International Journal of Scientific Research in Science, Engineering and Technology

Print ISSN - 2395-1990
Online ISSN : 2394-4099

Available Online at : www.ijsrset.com
doi : https://doi.org/10.32628/IJSRSET23102122

Study on Energy Efficient Operation by ship's Trim Optimization based on Computational Fluid Dynamics

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ARTICLEINFO

Article History :

Accepted: 01 Sep 2023
Published: 05 Sep 2023

Publication Issue :
Volume 10, Issue 5
September-October-2023

Page Number :
18-28

ABSTRACT

The prediction and optimization on resistance characteristics of marine vessels are getting important due to maritime environmental pollution, climate changes, impacts on human health near the coastal area and so on. Therefore, several methods were developed to reduce the fuel consumption of the vessel to improve the voyage performance. Among them, the trim optimization method is one of the popular methods to reduce the fuel consumption of ships. Trim optimization can be done by changing the trim by moving the cargo or ballast water and also can be applied on both new and existing ships. Moreover, this method needs not to change any structural arrangement or machinery of the vessels to apply it. Therefore, in this paper, this method was evaluated by using computational fluid dynamics with the help of commercial software Star-CCM+. Firstly, the numerical analysis of resistance data for KRISO Container Ship (KCS) in even keel were carried out and compared with experimental data from the model test to validate the results. After that, the optimum trim values for different service speeds were estimated using the calculated resistances. It is found that trim optimization at various speeds can be an effective and convenient way for vessels to decrease fuel consumption, emission of harmful substances and improve the energy efficiency by reducing the total drag force. Therefore, it could be one of the most practical ways to improve the environmental friendliness for both new and existing ships and also to fulfill the environmental related regulations.

Keywords: Energy Efficiency, Trim Optimization, KRISO Container Ship, Computational Fluid Dynamic (CFD), Environment

I. INTRODUCTION

The large share of all global trading is carried out by the marine transportation via ships in these days. There are thousands of ships operating and carrying the vast mass of cargoes around the world at any given time. And, the size and capacity of modern commercial vessels are becoming larger and larger together with their operating speed because of the global economic demand. Even though the marine transportation is the cheapest and most efficient mean to transport cargoes and passengers from one place to another with the cleaner operation compared to other, the shipping related emissions are investigated and found that these emissions are one of the major sources to the climate changes and global warming. International Maritime Organization (IMO) estimated that, in 2007, the approximately 2.4% of global emission of carbon dioxide which is about 870 million tonnes is responsible by the global shipping industry [1-2]. Therefore, IMO started implement the rules and regulations to address this issue and the member countries, societies, organizations and shipping companies are urged to find out the ways to reduce the emission from their ships.

As part of this issue, the IMO implemented a ship energy efficiency index called Energy Efficiency Design Index (EED) and operating management system called Ship Energy Efficiency Management Plan (SEEMP) to reduce the emission of greenhouse gases (GHG) from ships by introducing the IMO Resolution MEPC.203(62) in 2011 [3]. The EEDI regulation shall apply to all new ships and the regulation for SEEMP for both new and existing ships. Additionally, the calculation of Energy Efficiency Operational Indicator (EEOI) has been adopted by the IMO as voluntary instrument to indicate the operational efficiency based on ship's fuel consumption and transported cargo/passenger volume. By adopting these new requirements, the IMO aims to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of carbon dioxide (CO_2) emissions reduction consistent with the Paris Agreement temperature goals [4].

In this regard, this paper aimed to estimate the resistance characteristic of a container ship by using computational fluid dynamic method and to improve the voyage performance by investigating the influence of trim on ship resistance through calm water to find out the minimum drag force on hull at the certain service speeds. It will be the easiest and promising way to reduce the fuel consumption and emission of noxious gases from ship.

