CFD analysis of the increase in ship resistance due to biofouling growth represented by roughness length scale

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Abstract. Fuel consumption is heavily influenced by ship resistance, which mostly consists of friction resistance. During her operation, a ship is susceptible to the attachment of biofouling to its hull. The arbitrary form of biofouling induces an increase in surface roughness, which is responsible for the increase in friction resistance. This research analyses the increase in skin friction resistance due to biofouling, that is represented by a few variations of roughness length scale, in various orders throughout the models. Two-dimensional models of flat plates are utilized to investigate this issue by means of computational fluid dynamics (CFD) analysis. This study uses models with 0.56 m length to be tested in five Reynolds numbers, to be compared to a similar experiment conducted by using wind tunnel. Other models include 30 m and 60 m length to be tested in two Reynolds numbers each. It is found that the increase in skin friction reaches 3.5 – 31.4% for 0.6 m, 68.1 – 206.9% for 30 m with extreme regular roughness and 117.3 – 129.3% for 30 m with extreme irregular roughness, and 59.5 – 179.6% for 60 m with extreme regular roughness and 123.5 – 128.9% for 60 m with extreme irregular roughness.

Keywords: biofouling, CFD, friction resistance, roughness length scale, surface roughness.

1. Introduction

The shipping industry has been the backbone of the world’s trade market, as it transports 80 – 90% goods from all around the world. While it is beneficial, it also threatens the environment. In 2012, IMO published a research that declared 2.2% of the world’s CO₂ emission was a by-product of the world’s shipping activities. It is not until April 2018, that IMO adopted the initial strategy on reducing greenhouse gases (GHGs) emission by targeting at least 50% reduction of the 2008 GHGs emission from shipping activities by 2050. It is important to predict the required ship fuel in order to minimize its use. An important component in estimating the use of ship fuel is the ship’s resistance. Ships with high resistance values require more fuel use.

Ship resistance is consisted of several components, with friction resistance \((R_F)\) as the biggest component, reaching up to 80-85% of the total resistance \((R_T)\) on low-speed ships and 50% of the total resistance on high-speed ships [1]. This resistance is caused by the friction that occurs between the hull of the ship and the fluid. Ship resistance can increase due to various factors, one of them being the increase in the hull’s surface roughness, which in most cases is caused by the attachment and growth of biofouling on the hull.

To analyse the effect of biofouling on the ship’s drag, it is important to model the biofouling correctly. However, in numerical simulations, biofouling is almost impossible to model due to the shapes, sizes and the spread of biofouling may vary across the field. Due to this reason, researchers had to model biofouling using other methods. As recommended by ITTC, researchers are encouraged to develop a formula or method, based on experimental data, to predict the effect of coatings and biofouling on ship resistance [2]. A research found that the increase in drag due to biofouling and its
distribution reached up to 80% due to the attachment of heavy calcareous fouling and 34% for small calcareous fouling [3]. Numerical simulations have also been conducted to validate these results by means of Computational Fluid Dynamics (CFD) [4]. Another method to investigate the increase in drag due to biofouling involved testing a flat plate in a wind tunnel [5]. In this current study, the effects of biofouling on the increase of friction resistance on a flat plate are analysed by observing the plate’s friction resistance coefficient (C_F) using the CFD method. The use of flat plate instead of ship is based on the assumption that the value C_F are similar for both models. Variations in this study include the biofouling’s roughness and the plate’s size. Each roughness variation has a different effect on the increase of C_F. This difference is expected to provide a realistic insight on the effect of biofouling’s roughness in real life situations.

