Impact of Hard Fouling on the Ship Performance of Different Ship Forms

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Abstract: The successful optimization of a maintenance schedule, which represents one of the most important operational measures for the reduction of fuel consumption and greenhouse gas emission, relies on accurate prediction of the impact of cleaning on the ship performance. The impact of cleaning can be considered through the impact of biofouling on ship performance, which is defined with delivered power and propeller rotation rate. In this study, the impact of hard fouling on the ship performance is investigated for three ship types, keeping in mind that ship performance can significantly vary amongst different ship types. Computational fluid dynamics (CFD) simulations are carried out for several fouling conditions by employing the roughness function for hard fouling into the wall function of CFD solver. Firstly, the verification study is performed, and the numerical uncertainty is quantified. The validation study is performed for smooth surface condition and, thereafter, the impact of hard fouling on resistance, open water and propulsion characteristics is assessed. The differences in the impact of biofouling on the ship performance are noticed amongst different ship forms. They are mainly influenced by the portion of viscous resistance in the total resistance, relative roughness, roughness Reynolds number and advance coefficient for the self-propulsion point.

Keywords: biofouling; ship performance; container ship; oil tanker; bulk carrier; CFD

1. Introduction

Although recognized as an efficient mode of transport that has steadily enhanced safety, as well as environmental performance, over the past few decades, the maritime transport industry is transforming. Lately, in order to fulfil the new regulatory requirements and market needs, ship operators and ship owners have to improve capability of their ships to enable innovative, relevant and efficient services. Several technical and operational measures are adopted for increasing energy efficiency [1], however, it is crucial to accurately measure their effects. Namely, new regulations demand an increasing level of environmental performance, while ship operators and ship owners are faced with mounting pressure to keep up the competitiveness of their ships. As a result of this, ship operators and ship owners often hesitate to implement measure for increasing the energy efficiency due to the lack of reliable data on their effect [2,3]. The optimization of the maintenance schedule related to hull and propeller cleaning presents an important operational measure for increasing energy efficiency as ship operator or ship owner has large degree of control over it [4]. The successful optimization of maintenance schedule relies on accurate prediction of the impact of cleaning on the ship performance. The presence of biofouling on ship hull and propeller is causing an increase in roughness, which leads to an increase in ship resistance and if the ship speed is kept constant, an increase in the fuel consumption [5]. The biofouling occurrence is mostly prevented through the application of antifouling (AF) coatings, while hull and
propeller cleaning are usually performed in drydock. It should be noted that both of those measures are costly [6]. Consequently, an accurate assessment of the impact of biofouling on the ship performance is required for the proper selection of AF coatings and scheduling of hull cleaning [7].

There are different approaches for the assessment of this impact which can be classified into statistical studies, performance monitoring and approaches, based on the wall similarity hypothesis [8]. Approach based on the wall similarity hypothesis allows estimation of the fouling effect if the drag characterization of certain fouling type is performed. Drag characterization of a rough surface implies assessing the velocity decrement caused by the frictional drag of the surface as a function of the roughness Reynolds number \( (k^+) \). This velocity decrement, i.e., downward shift of the mean velocity in the log-law region of turbulent boundary layer (TBL) is called the roughness function \( (\Delta U^+) \). There is no universal roughness function, however, once \( \Delta U^+ \) for a certain fouling type is assessed, it can be used for the determination of frictional drag of any arbitrary body covered with that fouling type [9].

Over the last few decades, Granville similarity law scaling method has been imposed for the assessment of the impact of biofouling on the ship resistance with \( \Delta U^+ = f(k^+) \) known and it has been widely used in the literature [10–14]. Nevertheless, this method has several important drawbacks, as claimed by [15]. Namely, this method can be used for the prediction of the frictional resistance coefficient of the fouled flat plate having the same length as an investigated ship, and other resistance components of fouled ship are considered to be the same as for smooth ship. What is more, this method assumes only one \( k^+ \) value and thus one \( \Delta U^+ \) value over the entire flat plate. Since the \( k^+ \) value depends on friction velocity \( (u_f^+) \), this assumption may lead to certain errors, as, even on a flat plate \( u_f^+ \) is not constant over the entire plate. Lastly, using Granville similarity law scaling method only increase in effective power can be estimated. As shown in [16], due to the presence of biofilm the increase in the delivered power is significantly higher than the increase in effective power.

Recently, there have been an increasing number of studies using a computational fluid dynamics (CFD) approach based on the implementation of certain \( \Delta U^+ \) model within the wall function [17–20]. This approach can calculate \( u_f^+ \) for each discretized cell and, in that way, can obtain the distribution of \( u_f^+ \) values along the investigated surface. Consequently, \( k^+ \) distribution along the investigated surface will be obtained, and various \( \Delta U^+ \) values will be used along the surface. Furthermore, the fouling effects on the other resistance components can be investigated, as well as the impact of biofouling on the open water and propulsion characteristics. This approach for the assessment of the impact of hull roughness on the ship’s total resistance has been recently validated within [21]. Namely, within [21], it was demonstrated that CFD wall function approach can precisely determine not only the impact of roughness on the skin friction, but on the total resistance of 3D hull as well. The investigations related to the impact of barnacle and biofilm fouling on the ship propulsion performance have been presented in [8,22]. These studies demonstrated the impact of biofouling on the propulsion characteristics using CFD approach. However, both studies were performed on the example of Kriso Container Ship (KCS). Since ship resistance and propulsion characteristics can significantly vary amongst different ship forms, it would be beneficial to investigate the fouling effect on the ship performance of different ship forms.

In this study, the impact of biofouling on the ship performance of three merchant ships is analyzed. As already noted, the obtained increases due to the presence of biofouling in effective and delivered power are not equal. Therefore, it is more accurate to study the impact of biofouling on the ship performance through the analysis of the increase in delivered power and propeller rotation rate, than through analysis of the increase in effective power solely. To the best of the authors’ knowledge, the impact of biofouling on the ship performance of different hull forms is investigated in this paper for the first time. This investigation is performed utilizing the CFD simulations and a Colebrook-type \( \Delta U^+ \) of Grigson which is implemented within the wall function of CFD solver. Drag characterization study of hard fouling was performed by Schultz [12]. CFD model for the assessment of the impact of hard fouling on the ship resistance has been proposed in [16], where the CFD model is validated. This study can be considered as a continuation of study [16]. A verification study is carried out in order to assess grid and temporal uncertainty. A validation study for smooth surface conditions is
performed, by comparing the numerically obtained results with the extrapolated towing tank results. Finally, the detail investigation of the impact of hard fouling on the ship resistance and propulsion characteristics is performed for six different fouling conditions. The obtained results show the impact of hard fouling on the resistance and propulsion characteristics amongst different ship types, as well as on the increase in delivered power and propeller rotation rate.

2. Materials and Methods

2.1. Governing Equations

In this study Reynolds-averaged Navier–Stokes (RANS) and averaged continuity equations are used as governing equations, and they read:

\[
\frac{\partial (\rho \mathbf{u}_i)}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \mathbf{u}_i \mathbf{u}_j + \rho \overline{w_i w_j} \right) = \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{1}
\]

\[
\frac{\partial (\rho \mathbf{u}_i)}{\partial x_i} = 0 \tag{2}
\]

where \(\rho\) is the density, \(\mathbf{u}_i\) is the averaged velocity vector, \(\rho \overline{w_i w_j}\) is the Reynolds stress tensor, \(\bar{p}\) is the mean pressure and \(\tau_{ij}\) is the mean viscous stress tensor, given as:

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{3}
\]

where \(\mu\) is the dynamic viscosity coefficient.

In order to close Equations (1) and (2), \(k - \omega\) SST turbulence model with wall functions is applied. For the discretization of governing equations, the finite volume method (FVM) is utilized, and the volume of fluid (VOF) method with high resolution interface capturing (HRIC) is utilized for tracking and locating the free surface. After the discretization, Equations (1) and (2) are solved in a segregated manner, the second order upwind convection scheme is used for the discretization of convective terms, while temporal discretization is performed using the first order scheme.

As already noted, the impact of roughness, i.e., biofouling, can be noticed as a downward shift of the mean velocity profile within the log-law region of TBL:

\[
U^+ = \frac{1}{k} \ln y^+ + B - \Delta U^+ \tag{4}
\]

where \(k\) is the von Karman constant, \(U^+\) is the non-dimensional mean velocity, \(y^+\) is the non-dimensional normal distance from the wall and \(B\) is the smooth wall log-law intercept.

The drag characterization of a certain roughness or fouling type means finding the relation between \(\Delta U^+\) and \(k^+\), where \(k^+\) is defined as:

\[
k^+ = \frac{k \mu \tau}{\rho} \tag{5}
\]

where \(k\) is the roughness length scale, which cannot be directly measured.

Schultz has proposed following scaling for the hard fouling [12]:

\[
k = 0.059 R_t \sqrt{\%SC}, \tag{6}
\]

where \(R_t\) is the height of the largest barnacles, while \(\%SC\) is the percentage of the surface covered with barnacles.
Using Equation (6), Schultz has demonstrated excellent collapse for the obtained results with the Grigson roughness function, which is given with following equation:

\[ \Delta U^+ = \frac{1}{\kappa} \ln(1 + k^+) \] (7)

It should be noted that Schultz has proposed Equation (6) based on the assumption that the height of the larger barnacles has the dominant influence on drag and that the effect of increase in %SC is larger for lower %SC and smaller for higher %SC, and these assumptions were deduced from the obtained results, pipe flow experiments [23] and the observations from [24] for typical roughness types.

An explanation of the approach for the determination of the impact of biofilm on the ship resistance and propulsion characteristics is presented in [8,18] and is applied within this study. Firstly, an experimental study related to towing tank measurements of fouled flat plates was carried out within [12]. Based on the obtained results, Schultz has proposed Equation (6) for the determination of roughness length scale and Equation (7) as a \( \Delta U^+ \) model for hard fouling. This \( \Delta U^+ \) model was implemented within the wall function of CFD solver and CFD model was validated with the comparison of the numerically obtained frictional resistance coefficients for fouled flat plates [16] with the experimentally measured ones [12]. Additionally, CFD simulations for fouled full-scale plates representing two merchant ships were carried out, and the obtained results were compared with the results obtained using Granville similarity law scaling method [16]. Once the CFD model is validated, it can be utilized for the assessment of the impact of hard fouling on the resistance and propulsion characteristics. The impact of hard fouling on the ship resistance characteristics for two merchant ships is studied in [16] using CFD simulations of a towed ship. In this paper, the impact of hard fouling on the propeller performance in open water conditions is assessed through implementation of \( \Delta U^+ \) model for hard fouling within wall function of CFD solver and by performing CFD simulations of the open water test (OWT). CFD simulations of OWT are performed using the moving reference frame (MRF) method, and CFD simulations are performed as steady simulations. More details regarding this method can be found within [25]. The impact of hard fouling on ship propulsion characteristics is assessed utilizing the proposed \( \Delta U^+ \) model within CFD simulations of the self-propulsion test (SPT). It should be noted that CFD simulations of SPT are performed using the body force method and more details regarding this method can be found in [25]. The change in certain hydrodynamic characteristic is calculated as follows:

\[ \Delta \phi = \frac{\phi_R - \phi_S}{\phi_S} \cdot 100\% \] (8)

where \( \phi_R \) represents certain hydrodynamic characteristic for fouled condition and \( \phi_S \) represents certain hydrodynamic characteristic for smooth surface condition.