The remaining contents of this paper will be constructed as follows. Section 2 presents and reviews the related works on ship resistance prediction as literature review. Then, the methodology, the theory behind this paper, the introduction of the solution and the ship model are described in Section 3. In section 4, the simulation settings are presented. Afterwards, Section 5 describes and analyzes the experimental results Finally, the conclusion is given and the limitations and future work are discussed in Section 6.

II. LITERATURE REVIEW

Prediction of ship resistance characteristics is the key player in optimization of the ship performance during voyage. Therefore, many researchers have already been studying and developing many methods with various ways of approaches and theories to predict the resistance of the ships. There are several methods to investigate the resistance of the ships.

Among them, the empirical methods are the earliest and most common because these methods are relatively simple and easy to understand. The empirical methods like Holtrop-Mennen's Method are carried out by using years of tank testing data and plotting curves/charts to find out resistance coefficients [5]. By using these data, the resistance characteristic of a vessel can be predicted. Therefore, many researches were carried out with this method to estimate the influence of trimming position on ships. It is shown that the resistance of a bulk carrier can be reduced by about 14 percent by slightly trimming to stern depending on speed range and loading condition [6]. But this empirical method does not consider the effects of marine environment that can impact significantly on the performance of the vessel. Therefore, this method was enhanced and studied by many scholars by adding the marine environmental factors to predict the resistance data more accurately [7-12]. However, as the method was developed from the model tests performed in the 1970s and 1980s, the ship hull might be different from modern designs and the accuracy of the equations might be less.

The data-driven ship fuel consumption prediction model is also widely applied to investigate the voyage performance of the vessels by using data mining, deep learning, ensemble leaning, and other methods [13]. The relationship between speed of the vessels and the daily fuel consumption has been formulated by collecting the noon-report data provided by shipping company based on different size of container ships [14-15]. However, accuracy of the linear technique to predict fuel consumption of the vessel was questionable due to high dimensional and nonlinear nature of the ship fuel consumption data. Therefore, many researchers conducted experiments on other ship types and added environmental factors, sinkage and others into consideration to improve the accuracy [16-19]. Consequently, the data-driver ship fuel consumption model become gradually developed into nonlinear models and is able to obtain better prediction results [20-22].

Another method used to estimate the vessel performance is computational fluid dynamic (CFD) methods by approximating the integral and differential terms of the fluid dynamics control equations with the help of computer sciences [23-25]. With the development of computer technologies, the simulation-based prediction method become popular among scholars to investigate the resistance data for not only ocean-going vessels but also inland vessels [26-27]. Furthermore, the dynamic conditions of the vessels due to hydrodynamics while sailing the vessel in various speeds, especially trim and sinkage, were also studies by using CFD code to improve accuracy of this method [28].

III. RESEARCH METHODOLOGY

A. Trim Optimization Theory

The trim condition of a vessel has significant effect on hydrostatic and hydrodynamic properties of a vessel which are governing the resistance characteristic of this vessel. The hulls of the vessels are normally optimized for the contract speed with even keel position at the designed draught. However, the actual operating conditions are significantly different from that. Therefore, the optimum trim conditions of the vessels at different operating conditions with different draughts are needed for investigating to improve the fuel efficiency for every voyage.

The inclining condition of a vessel from the forwards and afterwards without heeling is called the trimming. Ship trim can be defined as the difference between the draught at the aft-perpendicular (T_A) and the draught at the forward perpendicular (T_F) [29].

$$\text{Trim} = T_F - T_A \tag{1}$$

The dependencies of ship performance on the trim is large because trim causes changes to wetted surfaces area which can alter the frictional resistance of the vessel. And, the different trimming could also transom the flow's field around the ship stern due to the transom submergence which can also improve the form resistance. Additionally, the wave resistance could also be change by trimming of the vessel.