2. Background
2.1. Ship resistance
Ship resistance is consisted of friction resistance (R_F) and residual resistance (R_R). A friction resistance is a force acting tangential to the hull as an accumulation of shear stress induced by the viscosity of the fluid. Meanwhile, one of the components of the residual resistance is induced by pressure: a normal force acting perpendicular to the hull, partly due to viscous pressure resistance (R_VP) and wave-making resistance (R_W). If a body is fully submerged in a fluid, the wave-making resistance equals to zero. This is because waves require an interaction between two fluids with different densities to be generated. Meanwhile, the viscosity of the fluid affects the amount of viscous pressure resistance experienced by the ship [6]. The components of the ship resistance can be expressed through (1)

\[ R_T = R_F + R_R + R_A \]  \hspace{1cm} (1)
\[ R_T = R_F + R_VP + R_W + R_A \]  \hspace{1cm} (2)

It is common to represent the ship’s total resistance in the form of non-dimensional coefficient (C_T) through (3), where \( \rho \) is the fluid’s density, \( S \) is the wetted surface area and \( V \) is the body’s velocity:

\[ C_T = \frac{R_T}{(0.5 \rho S V^2)} \]  \hspace{1cm} (3)

Using (3), each component of the ship’s resistance can be rewritten in a non-dimensional form:

\[ C_T = C_F + C_VP + C_W + C_A \]  \hspace{1cm} (4)

Appendages resistance are caused by underwater construction such as propeller, propeller shaft and bilge keels. In this study, the wave-making and appendages resistance are both equal to zero. So, the coefficient of the total resistance becomes:

\[ C_D = C_VP + C_F \]  \hspace{1cm} (5)
\[ C_D = (1 + k) C_F \]  \hspace{1cm} (6)

Where (1+k) is a form factor used in extrapolation process between a model and a ship. It represents the viscous pressure resistance because the pressure on a body is affected by its own form. Since the models used in this study is a flat plate, the value of form factor is equal to one.

2.2. Boundary layer on a flat plate
The boundary layer is a very thin flow region near the wall of an object where the viscosity and rotational forces cannot be ignored. It is defined as the distance from the wall of the object to a point where the velocity component moving parallel to the wall reaches 99% of the freestream velocity. For flat plates, the higher the freestream speed, the thinner the boundary layer becomes [7]. On flat plates, the boundary layer is divided based on its Reynolds Number (Re), namely the laminar boundary layer and the turbulent boundary layer. Between the laminar and turbulent boundary layers is a transition area, where the laminar flow begins to develop into a turbulent flow, which occurs at \( Re = 5 \times 10^5 \).
Dimensional analysis of a turbulent boundary layer as represented by Figure 1, are as follows:

1. The viscous sublayer is where the viscosity effect of the fluid dominates the flow. This area of fluid is close to the wall and experience direct contact with the surface, thus making the distance, represented by $y^+$, between them equal to zero. Hence, $(y^+ = 0)$. At that exact distance, the fluid is subjected to wall shear stress, rendering it static or in other words, travels with zero velocity $(u^+ = 0)$, so that:

$$u^+ = y^+$$  \((7)\)

2. In the log-law layer, the velocity profile varies in a logarithmic manner. Between the wall and the freestream, both the viscosity and the turbulent effects are equally influential. In this layer, the shear stress $(\tau)$ varies along the distance from the wall and is assumed to be constant and equal to the wall shear stress $(\tau_w)$. Where, $u^+$ and $y^+$ have a logarithmic relationship:

$$u^+ = \frac{1}{\kappa} \ln(y^+) + B = \frac{1}{\kappa} \ln(Ey^+)$$  \((8)\)

2.3. Surface roughness

Rough surface increases turbulence resulting in an increase in turbulent stress and wall shear stress. This causes a decrease of fluid velocity in the turbulent boundary layer. The effect of roughness on flow can be seen in the velocity profile [8] as illustrated by Figure 2. The rough surface results in a decrease in the velocity profile of the fluid in the log-law region, indicated by an increase in frictional resistance. This is caused by an increase in the momentum deficit due to roughness and is related directly to the increase in frictional drag on the surface [3]. The derivation of the velocity profile itself is also called $\Delta U^+$ or the roughness function. Hence, the log-law equation becomes:

$$U^+ = \frac{1}{\kappa} \ln(y^+) + B - \Delta U^+$$  \((9)\)

where $U^+$ = average of scaled viscous velocity, $\kappa$ = Von Kármán constant (0.41) and B = smooth-wall log-law intercept (5.0).
3. Methodology

3.1. Mathematical formulation
In this study, the turbulence is modeled using 2-equations, first order RANS Equation. To capture the roughness effect on the viscous sublayer area, the k - ω shear stress transport or k - ω SST turbulence model was used. The turbulence model is a combination of the k - ε turbulence model that models the freestream area, and the k - ω turbulence model, that models the near wall area [9]. In this research, the residual value is set to $10^{-5}$.