The impact of hard fouling on the ship performance is studied for six different fouling conditions presented in Table 1. The presented fouling conditions are investigated considering certain fouling condition present both at the hull and propeller.

| Fouling Condition | \( R_{r}, \mu m \) | %SC, % | \( k, \mu m \) |
|-------------------|-----------------|--------|-------------|
| R1                | 7000            | 25     | 2065        |
| R2                | 5000            | 25     | 1475        |
| R3                | 7000            | 5      | 923.5       |
| R4                | 5000            | 5      | 659.64      |
| R5                | 7000            | 1      | 413         |
| R6                | 5000            | 1      | 295         |
2.2. Resistance, Open Water and Propulsion Characteristics

The total resistance coefficient can be decomposed as follows:

\[ C_T = (1 + k)C_F + C_W \]  (9)

where \( k \) represents the form factor, \( C_F \) represents the frictional resistance coefficient and \( C_W \) represents the wave resistance coefficient. It should be noted that \( C_T \) is obtained by dividing total resistance (\( R_T \)) with \( \frac{1}{2} \rho v^2 S \) (where \( v \) is the ship speed and \( S \) is the wetted surface) and in that way, the non-dimensional form is obtained.

Effective power (\( P_E \)) can be obtained as a product of \( R_T \) and \( v \). Most studies related to the impact of biofouling on ship performance investigate the effect of biofouling on effective power. However, the fuel consumption and greenhouse gas (GHG) emission can be related to delivered power (\( P_D \)) and propeller rotation rate (\( n \)). The quasi-propulsive efficiency coefficient defines relation between \( P_E \) and \( P_D \) as follows:

\[ \eta_D = \frac{P_E}{P_D} = \eta_H \eta_O \eta_R \]  (10)

where \( \eta_H \) is the hull efficiency, \( \eta_O \) is the open water efficiency and \( \eta_R \) is the relative rotative efficiency. These efficiencies are defined as follows:

\[ \eta_H = \frac{1 - t}{1 - w} \]  (11)

\[ \eta_O = \frac{J \ K_{TO}}{2 \pi \ K_{QQ}} \]  (12)

\[ \eta_R = \frac{K_{QQ}}{K_Q} \]  (13)

where \( t \) is the thrust deduction coefficient, \( w \) is the wake fraction coefficient, \( J \) is the advance coefficient, \( K_{TO} \) is the thrust coefficient in open water conditions, \( K_{QQ} \) is the torque coefficient in open water conditions and \( K_Q \) is the torque coefficient obtained in SPT.

Delivered power can be obtained as follows:

\[ P_D = 2 \pi \rho Q n^3 D^5 \]  (14)

where \( D \) is the propeller diameter.

3. Computational Model

3.1. Case Study

Within this paper, the impact of hard fouling on the ship performance is presented on the example of three commercial ships: containership, oil tanker and bulk carrier. The portion of CO\(_2\) emission from containerships, bulk carriers and tankers in total CO\(_2\) emission from international shipping is significantly higher than for other ship types and accounts for almost 62% of CO\(_2\) emission from international shipping [26]. The Kriso Container Ship (KCS) was designed with an aim to represent a modern panamax container ship with a bulbous bow [27]. The Korea Research Institute for Ships and Ocean Engineering (KRISO) carried out an extensive towing tank experiments, in order to determine resistance, mean flow data and free surface waves [27]. Self-propulsion tests were performed at the Ship Research Institute (now the National Maritime Research Institute, NMRI) in Tokyo, and the obtained results were reported in the Proceedings of the CFD Workshop Tokyo in 2005 [28]. Kriso Very Large Crude-oil Carrier 2 (KVLCC2) was designed with the aim to represent a large oil tanker that can transport 300,000 t of crude oil, and it represents the second variant of KRISO tanker with more U-shaped stern frame lines in comparison with KVLCC. KRISO carried out resistance and self-propulsion tests,
as well as towing tank measurements for the determination of mean flow data and wave profile elevations [27]. Bulk Carrier (BC) represents a typical handymax bulk carrier. Extensive towing tank experiments, including resistance tests, self-propulsion tests, as well as nominal wake measurements were performed in Brodarski institute [29]. It should be noted that KCS, KVLCC2 and BC were only designed as models, i.e., full-scale ships have never been built. The geometry of the investigated ships is presented in Figure 1.

Figure 1. Geometry of the Kriso Container Ship (KCS) (upper), Kriso Very Large Crude-oil Carrier 2 (KVLCC2) (middle) and Bulk Carrier (BC) (lower).

From Figure 1. it is evident that all three ships have bulbous bow and transom stern. KCS has more slender form than BC and KVLCC2. The main particulars of the investigated ships are presented in Table 2.

| Parameter                      | KCS    | KVLCC2 | BC    |
|--------------------------------|--------|--------|-------|
| length between perpendiculars, $L_{pp}$ | 230 m  | 320 m  | 175 m |
| waterline length, $L_{wl}$       | 232.5 m| 325.5 m| 182.69 m |
| breadth, $B$                     | 32.2 m | 58 m   | 30 m  |
| draft, $T$                       | 10.8 m | 20.8 m | 9.9 m |
| Displacement, $\Delta$          | 53,382.8 t| 320,750 t| 41,775 t |
| Displacement volume, $V$         | 52,030 m$^3$ | 312,622 m$^3$ | 40,716 m$^3$ |
| Wetted surface, $S$             | 9645 m$^2$ | 27,467 m$^2$ | 7351.9 m$^2$ |
| Block coefficient, $C_B$         | 0.6505 | 0.8098 | 0.7834 |
| Froude number, $F_n$             | 0.26   | 0.1423 | 0.2026 |
| Design speed, $V$               | 24 kn  | 15.5 kn | 16.32 kn |
| Propeller center, longitudinal location from FP ($x/L_{pp}$) | 0.9825 | 0.9797 | 0.9800 |
| Propeller center, vertical location from WL ($-z/T$) | 0.62037 | 0.72115 | 0.6800 |

SPT were performed using the KP505 for KCS, the KP458 for KVLCC2 and one stock propeller from the Wageningen series (WB) for BC, and their geometry is shown in Figure 2. The main particulars of the investigated propellers are given in Table 3. Towing tank tests for all three investigated propellers are performed at Reynolds numbers ($R_n$) higher than $R_n = 2 \cdot 10^5$ as prescribed by ITTC [30], and the obtained results are given in [29,31,32].
Figure 2. KP505 (left), KP458 (middle) and Wageningen series (WB) (right) propeller.

Table 3. The main particulars of KP505, KP458 and WB.

| Propeller       | KP505     | KP458     | WB         |
|-----------------|-----------|-----------|------------|
| propeller diameter, $D$ | 7.900 m   | 9.860 m   | 6.199 m    |
| propeller pitch, $P$    | 7.505 m   | 7.085 m   | 5.294 m    |
| number of blades, $Z$    | 5         | 4         | 4          |
| chord length, $c$       | 2.844 m   | 2.233 m   | 1.633 m    |
| maximum thickness of profile, $t$ | 0.132 m   | 0.131 m   | 0.168 m    |
| Hub ratio, $d/D$         | 0.180     | 0.155     | 0.179      |

3.2. Computational Domain and Boundary Conditions

In this study, the impact of hard fouling on resistance, open water and propulsion characteristics is investigated using CFD simulations of resistance, open water and self-propulsion tests. It should be noted that the impact of hard fouling on resistance characteristics of KCS and KVLCC2 is already investigated in [16]. Therefore, within this paper, the impact of hard fouling on ship resistance characteristics is only briefly presented as it is important for further discussion. $R_F$ of a ship is determined using CFD simulations which include free surface effects, i.e., free surface simulations (FSS). Viscous resistance ($R_V$) is obtained using double body simulations (DBS), which do not take free surface effects into account. In DBS, the flow around deeply immersed double body ship is simulated and thus the obtained $R_F$ is equal to $R_V$. The frictional resistance ($R_F$) is obtained by integrating the tangential stresses over the wetted surface, while viscous pressure resistance ($R_{VP}$) is obtained by integrating the pressure over the wetted surface in DBS. Once $R_V$ and $R_F$ are determined, $1 + k$ is determined as a ratio between $R_V$ and $R_F$. Wave resistance ($R_W$) is obtained as difference between $R_F$ obtained in FSS and $R_V$ obtained in DBS. For more details regarding the performed CFD simulations of resistance tests, reference may be given to [16]. It should be noted that CFD simulations of resistance tests for BC are performed using the same computational domain and boundary conditions as in [16]. CFD simulations of OWT are performed using the cylindrical computational domain. The domain boundaries are placed sufficiently far from the investigated propeller and appropriate boundary conditions are applied in order to prevent their impact on the obtained solution, Figure 3. The computational domain for CFD simulations of SPT is the same as for CFD simulations of resistance test, however within CFD simulations of SPT symmetry condition is not applied, i.e., the whole computational domain is generated (Figure 4). In Figure 4, the applied boundary conditions are presented as well. It should be noted that the same boundary conditions are applied in CFD simulations of the resistance test, except for the symmetry boundary condition, which is applied at the symmetry plane within CFD simulations of resistance test. Possible occurrence of wave reflection is prevented by applying VOF wave damping at the inlet, outlet and side boundaries. More details regarding the applied damping function can be found in [33], and the VOF wave damping length is set to $L_{pp}$.
applied in CFD simulations of the resistance test, except for the symmetry boundary condition, which is applied at the symmetry plane within CFD simulations of resistance test. Possible occurrence of wave reflection is prevented by applying VOF wave damping at the inlet, outlet and side boundaries. More details regarding the applied damping function can be found in [33], and the VOF wave damping length is set to $L_{pp}$.

**Figure 3.** Computational domain for the open water test (OWT): KP505 (upper), KP458 (middle) and WB (lower).

**Figure 4.** Computational domain (left) and the applied boundary conditions (right) within computational fluid dynamics (CFD) simulations of the self-propulsion test (SPT).

### 3.3. Discretization of Computational Domain and Computational Setup

Cut-cell grids with prism layer mesh on the walls were made utilizing the surface remesher, prism layer mesher and trimmer mesher within STAR-CCM+. The unstructured hexahedral mesh is refined locally in the critical regions. Thus, within DBS and FSS of resistance test, as well as in CFD simulations of SPT, mesh is refined near the hull surface, near the bow and stern and hull surface is discretized very fine, i.e., the cell size at the hull surface is set to $1/1000 L_{pp}$. Within CFD simulations including free surface effects, mesh is refined in the region where free surface is expected, as well as in order to capture Kelvin wake around free surface. Additionally, mesh for CFD simulations of SPT is refined in the region where virtual disk is located. It should be noted that refinements are made in the same way within [8,25,34]. The mesh for CFD simulations of OWT is refined in the region around the propeller.
Additionally, mesh is particularly refined along the leading and trailing edges of propeller in order to allow proper demarcation between the suction and pressure sides. The thickness of the first cell on the wall surfaces within all CFD simulations is chosen in a way that $y^+$ values are higher than 30 and $k^+$ values, as recommended by [15]. As a result of this, near wall mesh for smooth and fouled surfaces is not the same since investigated surface conditions represent very severe fouling conditions with high $k$ values. The obtained mesh for CFD simulations of OWT is presented in Figure 5, while the obtained mesh for CFD simulations of SPT is shown in Figure 6. Within these two figures, the above mentioned refinements can be seen.

![Figure 5. Propeller surface (left) and profile view (right) cross section of the volume mesh for KP505 (upper), KP458 (middle) and WB (lower).](image)

![Figure 6. The profile view cross-section of the domain for KCS (upper left), KVLCC2 (middle left) and BC (lower left) and mesh refinement in stern region of KCS (upper right), KVLCC2 (middle right) and BC (lower right).](image)

CFD simulations of OWT are performed for full-scale KP505, KP458 and WB in a way that $n = 1.5$ rps is kept constant and advance velocity varies with $J$. CFD simulations for KP505 are performed for range of $J$ from 0.1 to 0.8, with a step equal to 0.1, for KP458 for range of $J$ from 0.1 to 0.7 with step equal to 0.1 and for WB for range of $J$ from 0.08 to 0.88 with step equal to 0.08. CFD simulations of SPT are performed without discretization of propeller geometry, as the body force method is applied. Therefore, a virtual disk model is placed at the propeller location with the inner...
radius of the virtual disk set to the propeller hub radius and the outer radius set to the propeller radius \((R)\). Thickness of virtual disk model is set as propeller thickness, the inflow plane radius is set as \(1.1 R\) and the inflow plane offset is set as \(2.2 R\) towards the bow from the half of virtual disk thickness.