There are two types of trimming which are trim by bow and trim by stern. If there is excessive trim by bow, it would reduce the propeller efficiency and the ship speed. Sometimes, the propeller would come out of water surface when the vessel is pitching and it would lead to undesirable hull vibration and engine unstable working load. If there is uncontrollable trim by stern, the maneuvering of the vessel will be difficult and the forward structure of the vessel such as sole plate would be damaged due to the slamming load when encountering the sea waves. Therefore, finding out the suitable trimming condition of the ship is an important task.

B. Simulation Solver

The performance of the vessel in different trimmed conditions is evaluated by many researchers in recent years with different theories and approaches because it is one of the promising methods to improve the operational efficiency and to reduce the fuel consumption and emission from ships. There are many methods to find out the optimum trim values such as model test, machine learning method, empirical method, CFD calculation, real ship trial test and so on.

In this study, the prediction of resistance of the ship will be performed with computational fluid dynamics (CFD) method using Star-CCM+ software. This software is a commercial simulation software for CFD calculation developed by Siemens Digital Industries Software.

C. Ship Model

The model used in this paper is KRISO Container Ship (KCS) which has 3600 TEU capacity and was developed by the Korea Research Institute for Ships and Ocean Engineering (KRISO) for research purpose. This model is very popular among researchers to perform various experiments and CFD tests and have been discussed in many workshops and conferences. As shown in table, the main particulars of the KCS vessel are 230 meters in length between perpendiculars, 32.2 meters in width at waterline, 19 meters in depth and 10.8 meters in designed draft. The towing tank experiment for this vessel was performed by KRISO research institute and the length of the model is 7.2786 m, width is 1.019 m, breadth is 0.6013, draft is 0.3418 and the scale factor is 1:31.599.

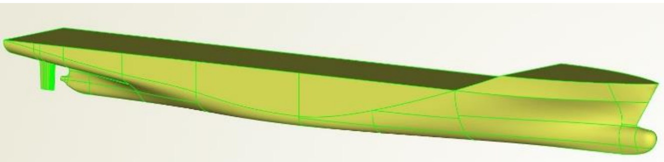

Figure 1
KCS Hull Model

TABLE 1

PRINCIPLE PARAMETERS FOR KCS CONTAINER SHIP

Main Particulars		Ship	Model
Scale ratio		1/31.599	
Length between perpendiculars	L_{PP} (m)	230	7.2786
Breadth	B (m)	32.2	1.019
Depth	D (m)	19	0.6013
Draft	T (m)	10.8	0.3418
Displacement volume	Δ (m^3)	52030	1.649
Wetted surface area	S_W (m^2)	9424	9.4379
Wetted surface area of rudder	S_R (m^2)	115	0.1152
LCB (%L_{PP}), fwd+		-1.48	-1.48

The CFD simulations in this study were performed under the same conditions as those of the model test. After that, the results of the simulations were compared and reviewed. According to the model tests, the various ship speeds were considered and the numerical calculations were carried out in free condition where trimming and sinkage were possible. In order to do so, the 823 kg is given as weight of the model, together with 3.5315 m, 0,0 m, -0.111 m as center of gravity. Therefore, the second moment of inertia became 136.7, 2725.117 and 2725.117 kg-m2 respectively, which were the same as in the model test.

TABLE 2

THE TEST CONDITION FOR THE SIMULATION

List	Test Conditions		
Pitch, Trim	Free		
Rudder	With		
Model speed (m/s)	2.196	1.922	1.647
Froude Number, F_r	0.26	0.227	0.195
Reynolds Number, R_e	1.26×10^7	1.10×10^7	9.42×10^6

Mass (kg)	823
Center of mass (m)	3.5315, 0.0, -0.111
Moment of inertia (kg-m^2)	136.7, 2725.117, 2725.117
Density of water (kg/m^3)	999.5

The simulations were carried out by varying the ship speed and trim conditions with 24 knots, 21 knots and 18 knots in speeds for the full-scale ship. Therefore, the relative speeds for the model were calculated as 2.196 m/s, 1.922 m/s and 1.647 m/s by using Froude Number (Fr) which are 0.26, 0.227 and 0.195 respectively. The Froude Number and Reynolds Number equations are as follows:

$$F_r = \frac{U}{\sqrt{g \cdot L_{PP}}} \tag{2}$$

$$R_e = \frac{U \cdot L_{PP}}{\nu} \tag{3}$$

where, U is the speed of the vessel, g is the gravitational acceleration, L_{PP} is the length between perpendiculars and ν is the kinematic viscosity [30].