3.2. Geometry and boundary condition
There are various combinations of boundary conditions that can be applied to solve the case of viscous flow on flat plates with accurate results. However, some combinations require excessive computational effort. A numerical simulation was conducted to validate the frictional resistance experiment due to antifouling paint on flat plates [3]. The domains that were used can be seen in Figure 3 and Figure 4.

A study described the techniques needed to validate the William Froude’s towing tank experiment [10] using the RANS solver. The area of the edges of the plate only accounted to 0.5% of the total area, allowing the friction resistance of those area to be neglected and allowing the use of a computational 2-dimensional model (Figure 5). The boundary condition was designed as follows: the distance between the leading edge of the plate and the inlet, the distance between the trailing edge of the plate and the outlet, as well as the distance between the upper inlet and the plate reached 2 times the length of the plate (to later be referred to as L). This 2-dimensional model was able to reduce computational effort and time while providing accurate predictions of the drag experienced by the plate.

Recently, a CFD simulation was conducted to investigate the characteristics of drag on a flat plate due to surface roughness caused by biofouling [11]. The study used a similar model of boundary
condition as illustrated by Figure 5, with a slight difference: there were no distance between the leading edge of the plate and the trailing edge of the plate to the inlet and outlet of the boundary conditions, respectively as represented by Figure 6.

![Figure 6](image)

**Figure 6** Flat plate boundary condition in a recent CFD study to investigate the characteristics of drag due to surface roughness caused by biofouling.

3.3. **Meshing**

Frictional resistance is dominated by the effect of fluid viscosity in the viscous sublayer. The mesh should be small and dense enough around the viscous sublayer in order to capture the turbulence effect at play. By using $y^+$, a universal non-dimensional value of distance from the wall to the first grid element (mesh/cell) in a CFD simulation, the value of the first cell height can be obtained by using Flat Plate Boundary Layer equation (10). The appropriate value of $y^+$ is chosen according to which area of the boundary layer is under observation. For viscous sublayer, the value should lie between $1 \leq y^+ < 5$ according to the law of the wall as illustrated by Figure 1. In this study, the value of $y^+$ is equal to 1.

$$y^+ = 0.172 \cdot \left( \frac{\Delta y_P}{L} \right) \cdot Re^{0.9}$$  \hspace{1cm} (10)

Since the first cell height value is affected by the Reynolds Number, each simulation in this study had different values as listed in Table 1 and Table 2.

**Table 1** First layer height for the CFD validation of wind tunnel experiment.

| Length (m) | No. | Velocity (m s$^{-1}$) | Re ($\times 10^5$) | $\Delta y$ ($\times 10^5$) |
|------------|-----|----------------------|------------------|------------------|
| 0.56       | 1   | 3                    | 1.1              | 9.6              |
| 2          | 2   | 6                    | 2.2              | 5.2              |
| 3          | 3   | 9                    | 3.2              | 3.6              |
| 4          | 4   | 12                   | 4.3              | 2.8              |
| 5          | 5   | 15                   | 5.4              | 2.3              |

**Table 2** First layer height for the CFD validation and prediction of characteristics of drag due to surface roughness study.

| Length (m) | No. | Velocity (m s$^{-1}$) | Re ($\times 10^8$) | $\Delta y$ ($\times 10^6$) |
|------------|-----|----------------------|------------------|------------------|
| 30         | 1   | 9.775                | 2.79             | 3.8              |
|            | 2   | 12                   | 3.4              | 3.1              |
| Length (m) | No. | Velocity (m s$^{-1}$) | Re ($\times 10^8$) | $\Delta y$ ($\times 10^6$) |
| 60         | 1   | 9.775                | 5.6              | 3.9              |
After the first cell heights were determined, the mesh can be generated. In this study, the mesh elements that were formed are hexahedral and quads (Figure 7 - Figure 9). The height of the first cell was set with a growth rate of 1.2 times.

