber upstream of the test section. The flow is tripped at the entrance through a two-dimensional nozzle with contraction ratio of 34.7:1. According to [24] and [25], for obtaining a fully-developed turbulent channel at Reynolds numbers >$3\times10^3$, a slot for fitting UNEW’s standard test panel (L×W=598mm×218mm) is opened at ~192H downstream to the channel inlet. This allows two identical test panels to be placed at the top and bottom of the pressured drop test section to form the top and bottom boundary of the test section.

Along one of the side walls of the test section there are nine pressure taps located at 164H–262H downstream of the trip at the inlet to the channel. These are 0.75 mm holes located along the centerline of the side wall of the test section. Two XMD Process Plant DP cell differential pressure transmitters are installed for measuring the pressure differences. Their measuring ranges are up to 75 and 500 mbar respectively with the accuracy of ±0.1% of full scale. A side LDA glass window (with a cross-section of 10×150mm) is installed between pressure taps 7 and 8 to allow optical access to the channel.
For the present investigation, four pressure taps from No.5 (x = 209H) to No.8 (x = 249H) were used for measuring the pressure difference from the test surfaces. Seven bulk velocities of 1.62 ms\(^{-1}\), 2.87 ms\(^{-1}\), 4.1 ms\(^{-1}\), 5.17 ms\(^{-1}\), 6.29 ms\(^{-1}\), 7.45 ms\(^{-1}\) and 8.30 ms\(^{-1}\) were applied with five pressure dropping distances of 0.075m, 0.150m, 0.250, 0.325m and 0.400m. The pressure drop data was collected at a sample rate of 10Hz for a sampling period of 100s until 10,000 data were obtained at each pressure dropping distance per each bulk velocity.

3. Uncertainty Analysis

The estimation of the overall uncertainty in the present investigation was made by using [26] method. Each pair of identical test panels were repeated five times. The 95% precision confidence limits for a given quantity were obtained by multiplying its standard error by the two-tailed t value (t=2.776) for four degrees of freedom provided by Coleman and Steele [27]. The resulting precision and bias uncertainties in the skin-friction coefficient, \(C_f\), ranged from ±3.2% to ±9.2% at the lowest Reynolds number for each test, to ±0.8% to ±1.5% at the highest Reynolds number for each test.

4. Results and Discussions

4.1 Application condition

All cuprous oxide specimens were applied on the UNEW standard test panels by air-assisted spray, and their overall coated surface conditions are presented in Figure 4. Figure 4 (a) shows the surface coated with C2 has spots and solid clumps remaining. Compared with C2, specimens of C7, C12, C17, C25 and C60 formulated smoother and uniform surfaces (Figure 4 (b) to (f)), and the differences between these surfaces can barely be recognized from the images. C100 and C250 have prominent rough surfaces.
To evaluate the surfaces objectively, topography mapping can be used to show the surface macro-structure conditions. As shown in Figure 5 (a), there are quite a number of protrusions...
unevenly distributed on the surfaces coated with specimen C2. By contrast, there are fewer protrusions and lower surface profiles from specimen C7 (Figure 5 (b)). Specimens C12 and C17 (Figure 5 (c) and (d)) gave smooth surfaces with a very low waviness profile. As specimen size increases, Figure 5 (e) to (h), the surfaces get rougher until the surface of C250 has a “thistles and thorns” profile.

Subsequent investigations indicated that there was particle coagulation of specimens C2 and C7, especially for the smallest specimen C2, which tended to block the spray nozzle and jam the spray gun chamber. Based on the procedure of air-assisted spray, particles can be delivered only under sufficient air pressure, and for better spray quality particles need to be constantly delivered with the air pressure. However the very minuscule particles, when mixed with larger coagulated particles, were pushed out inconsistently, and this resulted in pulsed spraying, with uneven surface textures. As a consequence, additional surface roughness was built up.