D. Governing Equations

The coordination system using in this simulation was a Cartesian coordinate system in which the opposite direction of the flow is the positive X-axis, the port direction of the ship is the positive Y-axis and the opposite direction of gravity is the positive Z-axis. The governing equations for incompressible turbulent flow are the continuity equation and the Reynolds Averaged Navier-Strikes equation (RANS), which are expressed by equation;

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{4}$$

$$\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_i} - \rho \overline{u_i u_j}\right) + F_i \tag{5}$$

Where, U_i= (U, V, W) is the velocity component in the x_i= (x, y, z) direction, ρ is the fluid density, P is the static pressure, μ is the viscosity of the fluid, $-\rho\overline{u_i u_j}$ is the Reynolds stresses and F_i is body forces per unit volume, respectively.

IV. SIMULATION

The origin of the coordination system is located at the point where the rudder stock of the stern and the waterline at the stern meet. The calculation area for the simulations was defined following ITTC (2011) guidelines [31]; the inlet was placed two ship lengths in the bow direction from zero point to reduce the free running length of incident waves, the outlet was placed three ship lengths in the stern direction to avoid wave reflections, the side symmetry plane was placed two ship lengths in port direction, the height of domain is one ship length and the depth is two ship length from free surface to prevent the shallow water effect.

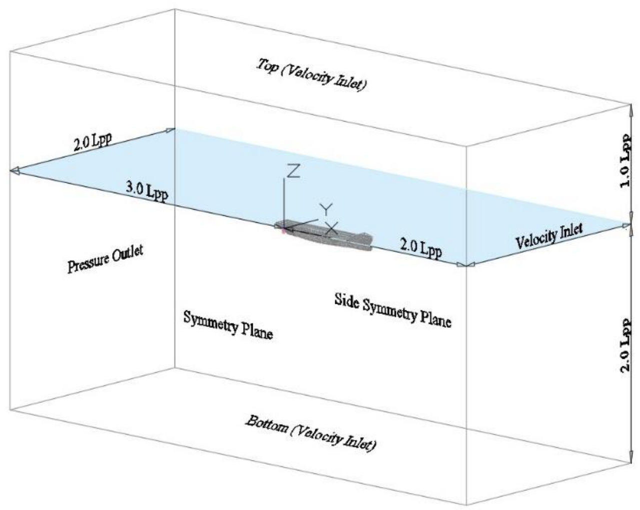

Figure 2
Coordination System and Computational Domain

The commercial software Star-CCM+ was used for grid generation and numerical calculations. The hull form of the model ship was provided in Parasolid format to the software and the computation domain was created by subtracting the model ship from the calculation area. For the simulation, the automated meshing tool was used to create the volume mesh and the grid was generated by using Trimmed Cell Mesher provided by Star-CCM+ program. And the grid size was set relatively small for a complex geometry area to capture the flow characteristic of the model and the large size of the grid was used for the simple flow area to reduce the calculation time. In addition, the prism layer technique was used in order to capture the boundary layer flow accurately on the hull surface by creating the six grid layers to get the required wall Y+ values. Y+ is the dimensionless wall distance value and it is important to have within the range of boundary layer treatment. The desired value for Y+ is to have 30<Y+<50. The trim angles for computation were made by rotating the hull form and then integrated to the computational domain.