| 2 | 12 | 6.9 | 3.2 |

A good meshing configuration does not compromise the results of the numerical simulation. It is important to ensure the reliability of the mesh by conducting grid independence test. The test is carried out by comparing the numerical results obtained by different number of cell/mesh. The difference should not be significant. In general, the tolerance is set to 2%.

3.4. Surface roughness modeling
Surface roughness is modeled with a roughness length scale based on two parameters, namely the roughness height \(k_s\) and the roughness constant \(C_s\). In CFD, this approach can only be used when roughness is constant or remains along the surface of the model. Non-constant roughness can be modeled with user-defined functions.

In this study, simulations were conducted as follows: a validation of a flat plate experiment in a wind tunnel [5], a validation and prediction of the numerical analysis of drag characteristics due to surface roughness on flat plates [11]. In the prediction study, extreme roughness length scales were used to analyze the effect of surface roughness that is in the range of different roughness heights.

3.4.1. Validation of wind tunnel experiment
The roughness height used in the wind tunnel experiment was obtained by scaling the biofoulings that were attached to KM Mentari Pratama’s hull at PT PAL during her dry-dock intermediate survey. Biofoulings were found to be the densest around the ship’s stern and much lesser around the midship.
This was because biofouling at the bow had experienced contact with stronger waves than at the stern. Strong waves are capable to wash biofouling out of the ship’s hull. The biofouling were modeled by sandpapers in the experiment by using a scale factor of 1: 175 [5]. The main dimension of the plate as presented by Table 3, while the roughness length scales can be seen in Table 4.

**Table 3** Wind tunnel experiment flat plate size.

| No. | Principal Dimension |
|-----|---------------------|
| 1   | Length              | 0.56 m |
| 2   | Width               | 0.75 m |
| 3   | Thickness           | 0.04 m |

**Table 4** Roughness length scale of biofouling in the first validation study.

| Section | ks (mm) | ks (μm) | Sand-paper grit | Notated as |
|---------|---------|---------|-----------------|------------|
| Stern   | 0.264   | 264     | Medium          | P60        | Ks 3       |
| Midship | 0.111   | 111     | Very Smooth     | P150       | Ks 1       |
| Bow     | 0.163   | 163     | Smooth          | P100       | Ks 2       |

In the wind tunnel experiment, sandpapers are attached to a flat plate as visualized in Figure 10. As the notation increases, the roughness elements of the sandpaper are rougher and denser to each other. This indicates the increase in the sandpaper’s density as the notation increases. However, the sandpaper is generally represented by a “grit”, a measurement of the sandpaper’s roughness (not to be confused with the notations used in this study). It is inversely related to the actual roughness of the paper. The smaller the grit value, the rougher the sandpaper is.

Figure 10 Sand-paper grit for each type of roughness.

Ten variations of surface roughness were tested in this study: smooth, regular roughness and irregular roughness. The variations order that were used in the wind tunnel experiment is as seen in Figure 11.

Figure 11 Roughness variation in the first validation study.
The second validation study utilized the following range of roughness shown in Table 5. While the sequence of roughness variations followed the same pattern as demonstrated by Figure 11.

**Table 5 Roughness length scale of biofouling in the second validation study.**

| No. | \( k_s (\mu m) \) | Notated as |
|-----|-------------------|------------|
| 0   | 0                 | S          |
| 1   | 81.25             | Ks 1 (P)   |
| 2   | 325               | Ks 2 (Q)   |
| 3   | 568.75            | Ks 3 (R)   |

Then, a prediction referring to the second study is conducted by using extreme roughness length scales. In this prediction, the model and domain used refer to the model used in the second validation study as listed in Table 6. The models were selected by considering the numerical capacity of the computer device that was used for this study. Each model was tested at two speed variations, namely 19 knots (9.78 m/s) and 23.32 knots (12 m/s).