CFD simulations without free surface effects, i.e., DBS of resistance test and CFD simulations of OWT, are performed as steady simulations. The remaining CFD simulations include free surface effect, and they are performed with time step equal to \(T / 200\), where \(T\) is the ratio between \(L_{pp}\) and ship speed \((\nu)\). FSS of resistance test and CFD simulations of SPT are stopped once \(R_T\) and thrust \((T)\) force became steady, i.e., once they oscillate around averaged value with oscillation amplitude lower than 0.5\% of \(R_T\) or \(T\) value.

4. Verification and Validation Study

4.1. Verification Study

A verification study is carried out in order to estimate sufficient grid spacings and adequate time steps. This study is carried out using three different meshes and three different time steps. Verification study for grid size is made with fine time step and verification study for time step is made with fine mesh. Thereafter, numerical uncertainty, which is consisted of both spatial and temporal uncertainties, is calculated using the grid convergence index (GCI) method. This method is recommended by the American Society of Mechanical Engineers, as well as by the American Institute of Aeronautics and Astronautics for the assessment of grid uncertainty \((U_G)\) [35], but can be used for the assessment of temporal uncertainty \((U_T)\) as well [35–37]. More details regarding the GCI method and numerical uncertainty can be found in [18].

For the purposes of verification study three meshes are generated for smooth surface condition and fouling condition R1. Since all mesh parameters, except prism layer mesh, are set to be relative to cell base size, mesh is refined by changing cell base size. It should be noted that all remaining CFD simulations, i.e., for the fouling conditions R2, R3, R4, R5 and R6 are performed using fine mesh. In Table 4, the number of cells used in the verification study is shown. Three different time steps, i.e., \(T / 50\), \(T / 100\) and \(T / 200\) are used in the verification study for time step.

| Smooth Surface Condition | Simulation | KCS/KP 505 | KVLCC2/KP 458 | BC/WB |
|--------------------------|------------|------------|---------------|------|
|                          | Coarse/Medium/Fine | Coarse/Medium/Fine | Coarse/Medium/Fine |
| OWT                      | 3.50/5.10/7.10 Million | 2.40/3.30/5.30 Million | 2.20/3.50/5.00 Million |
| SPT                      | 2.12/4.19/8.47 Million | 1.23/2.74/5.25 Million | 0.96/2.20/5.06 Million |

| Fouling Condition R1     | Simulation | KCS/KP 505 | KVLCC2/KP 458 | BC/WB |
|--------------------------|------------|------------|---------------|------|
|                          | Coarse/Medium/Fine | Coarse/Medium/Fine | Coarse/Medium/Fine |
| OWT                      | 2.30/3.50/5.30 Million | 1.80/2.30/3.90 Million | 1.60/2.40/3.40 Million |
| SPT                      | 1.89/3.83/7.54 Million | 1.14/2.54/4.86 Million | 0.89/2.01/4.61 Million |

It should be noted that the verification study for CFD simulations of resistance tests of KCS and KVLCC2 is carried out in [16]. Numerical uncertainties in the prediction of \(R_F\) and \(R_V\) consisted of grid uncertainties solely, and \(R_T\) consisted of grid and temporal uncertainties, which are calculated using the GCI method. The obtained numerical uncertainties in the prediction of \(R_F\) were below 1.3\% for both ships and for all analyzed fouling conditions (Table 1). Numerical uncertainties in the prediction of \(R_V\) were slightly higher, however, the highest obtained numerical uncertainty was equal to 2.86\%. Finally, the highest numerical uncertainties are obtained for the prediction of \(R_T\). Nevertheless, these grid and time step uncertainties were relatively low, i.e., the highest obtained grid uncertainty in the
prediction of $R_T$ was equal to 2.99%, while the highest time step uncertainty in the prediction of $R_T$ was equal to 0.1%. Within this paper, the numerical uncertainty in the prediction of $K_{TO}$ and 10$K_{QO}$ from CFD simulations of OWT are calculated for one $J$ value and the obtained results are presented in Tables 5 and 6. Additionally, numerical uncertainty in the prediction of $P_D$, $n$, $T$ and $J$ from CFD simulations of SPT are calculated.

As can be seen from Tables 5 and 6, relatively low numerical uncertainties are obtained, and are in line with numerical uncertainties of other CFD studies regarding open water tests [38,39]. Thus, the highest $U_G$ in the prediction of $K_{TO}$ and 10$K_{QO}$ is obtained for the WB propeller with smooth surface condition, and it is equal to 3.565% and 2.815%, respectively. It should be noted that numerical uncertainties obtained for smooth and fouled propellers are relatively close, i.e., numerical uncertainty has not raised due to the roughness effects.

From the results of verification study of SPT, Tables 7–9, it can be concluded that $U_T$ are lower than $U_G$. Generally, the obtained $U_G$ related to the prediction of $P_D$ for smooth and fouled ships are slightly higher than for the other investigated key variables and the highest $GCI_{fine}^{21}$ for KCS is equal to 3.123%, for KVLCC2 is equal to 1.174% and for BC is equal to 7.318%. The obtained $U_T$ related to the prediction of $P_D$ for smooth and fouled ships are lower and the highest $GCI_{fine}^{21}$ for KCS is equal to 1.366%, for KVLCC2 is equal to 1.502% and for BC is equal to 3.390%. The obtained $U_G$ related to the prediction of $n$ for smooth and fouled ships are the lowest amongst investigated key variables and the highest $GCI_{fine}^{21}$ for KCS is equal to 0.255%, for KVLCC2 is equal to 0.164% and for BC is equal to 1.661%. Interestingly, the obtained $U_T$ values related to the prediction of $n$ for smooth and fouled ships are higher than $U_G$ values and the highest $U_T$ for KCS is equal to 0.401%, for KVLCC2 is equal to 0.701% and for BC is equal to 2.909%. The obtained $U_G$ values related to the prediction of $T$ for smooth and fouled ships are low and the highest $GCI_{fine}^{21}$ for KCS is equal to 3.273%, for KVLCC2 is equal to 1.478% and for BC is equal to 4.717%. The obtained $U_T$ values related to the prediction of $T$ for smooth and fouled ships are lower or similar to $U_G$ and the highest $GCI_{fine}^{21}$ for KCS is equal to 0.807%, for KVLCC2 is equal to 1.529% and for BC is equal to 3.499%. Finally, the obtained $U_G$ values related to the prediction of $J$ for smooth and fouled ships are low and the highest $GCI_{fine}^{21}$ for KCS is equal to 0.452%, for KVLCC2 is equal to 1.257% and for BC is equal to 2.041%. The obtained $U_T$ values related to the prediction of $J$ for smooth and fouled ships are low as well, and the highest $GCI_{fine}^{21}$ for KCS is equal to 0.451%, for KVLCC2 is equal to 0.703% and for BC is equal to 2.719%.

### Table 5. The verification study for $K_{TO}$.

| Propeller | $J$ | $\phi_3$ | $\phi_2$ | $\phi_1$ | $\phi_{ext}^{21}$ | $GCI_{fine}^{21}$, % |
|-----------|----|----------|----------|----------|-------------------|-------------------|
| KP505 S   | 0.7| 0.18068  | 0.18047  | 0.18058  | 0.18071           | 0.092             |
| KP458 S   | 0.5| 0.18513  | 0.18576  | 0.18478  | 0.18264           | 1.443             |
| WB S      | 0.56| 0.17468 | 0.17338  | 0.17250  | 0.16738           | 3.565             |
| KP505 R1  | 0.6| 0.20722  | 0.20665  | 0.20668  | 0.20668           | 0.001             |
| KP458 R1  | 0.4| 0.15868  | 0.15883  | 0.15725  | 0.15698           | 0.217             |
| WB R1     | 0.4| 0.20876  | 0.20855  | 0.20878  | 0.21098           | 1.317             |

### Table 6. The verification study for $K_{QO}$.

| Propeller | $J$ | $\phi_3$ | $\phi_2$ | $\phi_1$ | $\phi_{ext}^{21}$ | $GCI_{fine}^{21}$, % |
|-----------|----|----------|----------|----------|-------------------|-------------------|
| KP505 S   | 0.7| 0.29436  | 0.29386  | 0.29387  | 0.29387           | 0.000             |
| KP458 S   | 0.5| 0.21219  | 0.21268  | 0.21169  | 0.21045           | 0.729             |
| WB S      | 0.56| 0.24312 | 0.24120  | 0.23910  | 0.23372           | 2.815             |
| KP505 R1  | 0.6| 0.40234  | 0.40168  | 0.40249  | 0.40615           | 1.136             |
| KP458 R1  | 0.4| 0.22703  | 0.22713  | 0.22531  | 0.22512           | 0.115             |
| WB R1     | 0.4| 0.32578  | 0.32591  | 0.32531  | 0.32524           | 0.024             |
Table 7. The obtained grid uncertainties in the prediction of $P_D$, $n$, $T$ and $J$.

| Ship | Surface Condition | $\phi_3$, MW | $\phi_2$, MW | $\phi_1$, MW | $\phi_{21}^{\text{ext}}$, MW | GCI$_{\text{fine}}$, % | $U_G$, MW |
|------|------------------|--------------|--------------|--------------|----------------------------|-------------------|----------|
| KCS  | S                | 26.744       | 25.321       | 24.624       | 24.009                     | 3.123             | 0.769    |
|      | R1               | 67.008       | 65.428       | 64.807       | 64.361                     | 0.860             | 0.558    |
| KVLCC2 | S              | 20.172       | 17.325       | 17.850       | 18.017                     | 1.174             | 0.209    |
|      | R1               | 58.651       | 55.524       | 55.940       | 56.036                     | 0.214             | 0.120    |
| BC   | S                | 7.384        | 7.267        | 6.725        | 6.573                      | 2.825             | 0.190    |
|      | R1               | 20.778       | 21.326       | 20.301       | 19.112                     | 7.318             | 1.486    |

| Ship | Surface Condition | $\phi_3$, rpm | $\phi_2$, rpm | $\phi_1$, rpm | $\phi_{21}^{\text{ext}}$, rpm | GCI$_{\text{fine}}$, % | $U_G$, rpm |
|------|------------------|--------------|--------------|--------------|----------------------------|-------------------|----------|
| KCS  | S                | 100.982      | 99.686       | 99.341       | 99.225                     | 0.146             | 0.145    |
|      | R1               | 118.374      | 117.672      | 117.376      | 117.137                    | 0.255             | 0.299    |
| KVLCC2 | S               | 73.068       | 70.484       | 70.858       | 70.951                     | 0.164             | 0.117    |
|      | R1               | 95.356       | 93.902       | 93.963       | 93.968                     | 0.007             | 0.006    |
| BC   | S                | 101.830      | 101.580      | 99.541       | 99.251                     | 0.364             | 0.362    |
|      | R1               | 130.805      | 132.033      | 131.120      | 128.345                    | 1.661             | 2.160    |

| Ship | Surface Condition | $\phi_3$, kN | $\phi_2$, kN | $\phi_1$, kN | $\phi_{21}^{\text{ext}}$, kN | GCI$_{\text{fine}}$, % | $U_G$, kN |
|------|------------------|--------------|--------------|--------------|----------------------------|-------------------|----------|
| KCS  | S                | 1903.77      | 1877.34      | 1810.89      | 1763.46                    | 3.273             | 59.281   |
|      | R1               | 3669.43      | 3630.48      | 3609.91      | 3557.73                    | 1.670             | 60.226   |
| KVLCC2 | S              | 2276.43      | 2015.69      | 2009.71      | 2009.41                    | 0.019             | 30.839   |
|      | R1               | 4557.62      | 4308.72      | 4390.60      | 4442.50                    | 1.478             | 64.872   |
| BC   | S                | 1616.88      | 1644.82      | 1592.13      | 1532.04                    | 4.717             | 75.107   |

| Ship | Surface Condition | $\phi_3$ | $\phi_2$ | $\phi_1$ | $\phi_{21}^{\text{ext}}$ | GCI$_{\text{fine}}$, % | $U_G$ |
|------|------------------|---------|---------|---------|-----------------|-------------------|------|
| KCS  | S                | 0.7196  | 0.7215  | 0.7293  | 0.7319          | 0.452             | 0.0033 |
|      | R1               | 0.5476  | 0.5442  | 0.5452  | 0.5456          | 0.094             | 0.0011 |
| KVLCC2 | S              | 0.4428  | 0.4603  | 0.4573  | 0.4564          | 0.248             | 0.0011 |
|      | R1               | 0.3066  | 0.3126  | 0.3099  | 0.3068          | 1.257             | 0.0039 |
| BC   | S                | 0.5160  | 0.5209  | 0.5328  | 0.5414          | 1.997             | 0.0106 |
|      | R1               | 0.3593  | 0.3580  | 0.3591  | 0.3649          | 2.041             | 0.0073 |