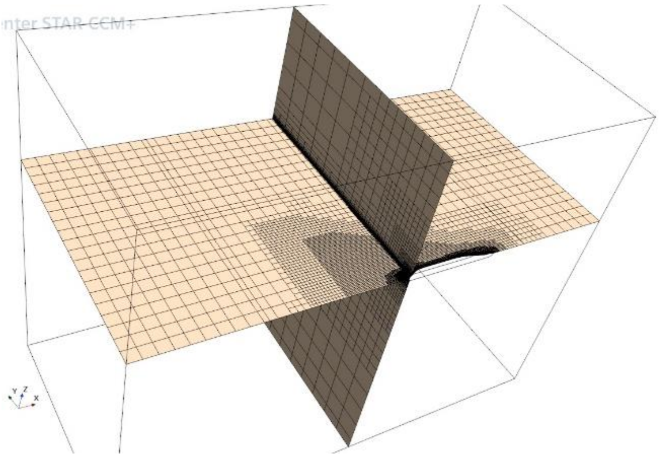

Figure 3-a

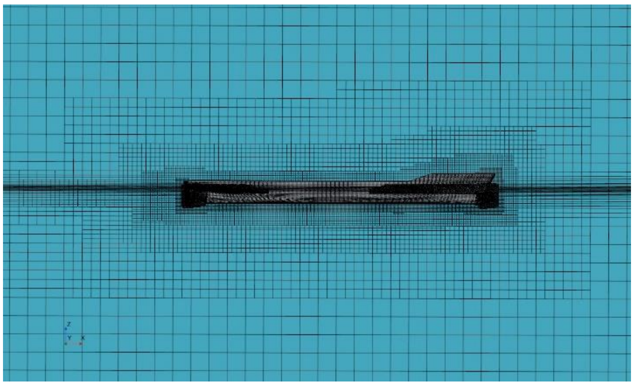

Figure 3-b
Grid System for Numerical Analysis

The grid resolution of 0.52 million cells was used to perform hull resistance simulations for all cases. There are a few variations of grid resolution for different trim angles; however, the variation was restricted to a few thousand cells to reduce the uncertainties. The quality of the mesh is important to achieved the valid simulation results. An invalid mesh can lead to no solution for simulation or cannot even be initialized the simulations. A mesh that contains the unclosed cells, zero area faces, zero or negative volume cells and so on can be considered as invalid mesh. Therefore, the mesh diagnostics are run to determine the validity of the mesh that will be used for the simulation by using diagnostic tool provided by the Star-CCM+ software. The diagnostic tool can report the entity count, mesh extents, mesh validity check, face validity, volume change and Fe cell quality for the generated mesh.

V. RESULTS AND DISCUSSION

This study aims to investigate the ship resistance incorporating the effect of dynamic trim and sinkage by using numerical simulation to determine the optimum trim. At first, calm water resistance simulation was performed to estimate drag force of the ship in the calm water while moving forward at the design speed. The resistance of the ship moving in the water can be generally divided into frictional resistance and wave-making resistance. The frictional resistance is the hull surface friction with the body of the water and influenced by the wetted surface area of the hull. The waves on the water surface were created by the bow of the ship while sailing forward. Thus, the energy from the ship transferred to the water as losses is called wave making resistance.

The simulations in calm water condition were performed for KCS model with different speeds at design draft to validate the results. The mesh resolution for simulation was 0.52 million cells and three cases with different Froude and Reynold numbers were simulated. And then, the results were compared with the experimental data. According to the comparison, the simulation results are good agreement with the experimental results.