**Table 6 Model sizes used in the drag characteristics validation and prediction study.**

| No. | L (m) | B (m) |
|-----|-------|-------|
| 1   | 30    | 3     |
| 2   | 60    | 6     |

The extreme values for the prediction of the second study were chosen based on a towing tank experiment in 2007. In the towing tank experiment, it was assumed that the technical roughness value of biofouling could be represented by an equivalent roughness length scale using the roughness heights. The drag characteristics study due to biofouling utilized roughness length scales that represented biofouling in the form of light slime to heavy slime [3]. Meanwhile, the prediction study used extreme roughness length scales (Table 7) that represented biofouling in the form of heavy slime to heavy calcareous fouling. The variation sequence for the prediction study is illustrated by Figure 11.

**Table 7 Roughness length scale of biofouling for the prediction of the second study.**

| No. | Description of Condition            | Extreme \( k_s (\mu m) \) | Notated as |
|-----|-------------------------------------|---------------------------|------------|
| 1   | Heavy slime                         | 300                       | Ks 1       |
| 2   | Small calcareous fouling or weed    | 3000                      | Ks 2       |
| 3   | Medium to high calcareous fouling   | 5700                      | Ks 3       |

4. Results

4.1. Wind tunnel experiment validation

4.1.1. Smooth plate

The CFD results as listed in Table 8, are compared to the wind tunnel experiment results (WT) [5] and the approximation values by the ITTC formula. As demonstrated in Table 8, the computed skin friction coefficient differed up to 3.89% from the wind tunnel (WT) experiment results. The difference between the CFD simulation and the wind tunnel experiment might be caused by a few unknown variables. One of them being the wind tunnel’s unknown turbulence intensity. There were no data available regarding the turbulence intensity of the wind tunnel in which the flat plate experiment was carried out. However, the computed skin friction coefficient was in excellent agreement with the ITTC ‘57 frictional correlation line, only differing up to 1.71% from the correlation line. Therefore, this CFD simulation of the wind tunnel experiment for the smooth plate condition can be validated and be used in further investigation, namely the regular roughness simulations. The comparison between each approach is shown in Figure 12.
Table 8 Skin friction coefficient for smooth plate comparison between the wind tunnel results and CFD simulation.

| No. | V (m/s) | Re   | C_F (10^-3) | ∆C_F (%) | C_F (10^-3) | ∆C_F (%) |
|-----|---------|------|-------------|----------|-------------|----------|
|     |         |      | ITTC        | CFD      | WT          | CFD      |
| 1   | 3       | 1.1×10^5 | 8,1080     | 8,0926   | 0.19        | 7,790    | 8,0926   | 3.88     |
| 2   | 6       | 2.2×10^5 | 6,7133     | 6,6335   | 1.19        | 6,400    | 6,6335   | 3.00     |
| 3   | 9       | 3.2×10^5 | 6,1045     | 6,0002   | 1.71        | 5,810    | 6,0002   | 3.27     |
| 4   | 12      | 4.3×10^5 | 5,6809     | 5,6311   | 0.88        | 5,420    | 5,6311   | 3.89     |
| 5   | 15      | 5.4×10^5 | 5,3838     | 5,3289   | 1.02        | 5,140    | 5,3289   | 3.68     |

Figure 12 Comparison between skin friction coefficient for smooth plate the wind tunnel results and CFD simulation.

4.1.2. Regular roughness
In addition to the smooth flat plate drag analysis, CFD analysis of flat plate drag due to regular roughness was also carried out. The results can be seen in Table 9.