(a). Surface topography of specimen C2  
(b). Surface topography of specimen C7  
(c). Surface topography of specimen C12  
(d). Surface topography of specimen C17  
(e). Surface topography of specimen C25  
(f). Surface topography of specimen C60
4.2. SEM observations

For a systematic study of the impact on cuprous oxide surfaces of the various particle sizes, SEM evaluations of coating micro-structure can effectively enhance the roughness analysis. The micro-image of all test specimen particles (i.e. C2-C250) are shown in Figure 6, along with their magnification ratios i.e. 6500×, 1500×, 1000×, 650×, 150× and 100×. On average, particles of C2 have the smallest size and they are more likely tending to keep a “huddling” status (Figure 6 (a)) instead of dispersing individually. As the particle size increases, C7 to C250, individual particles all get larger, with irregular shapes. Whereas C7 (Figure 6 (b)) has a flake shape, C250 (Figure 6 (h)) has a more rounded shape.
The cross-section of these specimens and their magnification ratios (i.e. 1500×, 800×, 650×, 350× and 150×) are shown in Figure 7. As seen in Figure 7 (a), there is an apparent “coral” shape coating structure on the surface with specimen C2. This “coral” shape structure has wider interspaces between the agglomerated particles and results in a rougher surface profile. Figure 7 (b) shows the cross-section of specimen C7 with higher powder packing density and individual particles adequately attached to each other, with less interspaces remaining.
Compared with the surface condition of specimen C2, specimen C7 has a smoother surface profile. For those larger size particles (i.e. C12 to C250), as their particle size increases (Figure 7 (c), (d), (e), (f), (g) and (h)) contact between particles changes from full contact into partial contact. As a consequence, the surface waviness gets rougher due to development of wider and deeper gaps.
4.3. Roughness Measurements

Surface roughness statistics are presented in Table 2. To form a closed channel, two identical coated panels are required to be installed on the top and bottom of the test section slots. Therefore, to distinguish the roughness statistics from each panel, the top and bottom panels are marked as “A” and “B” respectively. The analysis of the roughness parameters for all tested particles shows that, apart from specimens C2 and C7, the amplitude parameters ($R_a$, $R_q$, $R_T$ and $R_z$) are directly related to the particle size. For C12, C17, C25 and C60, roughness amplitude increases gradually with an increase in partial size. For particle size $D_{50}>60\mu$m (i.e. C100 and C250), the roughness parameters are dramatically increased. For specimens C2 and C7, even though these are the smallest sized particles, the roughness amplitudes are greater than most of the other tested specimens (i.e. C12, C17, C25 and C60). These results are corroborated by with their surface topography results (Figure 5).

Thus, by combining the macro and micro-structure observations, it can be seen that the overall surface roughness is affected by both microstructure roughness and macrostructure roughness, the latter of which dominates.

Table 2: Roughness Statistics (uncertainty represent the 95% confidence precision bounds for the measurements)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Surface</th>
<th>$R_a$ ($\mu$m)</th>
<th>$R_q$ ($\mu$m)</th>
<th>$R_T$ ($\mu$m)</th>
<th>$R_{sk}$</th>
<th>$R_{ku}$</th>
<th>$R_z$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>A</td>
<td>9.3±0.2</td>
<td>12.8±0.4</td>
<td>68.1±2.0</td>
<td>0.047±0.005</td>
<td>4.9±0.1</td>
<td>62.5±1.9</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5.3±0.1</td>
<td>7.3±0.2</td>
<td>39.4±1.3</td>
<td>0.046±0.009</td>
<td>5.1±0.2</td>
<td>35.6±1.2</td>
</tr>
<tr>
<td>C7</td>
<td>A</td>
<td>11.0±0.2</td>
<td>13.6±0.2</td>
<td>61.3±1.0</td>
<td>-0.017±0.002</td>
<td>3.0±0.1</td>
<td>57.5±1.0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>10.7±0.1</td>
<td>14.8±0.2</td>
<td>76.9±0.9</td>
<td>0.118±0.002</td>
<td>6.0±0.1</td>
<td>69.0±0.9</td>
</tr>
<tr>
<td>C12</td>
<td>A</td>
<td>2.4±0.0</td>
<td>3.0±0.0</td>
<td>17.7±0.2</td>
<td>0.022±0.007</td>
<td>3.7±0.1</td>
<td>14.7±0.2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.2±0.0</td>
<td>2.9±0.0</td>
<td>16.7±0.3</td>
<td>0.032±0.007</td>
<td>3.5±0.1</td>
<td>13.9±0.2</td>
</tr>
<tr>
<td>C17</td>
<td>A</td>
<td>2.8±0.0</td>
<td>3.5±0.0</td>
<td>20.0±0.2</td>
<td>0.031±0.006</td>
<td>3.5±0.1</td>
<td>16.7±0.2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4.9±0.1</td>
<td>6.4±0.2</td>
<td>34.1±0.9</td>
<td>0.072±0.005</td>
<td>3.9±0.1</td>
<td>30.2±0.9</td>
</tr>
<tr>
<td>C25</td>
<td>A</td>
<td>4.8±0.0</td>
<td>6.1±0.0</td>
<td>32.8±0.3</td>
<td>0.003±0.003</td>
<td>3.3±0.1</td>
<td>28.2±0.2</td>
</tr>
</tbody>
</table>
### 4.4. Frictional Drag