A. Resistance results in even keel position

The simulation results for design speed of 24 knots with even keel at design draft are shown as follows;

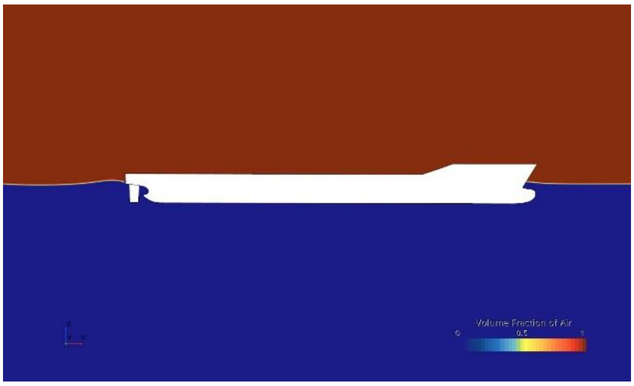

Figure 4
Free Water Surface around the Hull

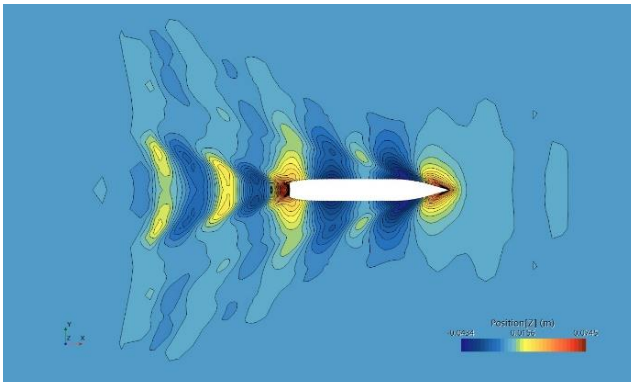

Figure 5
Wave Pattern around the Hull

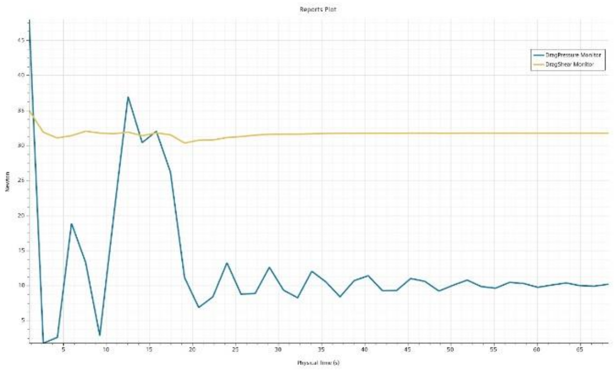

Figure 6
Shear and Pressure Drag Force Over Time

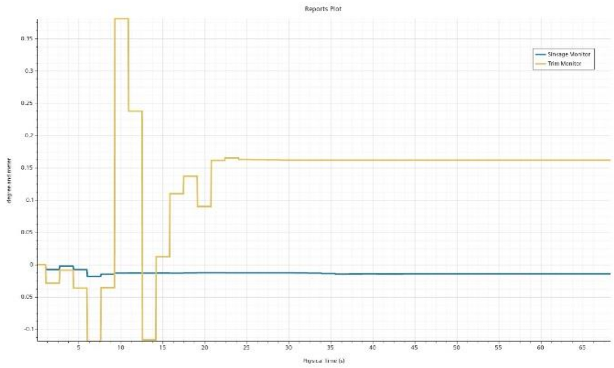

Figure 7
Trim and Sinkage Over Time

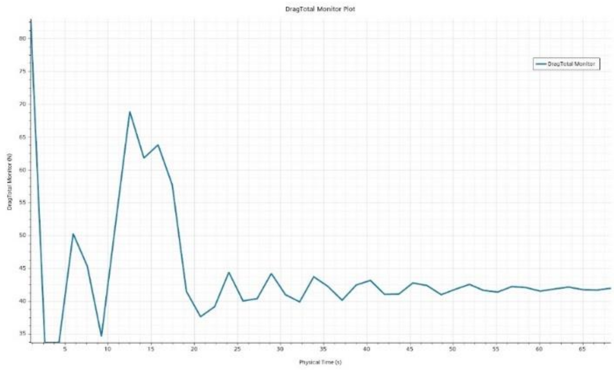

Figure 8
Total drag force over time

At the beginning of the simulation, the resistance data showed high oscillations. However, as the simulation progresses, the oscillations gradually reduced and reached to steady state after approximately 68 seconds of physical time. The total drag force of the vessel is 41.95 Newtons for the half body of the model in which the skin frictional resistance is 31.75 Newtons and the wave-making resistance is 10.2 Newtons as well. Therefore, the total drag force for full hull form will be 83.9 Newtons.