Table 9 Skin friction coefficient for smooth plate comparison between the wind tunnel results and CFD simulation.

| No | V (m/s) | Re   | C_F (10^-3) | ∆C_F (%) | C_F (10^-3) | ∆C_F (%) |
|----|---------|------|-------------|----------|-------------|----------|
|    |         |      | Smooth      | K1 | K2 | K3 | K1 (%) | K2 (%) | K3 (%) |
| 1  | 3       | 1.1×10^5 | 7.79        | 10.58    | 14.83       | 17.06    | 35.82   | 90.37   | 119.00 |
| 2  | 6       | 2.2×10^5 | 6.44        | 7.46     | 8.8         | 9.94     | 15.84   | 36.65   | 54.35  |
| 3  | 9       | 3.2×10^5 | 5.81        | 6.47     | 7.38        | 8.1      | 11.36   | 27.02   | 39.42  |
| 4  | 12      | 4.3×10^5 | 5.42        | 6.01     | 6.7         | 7.34     | 10.89   | 23.62   | 35.42  |
| 5  | 15      | 5.4×10^5 | 5.14        | 5.66     | 6.27        | 6.82     | 10.12   | 21.99   | 32.69  |

In the wind tunnel experiment [4], the ∆C_F decreased with the increase of velocity. On the other hand, the ∆C_F increased with the increase of velocity in the CFD analysis. This might be caused by the unknown value of the roughness constant (C_S) value in the wind tunnel experiment [4]. In the CFD simulation, the value was assumed to be equal to be 0.5, which was a default value in the CFD software. Figure 13 is an illustration of the C_F comparison between the wind tunnel experiment [4] and the CFD simulation.
4.2. CFD analysis of drag characteristics due to surface-roughness

4.2.1. Validation study
A validation of a prior CFD analysis of the drag characteristics on a flat plate [11] was also conducted in this study. The previous study analyzed a flat plate with surface conditions as follows: smooth, regular roughness and irregular roughness. The validation was only carried out on the smooth surface conditions and regular roughness. The model used is a flat plate with 30 m in length and a breadth of 3 m, at a Reynolds number of $2.79 \times 10^8$. The results of the recent CFD study were found to be in excellent agreement with the prior CFD analysis. The maximum difference between both simulations were below 5% as listed in Table 10. Therefore, this validation study can be verified as valid and may be used in the prediction study.

Table 10 Validation study of CFD analysis [11] on drag characteristics due to surface roughness.

| Notation | $K_s$ (micron) | $C_f (10^{-3})$ [11] | $C_f$ (%) | $C_f (10^{-3})$ CFD | $\Delta C_f$ (%) |
|----------|----------------|----------------------|-----------|---------------------|-----------------|
| S        | 0              | 1,8052               | -         | 1,7865              | -               |
| Ks1      | 81,25          | 2,2499               | 24,63     | 2,2536              | 24,84           |
| Ks2      | 325            | 2,9407               | 62,9      | 2,9392              | 62,82           |
| Ks3      | 568,75         | 3,2400               | 79,48     | 3,2573              | 80,44           |

4.2.2. Prediction study
4.2.2.1. Prediction for flat plate of 30 m in length
As shown in Table 11 and Table 12, the increase of $C_f$ due to regular roughness is compared to the value of $C_f$ for smooth surface. These results show a constant change of $C_f$ for each velocity.

Table 11 Prediction study on the friction coefficient due to extreme regular roughness on a 30 m flat plate.

| V (m/s) | Re     | $C_f$ CFD ($10^{-3}$) | $C_f$ K1 ($10^{-3}$) | $C_f$ K2 ($10^{-3}$) | $C_f$ K3 ($10^{-3}$) |
|---------|--------|-----------------------|----------------------|---------------------|---------------------|
| 9,775   | $2.79 \times 10^8$ | 1,7865               | 3,0025              | 5,2312              | 5,4131              |
| 12      | $3.40 \times 10^8$ | 1,7340               | 2,9457              | 5,1176              | 5,3214              |
The constant change in the $C_F$ values are an indication that the surface roughness belongs to the level of the fully rough regime. In the regime, the drag component is entirely caused by the pressure drag experienced by the roughness elements [3]. The changes in the $C_F$ values are illustrated in Figure 14.