The obtained $U_I$, $U_Q$, $U_n$, $U_P_D$ and $U_J$, which consist of both $U_G$ and $U_T$, are shown in Table 9. As can be seen from Table 9, the lowest $U_{SN}$ values for smooth and fouled ships are obtained for KCS, which was expected, since $U_G$ values are higher than $U_T$ values and the mesh for KCS had more cells than for KVLCC2 and BC. The highest $U_{SN}$ is obtained for the prediction of $U_{P_D}$ for BC fouled with R1 and it is equal to 7.421% and other obtained $U_{SN}$ values are lower than 5.5%. Higher $U_{P_D}$ were expected, since, for the prediction of $P_D$, both $n$ and the propeller torque should be determined. It should be noted that the obtained $U_{P_D}$ are in line with the previously published studies [8,25]. From Table 9, it can be seen that higher numerical uncertainties are obtained for the prediction of $P_D$ and $T$, than for $n$ and $J$, which was also obtained in [8]. Additionally, it can be seen that $U_{SN}$ in the prediction of key variables for R1 are mostly below $U_{SN}$ for smooth surface condition. Higher $U_{SN}$ obtained for R1 than for smooth surface condition can be ascribed to the lower cell number used in CFD simulations of SPT for rough surface condition (Table 4). Therefore, it can be concluded that the implementation of $\Delta U^+$ within the wall function did not cause higher uncertainties in the prediction of the key variables.
Table 8. The obtained temporal uncertainties in the prediction of $P_D$, $n$, $T$ and $J$.

$$
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
 & \text{Ship} & \text{Surface Condition} & \phi_3, \text{MW} & \phi_2, \text{MW} & \phi_1, \text{MW} & \phi^{21}_{\text{ext}}, \text{MW} & \text{GCI}_{21}, \% & U_T, \text{MW} \\
\hline
 & KCS & S & 25.058 & 24.918 & 24.624 & 24.355 & 1.436 & 0.236 \\
 & & R1 & 65.020 & 65.398 & 64.807 & 64.749 & 0.330 & 0.410 \\
 & KVLCC2 & S & 17.413 & 17.256 & 17.850 & 18.064 & 1.502 & 0.268 \\
 & & R1 & 56.335 & 55.490 & 55.940 & 56.454 & 1.147 & 0.642 \\
 & BC & S & 6.813 & 6.903 & 6.725 & 6.542 & 3.390 & 0.228 \\
 & & R1 & 20.546 & 20.458 & 20.301 & 20.101 & 1.233 & 0.250 \\
\hline
\end{array}
$$

$$
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
 & \text{Ship} & \text{Surface Condition} & \phi_3, \text{rpm} & \phi_2, \text{rpm} & \phi_1, \text{rpm} & \phi^{21}_{\text{ext}}, \text{rpm} & \text{GCI}_{21}, \% & U_T, \text{rpm} \\
\hline
 & KCS & S & 99.697 & 99.577 & 99.341 & 99.094 & 0.311 & 0.309 \\
 & & R1 & 117.477 & 117.628 & 117.376 & 116.999 & 0.401 & 0.471 \\
 & KVLCC2 & S & 70.490 & 70.249 & 70.858 & 71.255 & 0.701 & 0.496 \\
 & & R1 & 94.492 & 93.715 & 93.963 & 94.079 & 0.154 & 0.145 \\
 & BC & S & 99.638 & 100.066 & 99.541 & 97.225 & 2.909 & 2.896 \\
 & & R1 & 130.805 & 130.529 & 130.073 & 129.374 & 0.672 & 0.874 \\
\hline
\end{array}
$$

$$
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
 & \text{Ship} & \text{Surface Condition} & \phi_3, \text{kN} & \phi_2, \text{kN} & \phi_1, \text{kN} & \phi^{21}_{\text{ext}}, \text{kN} & \text{GCI}_{21}, \% & U_T, \text{kN} \\
\hline
 & KCS & S & 1833.25 & 1827.69 & 1810.89 & 1802.58 & 0.574 & 10.388 \\
 & & R1 & 3611.92 & 3621.12 & 3605.91 & 3582.67 & 0.807 & 29.104 \\
 & KVLCC2 & S & 2025.11 & 2018.75 & 2009.71 & 1988.26 & 1.334 & 26.816 \\
 & & R1 & 4371.42 & 4347.51 & 4390.60 & 4444.32 & 1.529 & 67.146 \\
 & BC & S & 774.04 & 784.54 & 763.94 & 742.56 & 3.499 & 26.730 \\
 & & R1 & 1609.60 & 1597.42 & 1592.13 & 1588.07 & 0.319 & 5.077 \\
\hline
\end{array}
$$

$$
\begin{array}{|c|c|c|c|c|c|c|}
\hline
 & \text{Ship} & \text{Surface Condition} & \phi_3 & \phi_2 & \phi_1 & \phi^{21}_{\text{ext}} & \text{GCI}_{21}, \% & U_T \\
\hline
 & KCS & S & 0.7269 & 0.7279 & 0.7293 & 0.7319 & 0.451 & 0.0033 \\
 & & R1 & 0.5457 & 0.5442 & 0.5452 & 0.5466 & 0.335 & 0.0018 \\
 & KVLCC2 & S & 0.4596 & 0.4600 & 0.4573 & 0.4569 & 0.114 & 0.0005 \\
 & & R1 & 0.3107 & 0.3116 & 0.3099 & 0.3082 & 0.703 & 0.0022 \\
 & BC & S & 0.5312 & 0.5276 & 0.5328 & 0.5444 & 2.719 & 0.0145 \\
 & & R1 & 0.3590 & 0.3590 & 0.3591 & 0.3591 & 0.007 & 0.0000 \\
\hline
\end{array}
$$

Table 9. The obtained simulation uncertainties ($U_{SN}$) in the prediction of $P_D$ ($U_{P_D}$), $n$ ($U_n$), $T$ ($U_T$) and $J$ ($U_J$).

$$
\begin{array}{|c|c|c|c|c|c|c|}
\hline
 & \text{Ship} & KCS & KVLCC2 & BC \\
\hline
\text{Surface condition} & U_{P_D}, \text{MW} & U_{P_D}, \% & U_{P_D}, \text{MW} & U_{P_D}, \% & U_{P_D}, \text{MW} & U_{P_D}, \% \\
\hline
S & 0.839 & 3.409 & 0.340 & 1.906 & 0.297 & 4.413 \\
R1 & 0.692 & 1.068 & 0.653 & 1.167 & 1.506 & 7.421 \\
\hline
\text{Surface condition} & U_n, \text{rpm} & U_n, \% & U_n, \text{rpm} & U_n, \% & U_n, \text{rpm} & U_n, \% \\
\hline
S & 0.341 & 0.343 & 0.510 & 0.720 & 2.918 & 2.932 \\
R1 & 0.558 & 0.475 & 0.145 & 0.154 & 2.331 & 1.791 \\
\hline
\text{Surface condition} & U_T, \text{kN} & U_T, \% & U_T, \text{kN} & U_T, \% & U_T, \text{kN} & U_T, \% \\
\hline
S & 60.185 & 3.323 & 26.819 & 1.334 & 60.185 & 3.323 \\
R1 & 66.890 & 1.855 & 93.365 & 2.126 & 66.890 & 1.855 \\
\hline
\text{Surface condition} & U_f & U_f, \% & U_f & U_f, \% & U_f & U_f, \% \\
\hline
S & 0.0047 & 0.638 & 0.0012 & 0.273 & 0.0180 & 3.374 \\
R1 & 0.0019 & 0.348 & 0.0045 & 1.440 & 0.0073 & 2.041 \\
\hline
\end{array}
$$
4.2. Validation Study

Relative deviations between numerically obtained and extrapolated results are calculated using the following equation:

\[ RD = \frac{\phi_{CFD} - \phi_{EX}}{\phi_{EX}} \cdot 100\% \]  
(15)

where \( \phi_{CFD} \) is the certain hydrodynamic characteristic obtained using CFD and \( \phi_{EX} \) is the certain hydrodynamic characteristic obtained using the ITTC 1978 Performance Prediction Method (PPM) and experimental results [30].

The obtained \( C_T \) for full-scale KCS and KVLCC2 is validated within [16] through comparison of the obtained numerical results with extrapolated values using original ITTC 1978 PPM, based on Equation (9). Within ITTC 1978 PPM, \( C_T \) is determined using the ITTC 1957 model-ship correlation line. In Table 10, the validation of the numerically obtained \( C_T \) for the smooth surface condition is presented. As can be seen from Table 10, the obtained results are in satisfactory agreement with the extrapolated results, i.e., the highest RD is obtained for BC and it is equal to \(-4.338\%\).

Table 10. The validation study for \( C_T \).

| Ship          | \( C_T \)  | RD, % |
|---------------|------------|-------|
|               | CFD        | EX    |       |
| KCS [16]      | 2.081      | 2.053 | 1.376 |
| KVLCC2 [16]   | 1.795      | 1.724 | 4.107 |
| BC            | 2.197      | 2.296 | -4.338|

The numerically obtained open water characteristics for all three propellers have been validated, with the towing tank results published in the literature [29,31,32]. It should be noted that CFD simulations of OWT are performed in full-scale, while experimental OWT are performed in model scale. Towing tank tests for all three investigated propellers are performed at \( Rn \) above \( Rn = 2 \cdot 10^5 \), as prescribed by ITTC [30]. In Figure 7, the comparison between the numerically and experimentally obtained open water characteristics is presented. From this figure, it can be seen that numerically obtained \( K_{TO} \), \( 10K_{QO} \) and \( \eta_O \) are in satisfactory agreement with the experimentally obtained ones. Slightly higher RD between numerically and experimentally obtained \( K_{TO} \) and especially \( 10K_{QO} \) is obtained at lower \( J \) values, however, at higher \( J \) values, these RD are significantly lower.