The resistance coefficient can be described as follow;

$$C_d = \frac{F_d}{\rho/_{2}v^2 A} \qquad (6)$$

Where, C_d is the resistance coefficient, F_d is the total drag force in Newton, v is the ship velocity in meter per second and A is the scaled area of ship hull and rudder in meter squared.

TABLE 3

SIMULATION RESULTS FOR KCS MODEL WITH EVEN KEEL POSITION AT DIFFERENT SERVICE SPEEDS

Speed (m/s)	Fr	Rn	$C_d \times 10^3$ (CFD)	$C_d \times 10^3$ (Experimental)	Deviation (%)
1.647	0.195	9.42×10^6	3.2	3.475	7.9
1.922	0.227	1.10×10^7	3.323	3.467	4.15
2.196	0.26	1.26×10^7	3.6443	3.711	1.8

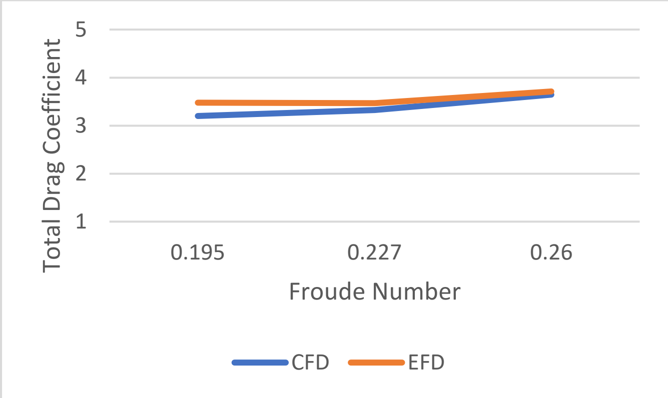

Figure 9
Total drag coefficient at various Froude number with even keel

The comparison between numerical calculations and experimental results is shown in the figure 9. According to the figure 9, it can be seen that the CFD results are in good agreement with Experimental results. However, the deviation from experiment results increased with the decreasing Froude number. Because, the cell resolution is rather coarse for this type of simulation. Therefore, the deviation of the simulation is expected to decrease with increasing mesh refinement. The required mesh resolution to capture this deviation was very high. So, it is not possible in this study due to the limitation of hardware and time. It is expected that the deviations can be reduced with increasing mesh quality in a future research study.

B. **Resistance results by various trims**

After validating the CFD results with the experimental results, the resistance characteristics of the vessel at different trim angles with various Froude numbers were investigated to find out the resistance values. The numerical simulations were carried out both trim by stern and trim by bow conditions and the negative trim angles mean the position of the stern downward (trim by stern), on the other hand, the positive trim angles represented trim by bow position. The simulation results are shown in table 4 and the graphical illustration can be seen in figure 10.

TABLE 4

COMPARISON OF TOTAL RESISTANCE FORCE AT DIFFERENT TRIM ANGLES WITH DIFFERENT SPEEDS AT DESIGN DRAFT

Trim Angle (deg)	Total Drag force (N)	Difference	Total Drag force (N)	Difference	Total Drag force (N)	Difference
	Fr: 0.26	(%)	Fr: 0.227	(%)	Fr: 0.195	(%)
-1.0	82.654	1.49	58.07	0.91	41.778	-1.00
-0.6	81.136	3.30	57.59	1.73	41.78	-1.00
-0.3	79.58	5.15	56.817	3.05	41.882	-1.25
0	83.904	0.00	58.602	0.00	41.366	0.00
0.3	79.79	4.90	57.813	1.35	40.18	2.87
0.6	79.57	5.17	57.888	1.22	41.434	-0.16