![Figure 14](image-url)

**Figure 14** The comparison between the frictional coefficient values due to extreme regular roughness and due to smooth surface of a 30 m flat plate.

Then, CFD predictions were also conducted for irregular extreme roughness which results are shown in Table 13, while the amount of change in the form of a percentage (%) is shown in Table 14.

| No | $V$ (m/s) | $Re$ | $C_F$ (10$^{-3}$) | $\Delta C_F$ K1 (%) | $\Delta C_F$ K2 (%) | $\Delta C_F$ K3 (%) |
|----|-----------|------|-------------------|---------------------|---------------------|---------------------|
| 1  | 9,775     | 2,79 x 10$^8$ | 1,7865            | 68,07               | 192,82              | 203,00              |
| 2  | 12        | 3,40 x 10$^8$ | 1,7340            | 69,89               | 195,14              | 206,89              |

**Table 12** Percentage of the increase in friction coefficient due to extreme regular roughness on a 30 m flat plate.

| No | $V$ (m/s) | $Re$ | $C_F$ (10$^{-3}$) | $\Delta C_F$ K1 (%) | $\Delta C_F$ K2 (%) | $\Delta C_F$ K3 (%) |
|----|-----------|------|-------------------|---------------------|---------------------|---------------------|
| 1  | 9,775     | 2,79 x 10$^8$ | 4,0298            | 125,57              | 125,63              | 128,15              |
| 2  | 12        | 3,40 x 10$^8$ | 3,8076            | 119,59              | 119,80              | 122,96              |

**Table 13** Prediction study on the friction coefficient due to extreme irregular roughness on a 30 m flat plate.

| No | $V$ (m/s) | $Re$ | $C_F$ (10$^{-3}$) | $\Delta C_F$ K1 (%) | $\Delta C_F$ K2 (%) | $\Delta C_F$ K3 (%) |
|----|-----------|------|-------------------|---------------------|---------------------|---------------------|
| 1  | 9,775     | 2,79 x 10$^8$ | 4,0309            | 4,0759              | 4,0971              | 3,8829              |
| 2  | 12        | 3,40 x 10$^8$ | 3,8112            | 3,8660              | 3,8690              | 3,8829              |

**Table 14** Percentage of the increase in friction coefficient due to extreme irregular roughness on a 30 m flat plate.

The extreme irregular roughness variations also belong to the fully rough regime, as can be seen from the constant change in the $C_F$ values. The range of increase in the $C_F$ values caused by irregular roughness was found to be around 117,28 – 129,34% for Reynolds number of $2,79 \times 10^8$ and around 119,59 – 123,94%. The constant increase of $C_F$ is more apparent in Figure 15.
Figure 15 The $C_F$ trend of the 30 m flat plate due to extreme irregular roughness was compared to each other and the smooth plate condition, showing a similar trend of $C_F$ between each extreme irregular roughness.

The prediction results of extreme regular roughness for the flat plate of 30 m in length had greater increase in $C_F$ than the increase in $C_F$ with extreme irregular roughness. In the previous research, it was found that the increase of $C_F$ due to irregular roughness is smaller than the increase of $C_F$ due to regular roughness, which has a similar averaged roughness length scale value. In Figure 14, it can be seen that the curve showing extreme irregular roughness is below the extreme regular roughness Ks 2 (3000 micron) curve and above the Ks 1 (300 micron) extreme regular roughness curve.

Figure 16 The increase of $C_F$ of the 30 m flat plate due to smooth surface, extreme regular and irregular roughness are compared to each other, showing that the extreme irregular roughness with an averaged roughness length (3000 micron) caused smaller increase in $C_F$ than the extreme regular roughness with the same roughness length (3000 micron).
4.2.2.2. Predictions for flat plate of 60 m in length

Subsequently, extreme roughness CFD simulations were performed for a flat plate of 60 m in length. The increase in $C_F$ is shown in Table 15 along with its change in the form of percentage. The increase of $C_F$ for the 60 m flat plate should be constant like the increase of $C_F$ for the 30 m flat plate. The illustration of this increase in $C_F$ can be seen more clearly in Figure 17.