In this investigation, uncoated cast acrylic panels were used to represent smooth surfaces. The skin-friction coefficient, $C_f$, is typically expressed as:

$$C_f = \left(\frac{\tau_w}{0.5\rho U^2}\right) = 2\left(\frac{u_T}{U}\right)^2$$  \hspace{0.5cm} \text{Eq. 6}

The wall shear stress, $\tau_w$, was determined by streamwise pressure drop values, $dp$ at each pressure dropping distance, $dx$. It is calculated as follows:

$$\tau_w = -\frac{D}{2} \frac{dp}{dx}$$  \hspace{0.5cm} \text{Eq. 7}

$$u_T = \left(\frac{\tau_w}{\rho}\right)^{\frac{1}{2}}$$  \hspace{0.5cm} \text{Eq. 8}

where $D$ is the hydraulic diameter, $p$ is the static pressure value, $x$ is the streamwise pressure dropping distance, $\rho$ is the fluid density, $U$ is the bulk mean velocity, $u_T$ is the frictional velocity and water density $\rho$ is taken as 998 kg/m$^3$ (at the temperature 20°C). For non-circular flow channel, the hydraulic diameter, $D$ is commonly calculated as follows.

$$D = \frac{4hb}{2(h+b)} = \frac{2hb}{h+b}$$  \hspace{0.5cm} \text{Eq. 9}

where $h$ and $b$ are inner dimension size of the channel height and beam. The Reynolds number based on hydraulic diameter, $D$ and bulk mean velocity, $\bar{U}$ (or mean velocity) can be expressed as:

$$Re_D = \frac{D\bar{U}}{\nu}$$  \hspace{0.5cm} \text{Eq. 10}

$\nu$ is the kinematic viscosity of the fluid.

Shown for smooth surface comparison, an empirical power relation proposed by Dean [21] and Zanoun, Nagib [28] is given in Eq. 11 and Eq. 12 respectively:

$$C_f = 0.073Re^{-0.25}$$  \hspace{0.5cm} \text{Eq. 11}

where the Reynolds number range: $6 \times 10^3 < Re < 6 \times 10^5$.

$$C_f = 0.0743Re^{-0.25}$$  \hspace{0.5cm} \text{Eq. 12}

Skin friction coefficients from eight specimens as well as the smooth surfaces, measured via each pressure drop test, are plotted in Figure 8. The smooth surface results show agreement...
with the mean line of Dean [21] and Zanoun, Nagib [28] over the entire Reynolds number range. For some of the test specimens results, there are apparently inflectional behaviour happened in the transitional regime. Within the entire Reynolds number range, the inflectional behaviour onset from specimen C25 with friction coefficient slightly turn-up. The uptrend of $C_f$ are getting evidently of specimens C2, C60, C7 and C100, whereas C12 and C17 keep as similar trend as smooth surface. The inflectional behaviour indicated the roughness effects are a function of both Reynolds number and roughness characteristics (Nikuradse, 1933). At the meanwhile, results of very large specimen (C250) show mild inflectional behaviour and parallel to the horizontal axis with Reynolds number increases. This shows the roughness effects are independent of the Reynolds number at higher Reynolds number.