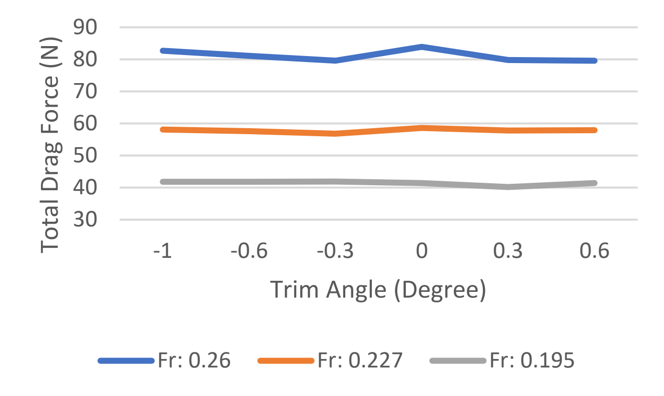

Figure 10
Total resistance, various trim and speed at design draft

In the figure 10, it can be clearly seen that the resistance characteristics of the vessel were changed due to trim effect. Generally, the vessel shows the significant reduction in total resistance in certain trim angle. The resistance characteristics for Froude numbers 0.26 and 0.227 are almost similar and -0.3 degree trim by stern for Froude number 0.26 can provide about 5 percent of reduction while Froude number 0.227 can reduce about 3 percent at the same trim angle. On the other hand, the Froude number 0.195 experienced a significant rise in resistance at -0.3 degree trim by stern, however, it can also decrease the resistance about 3 percent at 0.3 degree trim by bow condition. Therefore, trimming the vessel by stern performs better to reduce fuel consumption while the ship is sailing over 20 knots in speed. But it is better to trim the vessel by bow at slow steaming under service speed of 20 knots. Overall, the results of this study show that changing the trim angle of the ships can improve the ship performance significantly and reduce the emission of the noxious gases from ships.

VI. CONCLUSION

In this paper, the resistance prediction for a KCS model by using numerical computations with varying trim conditions and ship speeds. The simulations were performed at three different service speeds and compared the results with ship model experiments. After that, the trimming conditions of the vessel at various speeds were carried out to predict the optimum trim angles. This study confirmed that the performance of a vessels can be improved by changing the trim conditions for particular voyage condition by selecting the optimum trim angle. If the selecting of optimum trim is done properly, it can significantly increase the energy efficiency of the vessels, reduce harmful emission and fuel cost.

However, this study is only discussed and performed for the calm water conditions. The effect of waves and weather conditions in the real sea situation was not discussed in this paper. The effect of changing of propeller efficiency due to trimming conditions was also not mentioned. Furthermore, the ship maneuverability can also be affected by the changing of trim angle.

Overall, this study revealed that the ship trim optimization can significantly achieved the reduction of ship resistances by improving ship performance. It can also reduce the harmful emissions of noxious gases and fuel cost by operating the vessel at optimum trim. For the future work, the more various service speeds and draft conditions will be simulated with more grid refinement. And the simulations with full scale hull will also be investigated in order to find out the scale effects.

VII. ACKNOWLEDGE

I sincerely thank the Merchant Marine College, Shanghai Maritime University for supporting this research study. And I would like to express my gratitude to my supervisor, Prof. Yongxin Jin for his helpful suggestions, guidance, patience and support throughout this article.

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Cite this article as :

Soe Thiha, Prof. Yongxin Jin, "Study on Energy Efficient Operation by ship's Trim Optimization based on Computational Fluid Dynamics", International Journal of Scientific Research in Science, Engineering and Technology (IJSRSET), Online ISSN : 2394-4099, Print ISSN : 2395-1990, Volume 10 Issue 5, pp. 18-28, September-October 2023. Available at doi : https://doi.org/10.32628/IJSRSET23102122
Journal URL : https://ijsrset.com/IJSRSET23102122