The obtained results of the validation study for \( P_D \) and \( n \) are presented in Table 11, from which it can be concluded that satisfactory agreement is obtained. The highest obtained RD between numerical and extrapolated \( P_D \) is obtained for KVLCC2 and it is equal to \(-5.701\%\), while the highest obtained RD for \( n \) is obtained for BC and it is equal to \(-1.786\%\). The validation study for ship propulsion characteristics is presented in Table 12. From Table 12, it can be seen that the obtained RD for \( J \) are lower than 3.7\%, for \( K_T \) are lower than 2.9\% and for \( K_Q \) are lower than 6.2\% for all analyzed ships. It should be noted that slightly higher RD for \( J \) is obtained only for BC, and this can be attributed to the application of body force method. However, this RD is in line with previously published studies dealing with CFD simulations of SPT where the virtual disk model is applied [40,41]. The obtained RD for \( \eta_O \) are lower than 3.1\%, for propeller efficiency behind ship (\( \eta_R \)) are lower than 3.8\%, for \( \eta_R \) are lower than 2.9\% and for \( \eta_D \) is lower than 6.2\%. It should be noted that slightly higher RD for \( \eta_D \) is obtained only for KCS. However, in [42] where the authors carried out full-scale SPT for KCS using discretized propeller, \( \eta_D \) was equal to 0.766, which is also lower than the extrapolated result. From this result, the obtained \( \eta_D \) in this paper has RD equal to \(-3.394\%\). In Table 12, the validation for the obtained \( J \), \( K_T \) and \( K_Q \) for self-propulsion point is shown as well. It can be seen that the obtained RD for \( J \) are lower than 5.7\%, for \( K_T \) are lower than 4.1\% and for \( K_Q \) are lower than 3.4\% for all analyzed ships. Generally, the obtained RD presented in Tables 11 and 12 can be ascribed to different reasons. For example, insufficiently precise assessment of the nominal wake, as well as the
propeller performance in OWT can be related to the inaccurate assessment of $J$ for self-propulsion point, which then leads to inaccurate assessment of other propulsion characteristics. In addition to this, the modelling error should also be taken into account, as, in the body force method, the effect of propeller is modelled, rather than propeller itself. Furthermore, there is a numerical error as well, which is related to the applied mesh and time step. Lastly, there are also aspects regarding the applied PPM for the extrapolation of towing tank results. Namely, in [25] four different PPM are compared, and it was shown that extrapolated values can significantly vary with respect to the applied PPM. Thus, it was shown that for BC, extrapolated value of $P_D$ can vary up to 1.5%, for $n$ up to 0.4%, for $1 – t$ up to 0.5%, for $1 – w$ up to 6.3%, for $\eta_R$ up to 1.1% and for $\eta_B$ up to 2.6%. In addition to these variations, experimental uncertainty should also be considered. Considering all above mentioned aspects, it can be concluded that satisfactory agreement is achieved for $P_D$, $n$ and all propulsion characteristics.

![Graphs showing validation study for open water characteristics of KP505 (upper), KP458 (middle) and WB (lower).](image)

**Figure 7.** The validation study for open water characteristics of KP505 (upper), KP458 (middle) and WB (lower).

**Table 11.** The validation study for self-propulsion point.

| Ship  | $n_{\text{CFD}}$, rpm | $n_{\text{EX}}$, rpm | $RD$, % | $P_{D, \text{CFD}}$, MW | $P_{D, \text{EX}}$, MW | $RD$, % |
|-------|------------------------|----------------------|---------|-------------------------|--------------------------|---------|
| KCS   | 99.341                 | 100.359              | -1.014  | 24.624                  | 25.511                    | -3.476  |
| KVLCC2| 70.858                 | 71.417               | -0.784  | 17.850                  | 18.929                    | -5.701  |
| BC    | 99.541                 | 101.351              | -1.786  | 6.725                   | 6.961                     | -3.392  |
Table 12. The validation study for propulsion characteristics.

| Propulsion Characteristic | KCS        | KVLCC2     | BC         |
|---------------------------|------------|------------|------------|
|                           | EX         | CFD (RD,%) | EX         | CFD (RD,%) | EX         | CFD (RD,%) |
| $1 - t$                   | 0.853      | 0.867 (1.613) | 0.810      | 0.820 (1.199) | 0.794      | 0.764 (3.722) |
| $1 - w$                   | 0.803      | 0.773 (3.476) | 0.695      | 0.668 (3.904) | 0.705      | 0.653 (7.418) |
| $\eta_H$                  | 1.062      | 1.122 (5.596) | 1.165      | 1.227 (5.130) | 1.126      | 1.171 (3.992) |
| $\eta_O$                  | 0.690      | 0.700 (1.485) | 0.620      | 0.600 (3.146) | 0.623      | 0.622 (0.112) |
| $\eta_B$                  | 0.698      | 0.702 (0.565) | 0.623      | 0.600 (3.752) | 0.642      | 0.623 (2.964) |
| $\eta_R$                  | 1.011      | 1.002 (0.906) | 1.005      | 0.998 (0.626) | 1.030      | 1.000 (2.855) |
| $\eta_D$                  | 0.741      | 0.787 (6.193) | 0.726      | 0.736 (1.539) | 0.722      | 0.729 (0.910) |
| $J$                       | 0.750      | 0.729 (2.786) | 0.472      | 0.457 (3.145) | 0.565      | 0.533 (5.734) |
| $K_T$                     | 0.161      | 0.165 (2.954) | 0.155      | 0.149 (4.055) | 0.179      | 0.183 (2.312) |
| $10K_Q$                   | 0.275      | 0.274 (0.477) | 0.187      | 0.180 (3.449) | 0.251      | 0.250 (0.609) |

5. The Impact of Hard Fouling on the Ship Performance

Within this section, the impact of hard fouling on the resistance, open water and propulsion characteristics is presented for three investigated ships. While detail investigation of the impact of hard fouling on resistance characteristics for KCS and KVLCC2 is presented in [16], within this study this impact is only briefly mentioned as emphasis is given to the impact of hard fouling on the ship performance, which is defined by propeller operating point.

5.1. The Impact of Hard Fouling on Resistance Characteristics

As demonstrated within [16,18] the impact of biofouling on each resistance component is different. Thus, the presence of biofouling causes the increase in $C_T$, decrease in $C_W$, while the impact of biofouling on $1 + k$ value is almost negligible. Consequently, it is valuable to study the increase in $R_T$ due to the presence of hard fouling through analysis of decomposed $R_T$ and the portion of each resistance component in $R_T$ for certain fouling condition. In Figure 8, decomposition of $R_T$ for three investigated ships and fouling conditions is presented. Additionally, within Figure 8 the portions of $R_F$, $R_{VP}$ and $R_W$ in $R_T$ are given. From Figure 8, it is clear that, for all analyzed ships, the portion of $R_F$ in $R_T$ increases, due to the presence of hard fouling, and this increase is the highest for KCS, which can be attributed to the ship speed. Namely, KCS is investigated at the highest speed and therefore $u_\tau$ values along the KCS hull are higher than $u_\tau$ values along the KVLCC2 and BC hulls. Since $k^+$ values and consequently $\Delta U^+$ values for given fouling condition and fluid properties depend only on $u_\tau$ values, those values are higher for KCS than for KVLCC2 and BC resulting in higher increases in $C_T$ [16]. Additionally, $C_T$ for rough surface condition at high $Rn$ value depends solely on $k/L$ value, i.e., relative roughness [16]. The portion of $R_{VP}$ in $R_T$ due to the presence of hard fouling has increased for KCS and BC, while for KVLCC2 this portion has decreased. Regardless of this, from Figure 8, it is clear that the absolute value of $R_{VP}$, due to the presence of hard fouling, has increased, which is expected, since the impact...
of biofouling on $1 + k$ value is minimal [16]. Finally, the portion of $R_W$ in $R_T$ due to the presence of hard fouling decreases for all analyzed ships and this decrease is the highest for KCS, which can be also attributed to ship speed. What is more, from Figure 8 it is clear that absolute values of $R_W$ due to the presence of hard fouling have decreased for all analyzed ships [16]. Generally, KVLCC2 is the most affected, due to the presence of hard fouling in terms of the increase in $R_T$, which can be seen from Figure 9. Thus, the increase in $R_T$ due to the presence of hard fouling for KVLCC2 ranges from 63.8% (R6) to 120.9% (R1), for BC ranges from 59.5% (R6) to 114.6% (R1) and for KCS ranges from 49.9% (R6) to 95.8% (R1). This can be mostly attributed to the portion of $R_V$ in $R_T$, since, due to the presence of biofouling $R_V$, significantly increases. The portion of $R_V$ in $R_T$ is the highest for KVLCC2 and for smooth surface condition this portion is equal to 99.46%, as $R_W$ of KVLCC2 is negligible [28]. However, beside the portion of $R_V$ in $R_T$, the ship speed also affects the increase in $R_T$, as already explained. Thus, the increase in $R_T$ due to the presence of hard fouling is only slightly lower for BC than for KVLCC2 and the portion of $R_V$ in $R_T$ for smooth surface condition is equal to 83.6%. It should be noted that the significantly lower increase in $R_T$ is obtained for KCS, as KCS has relatively large portion of $R_W$ in $R_T$ (for smooth surface condition this portion is equal to 24.7%). Due to the presence of hard fouling, $R_W$ decreases, and, therefore, the increase in $R_T$ for KCS is lower.

![Figure 8](image-url)  
Figure 8. Decomposition of $R_T$ for KCS (upper), KVLCC2 (middle) and BC (lower) for smooth and fouled surface condition.
5.2. The Impact of Hard Fouling on Open Water Characteristics

The impact of hard fouling (R1) on the propeller performance in open water conditions is presented in Figure 10. The obtained changes in $K_{TO}$, $K_{QQ}$ and $\eta_O$, due to the presence of hard fouling, are presented in Table 13. As can be seen from Figure 10 and Table 13, due to the presence of hard fouling $K_{TO}$ has decreased and $K_{QQ}$ has increased resulting in significant reduction in $\eta_O$. As fouling severity increases (i.e., from R6 to R1), fouling penalties related to decrease in $K_{TO}$ and increase in $K_{QQ}$ increase as well. Additionally, at higher $J$ the fouling penalty related to decrease in $\eta_O$ is higher. Therefore, it can be concluded that the ships operating at higher $J$ values will experience a greater reduction in $\eta_O$, i.e., propeller fouling penalty on the ship performance will be greater. Thus, due to the presence of hard fouling $\Delta K_{TO}$ values for KP505 at $J = 0.6$ range from $-6.22\%$ (R6) to $-12.05\%$ (R1), for KP458 at $J = 0.4$ range from $-7.44\%$ (R6) to $-14.45\%$ (R1) and for WB at $J = 0.48$ range from $-7.86\%$ (R6) to $-12.09\%$ (R1). An increase in $\Delta K_{QQ}$ values for KP505 at $J = 0.6$ range from 4.66\% (R6) to 11.37\% (R1), for KP458 at $J = 0.4$ range from 2.59\% (R6) to 7.46\% (R1) and for WB at $J = 0.48$ range from 3.77\% (R6) to 11.19\% (R1). Fouling penalties on the propeller performance in open water conditions can be ascribed to fouling impact on the skin friction and the pressure field. Thus, due to the presence of hard fouling on propeller surfaces wall shear stress ($\tau_w$) increases, while the pressure difference between pressure and suction sides of propeller is reduced, which can be seen from Figures 11 and 12. In Figure 11, the obtained $\tau_w$ distributions at KP505 surface at $J = 0.7$ for both smooth and R1 surface condition are shown. It is clear that due to the presence of hard fouling $\tau_w$ values at KP505 surface are significantly increased resulting in increase in drag coefficient of the blade section and consequently in $K_{QQ}$. In Figure 12 the obtained pressure distribution shown as distribution of pressure coefficient ($C_p$), which is defined as a ratio between pressure and $\frac{1}{2} \rho v^2_{in}$ at KP505 surface is presented. Since the magnitudes of $C_p$ at both pressure and suction sides of fouled KP505 are significantly reduced, the pressure difference between pressure and suction sides is reduced as well, resulting in a decrease in the lift coefficient of the blade section and, consequently, in $K_{TO}$.
Figure 10. The impact of hard fouling (R1) on KP505 (upper), KP458 (middle) and WB (lower) performance in OWT.