**Table 15** The increase of the friction resistance coefficient due to extreme regular roughness on a 60 m flat plate.

| Re          | $C_F$ CFD | $C_F$ K1 | $C_F$ K1 (%) | $C_F$ K2 | $C_F$ K2 (%) | $C_F$ K3 | $C_F$ K3 (%) |
|-------------|-----------|----------|--------------|----------|--------------|----------|--------------|
| $5.60 \times 10^8$ | 1.6960    | 2.8852   | 70.12        | 4.9625   | 192.61       | 4.7425   | 179.63       |
| $6.90 \times 10^8$ | 1.5601    | 2.4880   | 59.47        | 3.8345   | 145.78       | 4.2511   | 172.50       |

**Figure 17** The increase of the friction resistance coefficient of the 60 m flat plate due to extreme regular roughness variation is compared to each other and the smooth plate condition.

Then, CFD simulations of irregular roughness were performed on a flat plate of 60 m in length with extreme irregular roughness variations. The increase of $C_F$ value for each irregular roughness variations on the flat plate of 60 m in length is shown in Table 16. While the $\Delta C_F$ in percentage is shown in Table 17.

**Table 16** The increase of $C_F$ for flat plate of 60 m in length due to irregular roughness.

| Re          | $C_F$   |
|-------------|---------|
| $5.60 \times 10^8$ | 123, 132, 213, 231, 312, 321 |
| $6.90 \times 10^8$ | 3,5276, 3,5249, 3,5541, 3,5278, 3,5487, 3,5392 |

**Table 17** The increase of $C_F$ for flat plate of 60 m in length due to irregular roughness in percentage form.

| Re          | $\Delta C_F$ (%) |
|-------------|------------------|
| $5.60 \times 10^8$ | 123, 132, 213, 231, 312, 321 |
| $6.90 \times 10^8$ | 3,5276, 3,5249, 3,5541, 3,5278, 3,5487, 3,5392 |

An illustration of the increase of $C_F$ due to extreme irregular roughness for a flat plate with 60 m length can be seen in Figure 18.
Figure 18 The increase of the friction resistance coefficient of the 60 m flat plate due to extreme irregular roughness variation is compared to each other and the smooth plate condition.

Finally, the prediction results of the CFD simulations for the flat plate with 60 m in length are combined in Figure 19.

Figure 19 The increase of $C_F$ of the 60 m flat plate due to smooth surface, extreme regular and irregular roughness are compared to each other.

Due to the uneven nature of biofouling spread around a ship, the final assumption of the increase in $C_F$ due to biofouling is based on the values found in the CFD simulations of flat plates with irregular roughness. Thus, it can be said that the rise of $C_F$ on a flat plate due to extreme irregular roughness leads up to 117.3 – 129.34%.
5. Conclusion
Based on the results of this study, the CFD software is found to be sufficient in solving the problems that were raised. The $C_F$ value for the smooth surface of the simulation is close to the $C_F$ ITTC value. The $C_F$ value of the simulation results for regular rough surfaces is also close to the results in the previous CFD study [11]. This study shows that the increase in friction resistance that occurs depends on the roughness conditions, hence:

1. Surface roughness affects the increase of $C_F$ depending on the level of roughness (the smooth regime, transitionally rough regime and fully rough regime) and on the level of the roughness density ($C_S$),
2. Different variations of regular roughness and irregular roughness have different effects on the increase in $C_F$. The increase in $C_F$ due to irregular roughness is lower than the increase in $C_F$ due to regular roughness with the same averaged roughness height,
3. The CFD simulation obtained different $\Delta C_F$ values from the wind tunnel experiment. This difference may be caused by the unknown value of $C_S$ in the wind tunnel experiment. However, the trend was found to be similar,
4. The CFD simulation for the validation and the prediction of the previous CFD study [11] obtained the appropriate $\Delta C_F$ results, as the $C_S$ values that was used in this study was similar with the previous study. The results were also able to obtain the conclusion explained in point number 2.

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