Table 3 shows further detailed evidence of the friction drag vs. cuprous oxide particle size, with the friction coefficient increase (%) for the test surfaces compared to the smooth surface. The experimental results indicate that the frictional coefficient of Cuprous Oxide_C2 to C250 increased from that of the smooth surface between approximately 14% to 156% in line with the increase in particle size. Among all eight tested specimens, the lowest drag was demonstrated by Cuprous Oxide_C12 (14%) and this was followed by Cuprous Oxide_C17 (25%). For the very small size particles, Cuprous Oxide_C2 has on average about a 52% increase in $C_f$, which is 4% less than Cuprous Oxide_C7. The highest average friction was 156% and this was obtained from Cuprous Oxide_C250. This is followed by 90% and 50% respectively for Cuprous Oxide_C100 and C60.

Based on the experiments presented here, it can be noted that the relative higher $C_f$ values of specimens C2 and C7 are directly affected by their surface macro finish quality.
Figure 8: Frictional coefficient results for the first pressure drop test

Table 3: Increase in overall $C_f$ for the test specimens compared to the cast acrylic surface

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average Increase in $C_f$ (%)</th>
<th>Range of Increase in $C_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuprous Oxide_C2</td>
<td>51.7</td>
<td>40.5–66.3</td>
</tr>
<tr>
<td>Cuprous Oxide_C7</td>
<td>55.6</td>
<td>41.9–73.5</td>
</tr>
<tr>
<td>Cuprous Oxide_C12</td>
<td>13.5</td>
<td>5.4–19.8</td>
</tr>
<tr>
<td>Cuprous Oxide_C17</td>
<td>24.9</td>
<td>17.0–31.5</td>
</tr>
<tr>
<td>Cuprous Oxide_C25</td>
<td>41.0</td>
<td>33.4–50.9</td>
</tr>
<tr>
<td>Cuprous Oxide_C60</td>
<td>50.3</td>
<td>38.7–68.7</td>
</tr>
<tr>
<td>Cuprous Oxide_C100</td>
<td>90.0</td>
<td>67.2–115.2</td>
</tr>
<tr>
<td>Cuprous Oxide_C250</td>
<td>155.9</td>
<td>127.9–181.6</td>
</tr>
</tbody>
</table>

5. Conclusions

For investigating surface roughness and drag penalties of flat surfaces coated with cuprous oxide particles, experimental roughness analyses and skin-friction measurements have been presented and discussed in this paper. SEM and an optical surface profilometer were employed for the roughness characteristics evaluation. The effects of roughness on the frictional drag characteristics of the test surfaces were evaluated using pressure drop measurements which were achieved from a turbulent flow channel. According to the test results, the following conclusions can be drawn:

i. Observations of microstructure show that the initial roughness of the cuprous oxide-based surfaces is dependent on the particle size. However, observations from the very small size particles (i.e. specimens C2 and C7) indicate that the quality of coating application can also affect the surface waviness profile.

ii. Macrostructure observations clearly showed a bad coating application for specimens C2 and C7, caused by the particle agglomeration that directly affects the surface roughness. As a consequence, the very small size specimens did not give the expected lowest roughness characteristics.

iii. The frictional drag penalties, analysed from pressure drop measurements, increase with the particles size increases. Compared to the uncoated cast acrylic smooth surface, the specimens C12 and C17 kept an average low drag increase, about 14% and 25% respectively. Specimens C250 resulted in an average with the highest drag penalty increase, of about 156%.

iv. Due to particle agglomeration and poor surface application, the very small particles (i.e. specimens C2 and C7) resulted in unexpectedly high drag increase, 52% and 56% on average respectively.

6. Nomenclature

$h, b$  Inner dimension size of the channel height and beam
$C_f$ 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.
$g$ Gravity
$H$ Channel height
$\Delta P$ Pressure Drop values
$Re_D$ Reynolds number based on duct hydraulic diameter
$R_a$ Arithmetic Average height
$R_q$ Root Mean Square Roughness height
$R_t$ Peak to trough roughness height
$R_{sk}$ Skewness
$R_{ku}$ Kurtosis
$R_p$ Ten-point roughness of the roughness profile
$\overline{U}$ Bulk mean velocity
$u_\tau$ Friction velocity
$\Delta x$ Streamwise Pressure Dropping Distance
$\nu$ Kinematic Viscosity
$\rho$ Density
$\tau_w$ Wall shear stress

7. References