Table 13. The obtained changes in $K_{TD}$, $K_{QO}$ and $\eta_{O}$ due to the presence of hard fouling.

| Propeller | $K_{TD}$ | $K_{QO}$ | $\eta_{O}$ | $K_{TD}$ | $K_{QO}$ | $\eta_{O}$ | $K_{TD}$ | $K_{QO}$ | $\eta_{O}$ |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Surface Condition | $\Delta K_{TD}$% | $\Delta K_{QO}$% | $\Delta \eta_{O}$% | $\Delta K_{TD}$% | $\Delta K_{QO}$% | $\Delta \eta_{O}$% | $\Delta K_{TD}$% | $\Delta K_{QO}$% | $\Delta \eta_{O}$% |
| R1        | -12.05   | 11.37    | -21.03   | -14.45   | 7.46     | -20.39   | -12.09   | 11.19     | -20.93   |
| R2        | -10.77   | 9.56     | -18.55   | -12.81   | 6.11     | -17.83   | -11.18   | 9.75      | -19.07   |
| R3        | -9.24    | 7.66     | -15.69   | -11.66   | 4.69     | -15.62   | -10.10   | 7.65      | -16.49   |
| R4        | -8.13    | 6.49     | -13.73   | -9.72    | 3.81     | -13.03   | -9.39    | 6.34      | -14.79   |
| R5        | -6.85    | 5.30     | -11.54   | -8.20    | 2.99     | -10.87   | -8.47    | 4.75      | -12.62   |
| R6        | -6.22    | 4.66     | -10.39   | -7.44    | 2.59     | -9.77    | -7.86    | 3.77      | -11.21   |

Figure 11. The obtained $\tau_{w}$ distribution for smooth (left) and R1 (right) surface condition for KP505.
which propeller operates changes as well. Thus, the change in \( J \) on the propeller performance is higher. The absolute value of \( a \) is also important, as, for ships which operate at higher \( J \) values, the fouling penalty on the propeller performance is higher.

The increase in \( P_D \) due to the presence of hard fouling is dependent on many parameters. Thus, besides the portion of \( R_V \) in \( R_T \), \( k/L \) and ship speed, which are important for the increase in \( P_E \), it is also important at which \( J \) propeller operates and the way the propeller loading defined with \( K_T/J^2 \) is affected due to the presence of hard fouling. Namely, due to change in propeller loading, \( J \) value at which propeller operates changes as well. Thus, the change in \( J \) at which propeller operates as well as the absolute value of \( J \) is important, as, for ships which operate at higher \( J \) values, the fouling penalty on the propeller performance is higher.

After CFD simulations of resistance and open water tests are carried out, CFD simulations of SPT for smooth and fouled ships are performed. As said before, the fouling penalty on the ship performance should be considered through the change in \( P_D \) and \( n \). The obtained increases in \( P_D \) and \( n \) due to the presence of hard fouling are presented in Figure 13. From this figure, it is clear that for surface conditions R1, R2 and R3 KVLCC2 is most affected due to the presence of hard fouling, while for surface conditions R4, R5 and R6 the fouling penalties for KVLCC2 and BC are almost the same and higher than fouling penalties for KCS. The obtained increases in \( P_D \) due to the presence of hard fouling for KVLCC2 range from 90.7% (R6) to 213.4% (R1), for BC range from 90.6% (R6) to 201.9% (R1) and for KCS range from 75.0% (R6) to 163.2% (R1), while the obtained increases in \( n \) for KVLCC2 range from 16.7% (R6) to 32.6% (R1), for BC range from 16.6% (R6) to 30.7% (R1) and for KCS range from 9.4% (R6) to 18.2% (R1). It is clear that the obtained increases in \( P_D \) are significantly higher than the obtained increases in \( P_E \) due to the presence of hard fouling, which can be related with the decrease in \( \eta_{PD} \). This highlights the importance of the assessment of the impact of biofouling on \( P_D \) rather than on \( P_E \). The increase in \( P_D \) due to the presence of biofouling is dependent on many parameters. Thus, besides the portion of \( R_V \) in \( R_T \), \( k/L \) and ship speed, which are important for the increase in \( P_E \), it is also important at which \( J \) propeller operates and the way the propeller loading defined with \( K_T/J^2 \) is affected due to the presence of hard fouling. Namely, due to change in propeller loading, \( J \) value at which propeller operates changes as well. Thus, the change in \( J \) at which propeller operates as well as the absolute value of \( J \) is important, as, for ships which operate at higher \( J \) values, the fouling penalty on the propeller performance is higher.

5.3. The Impact of Hard Fouling on Propulsion Characteristics

After CFD simulations of resistance and open water tests are carried out, CFD simulations of SPT for smooth and fouled ships are performed. As said before, the fouling penalty on the ship performance should be considered through the change in \( P_D \) and \( n \). The obtained increases in \( P_D \) and \( n \) due to the presence of hard fouling are presented in Figure 13. From this figure, it is clear that for surface conditions R1, R2 and R3 KVLCC2 is most affected due to the presence of hard fouling, while for surface conditions R4, R5 and R6 the fouling penalties for KVLCC2 and BC are almost the same and higher than fouling penalties for KCS. The obtained increases in \( P_D \) due to the presence of hard fouling for KVLCC2 range from 90.7% (R6) to 213.4% (R1), for BC range from 90.6% (R6) to 201.9% (R1) and for KCS range from 75.0% (R6) to 163.2% (R1), while the obtained increases in \( n \) for KVLCC2 range from 16.7% (R6) to 32.6% (R1), for BC range from 16.6% (R6) to 30.7% (R1) and for KCS range from 9.4% (R6) to 18.2% (R1). It is clear that the obtained increases in \( P_D \) are significantly higher than the obtained increases in \( P_E \) due to the presence of hard fouling, which can be related with the decrease in \( \eta_{PD} \). This highlights the importance of the assessment of the impact of biofouling on \( P_D \) rather than on \( P_E \). The increase in \( P_D \) due to the presence of biofouling is dependent on many parameters. Thus, besides the portion of \( R_V \) in \( R_T \), \( k/L \) and ship speed, which are important for the increase in \( P_E \), it is also important at which \( J \) propeller operates and the way the propeller loading defined with \( K_T/J^2 \) is affected due to the presence of hard fouling. Namely, due to change in propeller loading, \( J \) value at which propeller operates changes as well. Thus, the change in \( J \) at which propeller operates as well as the absolute value of \( J \) is important, as, for ships which operate at higher \( J \) values, the fouling penalty on the propeller performance is higher.
Figure 13. The obtained increases in $P_D$ (upper) and $n$ (lower) due to the presence of hard fouling.

In order to study the differences in the obtained fouling penalties more detailly, the impact of hard fouling on propulsion characteristics should be investigated. Within Tables 14–16, the obtained impact of hard fouling on propulsion characteristics is presented. From the obtained results, it is clear that most of the propulsion characteristics are affected by the presence of hard fouling on the hull and propeller surfaces. However, from Tables 14–16, it is clear that the impact of hard fouling on $\eta_T$ is minimal, i.e., it is lower than 0.45% for all analyzed fouling conditions and ships. What is more, the impact of hard fouling on $1 - t$ is present, however, it is relatively low. Thus, due to the presence of hard fouling, the $1 - t$ value for KCS and KVLCC2 decreases, while for BC, it increases. It should be noted that the $1 - t$ value depends on many different parameters, i.e., on the fouling penalty related to increase in $R_F$, to propeller performance, as well as hull and propeller interaction. Obviously, the assessment of the effect of biofouling on $1 - t$ value is very complex. It should be noted that the obtained impact of hard fouling on $1 - t$ is within the obtained numerical uncertainty in the assessment of $R_F$ and $T$. Additionally, within the assessment of $1 - t$, a modelling error is present as well, and it is related to turbulence modelling, modelling of the effect of ship propeller with body force method etc. Consequently, in order to assess this impact more accurately, numerical uncertainty as well as modelling error should be reduced through the application of more dense grids and lower time steps, as well as through the discretization of the propeller itself. Thus, a more accurate prediction of the impact of biofouling on $1 - t$ would be assessed. Therefore, based on the obtained results, it can be concluded that the impact of hard fouling on $1 - t$ is present, however, it is minimal. On the other hand, the impact of hard fouling on $1 - w$ is significant and detrimental, since it causes a decrease in the $1 - w$ value. Due to the presence of hard fouling, the obtained decreases in $1 - w$ values range from $-6.99\%$ (R6) to $-11.7\%$ (R1) for KCS, from $-6.29\%$ (R6) to $-10.1\%$ (R1) for KVLCC2 and from $-8.46\%$ (R6) to $-12.0\%$ (R1) for BC. The decrease in $1 - w$ can be attributed to slower flow around the propeller location for fouled ship, due to thicker boundary layer. The decrease in $1 - w$ has beneficial effect on $\eta_H$ (Equation (11)). Thus, due to the presence of hard fouling the obtained $\Delta \eta_H$ values range from $6.13\%$ (R6) to $11.3\%$ (R1) for KCS, from $6.11\%$ (R6) to $10.2\%$ (R1) for KVLCC2 and from $-11.3\%$ (R6) to $16.9\%$ (R1) for BC. Regardless of the fact that the decrease in $1 - w$ has beneficial effect on $\eta_H$, in general, the decrease in $1 - w$ has detrimental effect on $\eta_D$ and $P_D$. Namely, the decrease in $1 - w$ points out...
that the flow around propeller is slower and consequently propeller operating point is changed when compared with the smooth hull surface. Additionally, due to the presence of hard fouling, the nominal wake field behind the fouled ship is more inhomogeneous than nominal wake field behind the smooth ship, and because of this, the operating point is changed as well. Therefore, $J$ for self-propulsion point decreases since $v_A$ is lower. What is more, $J$ for self-propulsion point decreases because of the increase in $n$ as well. Due to the presence of hard fouling the obtained $\Delta J$ values for self-propulsion point range from $-15.0\%$ (R6) to $-25.3\%$ (R1) for KCS, from $-19.7\%$ (R6) to $-32.2\%$ (R1) for KVLCC2 and from $-21.5\%$ (R6) to $-32.6\%$ (R1) for BC. The decrease in the $J$ value is unfavorable, as KP 505, KP 458 and WB operate at $J$ lower than $J$, for which the $\eta_D$ function has a maximum value, which is common for all marine propellers. Consequently, due to the decrease in $J$ value, $\eta_O$ value decreases as well. The decrease in $\eta_O$ value is related to the detrimental impact of hard fouling on the propeller performance in open water conditions. Thus, the obtained decreases in $\eta_O$ values are higher than the obtained increases in $\eta_H$ values. Due to the presence of hard fouling the obtained $\Delta \eta_O$ values range from $-19.2\%$ (R6) to $-32.9\%$ (R1) for KCS, from $-21.1\%$ (R6) to $-37.3\%$ (R1) for KVLCC2 and from $-24.9\%$ (R6) to $-39.2\%$ (R1) for BC. The obtained decreases in $\eta_B$ values are similar to the ones obtained for $\eta_O$ values, as the impact of hard fouling on $\eta_B$ value is negligible. The presence of hard fouling, therefore, has two detrimental effects on $\eta_O$, because of detrimental effect on the open water characteristics and on the propeller operating point. These two effects can be equally meaningful. The importance of the impact of hard fouling on the propeller operating point can be seen from the obtained impact of biofouling on $K_T$ values. Even though the presence of hard fouling on the propeller surfaces causes the decrease in $K_T$, due to the impact of hard fouling on the propeller operating point, $K_T$ increases as $J$ for self-propulsion point of fouled ship is lower than $J$ for self-propulsion point of smooth ship. The obtained $\Delta K_T$ values due to the presence of hard fouling range from $26.8\%$ (R6) to $42.6\%$ (R1) for KCS, from $18.2\%$ (R6) to $24.2\%$ (R1) for KVLCC2 and from $15.1\%$ (R6) to $22.1\%$ (R1) for BC. The presence of hard fouling on hull and propeller surfaces causes an increase in $K_Q$ due to two reasons. Firstly, due to the presence of hard fouling on propeller surfaces $K_Q$ values in open water conditions are higher, and secondly due to the change in $J$ for self-propulsion point $K_Q$ value increases. The obtained increases in $K_Q$ values due to the presence of hard fouling range from $33.6\%$ (R6) to $59.6\%$ (R1) for KCS, from $20.0\%$ (R6) to $34.4\%$ (R1) for KVLCC2 and from $20.2\%$ (R6) to $35.3\%$ (R1) for BC. Finally, from Tables 14–16, it is clear that the presence of hard fouling on the hull and propeller surfaces causes a significant decrease in $\eta_H$, since decreases in $\eta_B$ are higher than increases in $\eta_H$. The obtained decreases in $\eta_D$ values due to the presence of hard fouling range from $-14.4\%$ (R6) to $-25.6\%$ (R1) for KCS, from $-16.1\%$ (R6) to $-31.0\%$ (R1) for KVLCC2 and from $-16.3\%$ (R6) to $-28.9\%$ (R1) for BC. Since the impact of biofouling on $\eta_D$ value is not negligible, the increases in $P_E$ and $P_D$ are not the same, and it is therefore necessary to investigate the impact of biofouling on $P_D$ rather than on $P_E$. It should be noted that the results presented in this subsection are obtained for the presence of biofouling on both propeller and hull surfaces. For clean propeller surfaces and fouled ship hull the obtained results, i.e., trends may not be the same. Thus, Song et al. [22], have obtained slight increases in $\eta_D$ values due to the presence of barnacles at hull surfaces, i.e., with a clean propeller. This can be attributed to the fact that the authors have obtained higher increases in $\eta_H$ due to the presence of barnacles than decreases in $\eta_B$ due to change in operating point. As a result of all this, the analysis of the impact of biofouling on propulsion characteristics is very important, i.e., the assessment of biofouling on the resistance characteristics and $P_E$ is not sufficient.
Table 14. The obtained impact of hard fouling on the propulsion characteristics for KCS.

| Propulsion Characteristic | S   | R1          | R2          | R3          | R4          | R5          | R6          |
|--------------------------|-----|-------------|-------------|-------------|-------------|-------------|-------------|
| $1 - t$                  | 0.867 | -1.67%     | -1.15%     | -1.07%     | -1.06%     | -1.28%     | -1.29%     |
| $1 - w$                  | 0.773 | -11.7%     | -10.8%     | -9.56%     | -8.54%     | -7.64%     | -6.99%     |
| $\eta_H$                | 1.122 | 1.249       | 1.243       | 1.227       | 1.214       | 1.199       | 1.191       |
| $\eta_O$                | 0.700 | -32.9%     | -30.2%     | -26.6%     | -24.8%     | -21.1%     | -19.2%     |
| $\eta_R$                | 1.002 | -0.40%     | -0.16%     | -0.29%     | -0.18%     | -0.11%     | -0.16%     |
| $\eta_D$                | 0.787 | -25.6%     | -22.8%     | -19.9%     | -18.8%     | -15.7%     | -14.4%     |
| $J$                      | 0.729 | 0.545       | 0.607       | 0.630       | 0.639       | 0.663       | 0.674       |
| $K_T$                    | 0.165 | 42.6%       | 39.6%       | 35.6%       | 32.0%       | 29.3%       | 26.8%       |
| $10K_Q$                  | 0.274 | 59.6%       | 53.7%       | 47.0%       | 42.7%       | 36.9%       | 33.6%       |

From the results presented in Tables 14–16, it can be concluded that the impact of hard fouling on the propulsion characteristics is the most pronounced for BC. Namely, the obtained changes in $1 - t$, $1 - w$, $J$, $\eta_H$, $\eta_O$ and $\eta_B$ due to the presence of hard fouling are largest for BC. What is more, the obtained changes in $\eta_D$ due to the presence of hard fouling for fouling conditions R4, R5 and R6 are the largest for BC as well. However, for fouling conditions R1, R2 and R3 the obtained decreases in $\eta_D$ are larger for KVLCC2 than for BC. For these fouling conditions, larger increase in $\eta_H$ which is obtained for BC has surpassed the larger decrease in $\eta_B$, which has also been obtained for BC and because of this the obtained decreases in $\eta_D$ are larger for KVLCC2. The largest changes in $\Delta K_T$ and $\Delta K_Q$ are obtained for KCS and this can be attributed to the fact that KCS operates at a higher $J$ value than KVLCC2 and BC. The largest decrease in the ratio between $K_T$ and $K_Q$ has been noticed, due to the presence of hard fouling for KCS as well. Nevertheless, amongst the investigated ships, the decrease in $\eta_O$ is the lowest, which can be attributed through the lowest obtained decrease in $J$ for KCS. Namely, $J$ for self-propulsion point decreases due to the increases in $n$ and $1 - w$. As can be seen from Figure 13,
the obtained increases in \( n \) due to the presence of hard fouling are significantly lower for KCS than for KVLCC2 and BC, while increases in \( 1 - w \) due to the presence of hard fouling are relatively similar for all analyzed ships, Tables 14–16.

Table 16. The obtained impact of hard fouling on the propulsion characteristics for BC.

| Propulsion Characteristic | S   | R1      | R2      | R3      | R4      | R5      | R6      |
|--------------------------|-----|---------|---------|---------|---------|---------|---------|
| \( 1 - t \)              | 0.764 | 0.787   | 0.785   | 0.782   | 0.781   | 0.779   | 0.779   |
|                          |      | 2.95%   | 2.76%   | 2.31%   | 2.22%   | 1.95%   | 1.88%   |
| \( 1 - w \)              | 0.653 | 0.575   | 0.579   | 0.583   | 0.590   | 0.595   | 0.598   |
|                          |      | -12.0%  | -11.3%  | -10.7%  | -9.68%  | -8.89%  | -8.46%  |
| \( \eta_H \)             | 1.171 | 1.369   | 1.356   | 1.341   | 1.325   | 1.310   | 1.303   |
|                          |      | 16.9%   | 15.8%   | 14.5%   | 13.2%   | 11.9%   | 11.3%   |
| \( \eta_O \)             | 0.622 | 0.378   | 0.396   | 0.416   | 0.436   | 0.456   | 0.468   |
|                          |      | -39.2%  | -36.4%  | -33.1%  | -30.0%  | -26.8%  | -24.9%  |
| \( \eta_R \)             | 1.000 | 1.000   | 0.999   | 1.001   | 0.999   | 0.999   | 1.001   |
|                          |      | -0.03%  | -0.09%  | 0.10%   | -0.14%  | -0.15%  | 0.10%   |
| \( \eta_D \)             | 0.729 | 0.518   | 0.536   | 0.559   | 0.577   | 0.596   | 0.61    |
|                          |      | -28.9%  | -26.4%  | -23.4%  | -20.8%  | -18.2%  | -16.3%  |
| \( J \)                  | 0.533 | 0.359   | 0.371   | 0.384   | 0.397   | 0.410   | 0.418   |
|                          |      | -32.6%  | -30.3%  | -27.8%  | -25.6%  | -23.1%  | -21.5%  |
| \( K_T \)                | 0.183 | 0.224   | 0.221   | 0.219   | 0.217   | 0.213   | 0.211   |
|                          |      | 22.1%   | 20.8%   | 19.5%   | 18.4%   | 16.4%   | 15.1%   |
| \( 10K_Q \)              | 0.250 | 0.338   | 0.331   | 0.321   | 0.314   | 0.306   | 0.300   |
|                          |      | 35.3%   | 32.5%   | 28.6%   | 26.0%   | 22.5%   | 20.2%   |

5.4. The Impact of Hard Fouling on the Flow Around Fouled Ship

The impact of hard fouling on the ship performance is investigated for three ships at their design speeds presented in Table 2. This resulted in different \( \tau_w \) distributions for smooth surface condition, Figure 14. From this figure it is clear that the highest \( \tau_w \) values are obtained for KCS, followed by BC and KVLCC2, which was expected as KCS is investigated at the highest design speed. As a result of this, the highest \( k^+ \) values are also obtained along the KCS hull, which can be seen from Figure 15. The obtained \( k^+ \) distributions for R1 fouling condition along the KCS, KVLCC2 and BC hull are shown. Since the highest \( k^+ \) values are obtained along the KCS hull, the highest \( \Delta U^+ \) values are present as well, which resulted in more significant increase in \( \tau_w \) and \( C_f \) for KCS than for BC and KVLCC2. The obtained \( \tau_w \) distributions for R1 fouling condition along the KCS, KVLCC2 and BC hull are presented in Figure 16.

Figure 14. The obtained \( \tau_w \) distributions for smooth surface condition along the KCS (upper), KVLCC2 (middle) and BC (lower) hull.
The increase in $\tau_w$ along the hull causes a decrease in the velocity in the turbulent boundary layer, i.e., turbulent boundary layer thickness increases due to the presence of roughness, which can be seen from Figure 17. In this figure, boundary layers, which are defined as the distance between the hull surface and the point where the axial velocity magnitude of the flow reaches the proportion of 0.99 of the ship speed, are shown for smooth and R1 surface condition. The boundary layers for KCS are given at locations $x = 30$ m and $x = 50$ m, for KVLCC2 at locations $x = 50$ m and $x = 70$ m and for BC at $x = 17.5$ m and $x = 35$ m. The obtained increases in the boundary layer thickness, due to the presence of biofouling or roughness, is in line with previously published experimental results in the literature [43,44].

As the boundary layer thickness increases it is obvious that the presence of hard fouling will cause the change in the nominal wake distribution. In Figure 18, the obtained contours of $1 - \frac{N_w}{J}$ for...
smooth and fouled ships (R1) in the propeller disc plane are shown. It should be noted that $1 - w_N$ is calculated as the ratio between axial velocity and ship speed [45]. From this figure, it is clear that the presence of hard fouling causes the significant reduction of the flow in the propeller disc plane for all three investigated ships. This reduction causes the change of $f$ for self-propulsion point and in that way, it affects propeller efficiency, as already explained.

![Figure 18. The obtained contours of $1 - w_N$ for smooth and fouled KCS (left), KVLCC2 (middle) and BC (right) with fouling condition R1 in the propeller disc plane.](image)

In addition to the impact of hard fouling on $\tau_{w}$ values, the presence of hard fouling causes the change in pressure distribution along the hull. However, this change mainly occurs in the area near the stern of fouled ship [16]. In Figure 19, the obtained $C_p$ distributions are presented for the area near the stern of investigated ships for smooth and R1 fouling conditions within CFD simulations of SPT. It should be noted that $C_p$ is obtained as a ratio between pressure and $\frac{1}{2} \rho v^2$. From this figure, it is clear that due to the presence of hard fouling pressure recovery at the stern is reduced and because of this $R_{vp}$ increases. Additionally, the impact of hull and propeller fouling on $C_p$ distribution at the rudder can be noticed, i.e., $C_p$ values at the rudder surface are slightly reduced.

![Figure 19. The impact of hard fouling on $C_p$ distribution for the area near the stern.](image)

In Figure 20, the obtained wave patterns around the hulls of the investigated ships for smooth surface condition and R1 fouling condition from CFD simulations of resistance tests are presented. From the comparison between wave pattern for smooth KCS and BC and wave pattern for KCS and BC fouled with R1, it can be noticed that due the presence of hard fouling wave elevations are reduced. On the other hand, wave elevations for KVLCC2 are almost the same for smooth and R1 fouling condition. The similar finding is noticed within [16,20]. Reductions of wave elevations and consequently $R_W$, due to the presence of hard fouling can be related to the increase in viscosity [15].
It can be concluded that the impact of hard fouling on the wave elevations is in agreement with the obtained decreases in \( R_W \), i.e., for KCS and BC this impact is relevant, while for KVLCC2 this impact is negligible.

![Image of wave patterns for KCS, KVLCC2, and BC](image)

**Figure 20.** The obtained wave patterns around KCS (left), KVLCC2 (middle) and BC (right).

6. Conclusions

In this paper, the impact of hard fouling on ship performance for three different ship types is investigated. This impact is investigated using the CFD simulations of resistance, open water and self-propulsion tests. The impact of hard fouling is represented through the modification of wall function, i.e., through the implementation of the Grigson \( \Delta U^+ \) model in the wall function within CFD solver. The verification study for grid size and time step is carried out, and grid and temporal uncertainties are estimated using GCI method. The verification study is performed for several key variables, i.e., \( K_{TO} \) and \( K_{QQ} \) for open water test and for \( P_D \), \( n \), \( T \) and \( J \) for self-propulsion test. Relatively low simulation uncertainties are obtained for all key variables. Thereafter, the obtained results of the performed CFD simulations for smooth surface condition are validated with the extrapolated towing tank results using the ITTC 1978 Performance Prediction Method. Satisfactory agreement is achieved for all resistance, open water and propulsion characteristics. After the verification and validation study, the impact of hard fouling on the ship performance is studied in terms of the impact on resistance, open water and propulsion characteristics. The obtained results demonstrated the significant impact of hard fouling on the increase in frictional resistance and viscous resistance, as well for all three ships. It should be noted that the viscous resistance of KCS is mostly affected due to the presence of hard fouling, which is ascribed to the fact that KCS is investigated at the highest speed. As a result of this, friction velocity along the KCS hull is higher than along the KVLCC2 and BC hulls. Higher \( \Delta U^+ \) values are obtained along the KCS hull in comparison with KVLCC2 and BC hulls, since the roughness Reynolds number and therefore \( \Delta U^+ \) are dependent on the friction velocity. However, wave resistance has decreased for KCS and BC, due to the presence of hard fouling, while for KVLCC2, it is almost negligible, and has remained almost the same as for smooth surface condition. The impact of hard fouling on the wave resistance is in agreement with the impact of hard fouling on the wave elevations, i.e., wave elevations for KCS and BC due to the presence of hard fouling are decreased, while for KVLCC2, it remained the same as for the smooth surface condition. Therefore, the most affected ship due to the presence of hard fouling, related to the fouling penalty on the ship resistance, is KVLCC2. Obviously, beside the ship speed the portion of viscous resistance in total resistance is very important for the estimation of the fouling penalty on the ship resistance, as well as the ratio \( k/L \). Significant detrimental effects due to the presence of hard fouling on the propeller performance in open water conditions are found. Thus, due to the presence of hard fouling on the propeller surfaces, \( K_{TO} \) decreases and \( K_{QQ} \) increases, which results in a significant decrease in \( \eta_D \). Namely, due to the
presence of hard fouling drag coefficient of propeller blade section increases, causing the increase in $K_{QO}$, and lift coefficient decreases, causing the decrease in $K_{TQ}$. The impact of hard fouling on the ship performance is best reflected through the impact on the delivered power and propeller rotation rate. From the obtained results, it is clear that increases in the delivered power are significantly larger than increases in the effective power, due to the presence of hard fouling for all three investigated ships. Therefore, the impact of hard fouling on propulsion efficiency must not be neglected, especially for fouled ship and propeller. The impact of hard fouling on the delivered power and propeller rotation rate is most pronounced for KVLCC2 for fouling conditions R1, R2 and R3, while for R4, R5 and R6, the obtained changes in the ship performance due to hard fouling are similar for BC and KVLCC2. This can be attributed to different impact of hard fouling on propulsion characteristics, as the fouling penalty on effective power for R4, R5 and R6 fouling conditions is higher for KVLCC2 than for BC. Namely, the additional important parameter that affects the impact of biofouling on the ship performance is the value of advance coefficient for self-propulsion point, since it is demonstrated that ships which operate at higher values of advance coefficient will be more affected in terms of propeller performance in open water conditions than ships which operate at lower values of advance coefficient. The impact of hard fouling on propulsion characteristics is presented for all three ships. From the obtained results it can be seen that propulsion characteristics of BC are mostly affected due to the presence of hard fouling, as the obtained changes in $1 - l$, $1 - w$, $f$, $H/Q$, $O/Q$ and $η_B$ due to the presence of hard fouling are largest for BC. Additionally, the obtained changes in $η_D$ due to the presence of hard fouling for fouling conditions R4, R5 and R6 are the largest for BC as well, while, for R1, R2 and R3, they are the largest for KVLCC2. The largest change in $K_T$ and $K_Q$ values due to the presence of hard fouling are obtained for KCS, which is expected as KCS operate with the highest advance coefficient. Finally, the impact of hard fouling on the flow around fouled ship is studied through the analysis of the impact on wall shear stress distribution, boundary layer thickness, nominal wake distributions, wave elevations and pressure distributions.

The paper provided several valuable insights related to the impact of hard fouling on the ship performance amongst different ship forms. Future study will be focused on investigations related to the impact of biofouling for systematic series of certain ship at different speeds, which will allow more comprehensive insight into the impact of biofouling on the ship performance will be assessed. In this paper, the investigations related to the impact of hard fouling on the ship performance are performed for the presence of hard fouling on both propeller and hull surfaces. If analyzed per unit area, the impact of propeller fouling condition on the ship performance is significantly more important than the impact of hull fouling condition. Therefore, the future studies will be also focused on the investigations related to the impact of solely propeller cleaning on the ship performance. Thus, relatively cheap and effective practice for achieving significant energy saving will be demonstrated. The optimization of maintenance schedule is an important operational measure for reducing ship emissions and the successful application of this measure relies on the accurate assessment of the impact of cleaning, i.e., the impact of fouling on the ship performance. Currently, these predictions are carried out using performance monitoring. However, performance monitoring has several important drawbacks [8], and the approach presented in this paper presents another way for this assessment. The important benefit of the proposed approach over the performance monitoring is that fouling effects on the ship performance can be analyzed independently of all other additional resistances, which may occur during sailing. However, since drag characterization studies are performed only for limited number of fouling conditions, CFD approach based on the modified wall function approach is limited to these fouling conditions. For more comprehensive assessment there is a need for further drag characterization studies. Additionally, the investigations performed in this paper are carried out for hull surface, which is treated as a uniformly rough surface with certain roughness length scale determined using Equation (6), as done in most of the conventional CFD studies dealing with biofouling. Since the fouling pattern along the immersed surface is not uniform, future studies will be focused on the investigations of the influence of fouling settlement on the ship performance. The locations of niche
areas along the hull surface will be found from the literature and in that areas, wall function model for
certain fouling condition will be implemented within the wall function of CFD solver. In that way,
more realistic fouling conditions will be analyzed, and the investigations regarding the partial cleaning
of the ship hull will be performed as well. Based on that, the proposed method can be used for the
assessment of fouling penalties on the ship performance, after the fouling condition of the hull and
propeller are determined by divers in the port.

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Abbreviations

AF antifouling
CFD Computational Fluid Dynamics
GCI Grid Convergence Index
GHG Greenhouse Gas
ITTC International Towing Tank Conference
MRF Moving Reference Frame
PPM Performance Prediction Method
OWT Open Water Test
RANS Reynolds Averaged Navier-Stokes
RD Relative Deviation
R1-R6 fouling conditions
S Smooth surface condition
SPT Self-Propulsion Test
VOF Volume Of Fluid
HRIC High Resolution Interface Capturing
FVM Finite Volume Method
SST Shear Stress Transport
KCS Kriso Container Ship
KVLCC2 Kriso Very Large Crude Carrier 2
BC Bulk Carrier
B breadth (m)
B smooth wall log-law intercept (-)
C\text{\textsubscript{B}} block coefficient (-)
C\text{\textsubscript{F}} frictional resistance coefficient (-)
C\text{\textsubscript{p}} pressure coefficient (-)
C\text{\textsubscript{T}} total resistance coefficient (-)
C\text{\textsubscript{W}} wave resistance coefficient (-)
c chord length at radius 0.75R (m)
D propeller diameter (m)
d shaft diameter (m)
F\text{\textsubscript{n}} Froude number (-)
J advance coefficient (-)
k roughness length scale (\text{\mu m})
k form factor (-)
k\text{\textsuperscript{+}} roughness Reynolds number (-)
K\text{\textsubscript{T}} thrust coefficient (-)
K\text{\textsubscript{Q}} torque coefficient (-)
K\text{\textsubscript{TO}} thrust coefficient in open water conditions (-)
\( K_{QQ} \)  
- torque coefficient in open water conditions (-)

\( L_{pp} \)  
- length between perpendiculars (m)

\( L_{wl} \)  
- length of waterline (m)

\( n \)  
- propeller rate of revolution (rpm)

\( S \)  
- wetted surface area (m²)

\( P \)  
- propeller pitch (m)

\( \bar{p} \)  
- mean pressure (Pa)

\( P_E \)  
- effective power (W)

\( P_D \)  
- delivered power at propeller (W)

\( Rn \)  
- Reynolds number (-)

\( R \)  
- propeller radius (m)

\( R_F \)  
- frictional resistance (N)

\( R_T \)  
- total resistance (N)

\( R_l \)  
- height of the largest barnacle (µm)

\( R_V \)  
- viscous resistance (N)

\( R_{VP} \)  
- viscous pressure resistance (N)

\( T \)  
- thrust (N)

\( T \)  
- time interval calculated as the ratio between ship length and speed (s)

\( T \)  
- draught (m)

\( t \)  
- thrust deduction fraction (-)

\( t \)  
- maximum thickness at radius 0.75\( R \) (mm)

\( \bar{u}_i \)  
- averaged velocity vector (m/s)

\( U^+ \)  
- non-dimensional mean velocity (-)

\( U_G \)  
- grid uncertainty (-)

\( U_J \)  
- numerical uncertainty in the prediction of \( J \) (-)

\( U_n \)  
- numerical uncertainty in the prediction of \( n \) (-)

\( U_{PD} \)  
- numerical uncertainty in the prediction of \( P_D \) (-)

\( U_T \)  
- time step uncertainty (-)

\( U_T \)  
- numerical uncertainty in the prediction of \( T \) (-)

\( u_t \)  
- friction velocity (m/s)

\( v \)  
- speed (m/s)

\( V \)  
- ship design speed (kn)

\( y^+ \)  
- non-dimensional wall distance (-)

\( w \)  
- wake fraction coefficient (-)

\( Z \)  
- number of blades (-)

\( %SC \)  
- percentage of the surface coverage (-)

\( \Delta \)  
- displacement (t)

\( \Delta U^+ \)  
- roughness function (-)

\( \Delta \phi \)  
- change in certain hydrodynamic characteristic (-)

\( V \)  
- displacement volume (m³)

\( \eta_B \)  
- propeller efficiency behind ship (-)

\( \eta_Q \)  
- quasi-propulsive efficiency coefficient (-)

\( \eta_H \)  
- hull efficiency (-)

\( \eta_O \)  
- propeller efficiency in open water (-)

\( \eta_R \)  
- relative rotative efficiency (-)

\( \kappa \)  
- von Karman constant (-)

\( \mu \)  
- dynamic viscosity coefficient (Pas)

\( \rho \)  
- fluid density (kg/m³)

\( \rho u' u' \)  
- Reynolds stress tensor (N/m²)

\( \pi_{ij} \)  
- mean viscous stress tensor (N/m²)

\( \tau_w \)  
- wall shear stress (N/m²)

\( \phi \)  
- certain hydrodynamic characteristic (-)

\( \phi_{ext} \)  
- extrapolated value (-)

EXP  
- experimental
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