Indonesian Journal of Maritime Technology (ISMATECH)
Vol. 2, Issue 1, June 2024
eISSN: 3025-518X
DOI: https://doi.org/10.35718/ismatech.v2i1.1062

Impact of Hull Breadth Modification on Tugboat Resistance: A Comparative Analysis Using Holtrop and CFD Methods

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KEYWORDS
Hull
Holtrop
CFD
Resistance
Power
Fuel Consumption

ABSTRACT – Estimating resistance experienced by a ship is crucial for determining the required engine power and fuel consumption to maintain a required speed. This study examines the comparative effects of altering the breadth of a tugboat from the approved initial design of 9 meters to a modified design of 8.6 meters, both utilizing the same engine power of 2x1018 HP. The analysis employs the Holtrop method, and Computational Fluid Dynamics (CFD). Using the Holtrop method, the largest differences at a speed of 14 knots were found to be 11.577 kN in resistance, 198.66 HP in engine power, and 0.617 g/kW.h in Specific Fuel Oil Consumption (SFOC), corresponding to a 5.141% difference in engine load. CFD results indicated the largest differences at 10 knots, with 9.009 kN in resistance, 102.47 HP in engine power, and 3.192 g/kW.h in SFOC, translating to a 5.034% difference in engine load. The modification of the breadth by 0.4 meters, while keeping the engine constant, impacts the resistance, engine power, and fuel consumption of the vessels.

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INTRODUCTION

Estimating the resistance is a critical aspect of ship design, as it determines the engine power and fuel consumption required to propel the ship at a desired speed. Ship resistance is affected by several factors, including the speed of the ship, the shape of the hull, and the ship's displacement. The magnitude of the resistance experienced by a ship directly impacts the power requirements of its engines. Effective power estimation involves calculating the total resistance and considering various factors within the propulsion system. This calculation is essential for determining the engine power needed to navigate the ship on the water's surface.

The engine's specifications and power output significantly influence the operational costs of the ship, with fuel consumption being a key determinant [1][2]. Proper engine power planning is necessary to optimize fuel efficiency during voyages, thereby reducing operational costs. A plethora of studies have been performed to optimize the performance of engine power of ships and reduce fuel cost. For example, researching for alternative fuel [3]–[7], optimal ship design [8], ship voyage optimization [9], application of energy saving device [10], and other methods are proposed and investigated

An illustrative example of the impact of hull dimension changes on engine performance is seen in a 360 HP tugboat with extention the length at the stern from 13.50 meters to 14.80 meters. After modifying the hull dimensions, re-analysis is performed to determine resistance and engine power, and the findings suggested the ship would need to increase engine power to 2x500 HP for optimal performance [11]. This example highlights the significance of examining the effects of changing the primary dimensions of ships. Moreover, dimension change is often found in all ship buliding process which are design process, fabrication, and docking including ship conversion. this change effect ship characteristic such as stability [12], speed [13], and structural strength [14], and others.

In this study, we investigate the impact of altering the breadth of a tugboat from the initially planned 9 meters to the produced design of 8.6 meters. Both designs use the same engine power, namely 2x759 kW or 2x1018 HP. The difference in breadth, despite having identical engine power specifications, is expected to affect the ship's resistance, engine power requirements, and operational costs.

The methodology adopted in this research involves two approaches: the Holtrop method, and Computational Fluid Dynamics (CFD) simulations. The Holtrop method provides a semi-empirical approach to estimating ship resistance based on hull form parameters, this method is easily implemented. However. It only can be aplied on simple hull shapes [15]. CFD simulations offer detailed insights into flow patterns and hydrodynamic forces around the hull. The main advantage of using CFD is that anaysis can be performed with various hull forms [16].

The significance of this study lies in its potential to inform ship design and operation decisions. Quantifying the differences in resistance, engine power, and fuel consumption between the two hull configurations can guide designers in optimizing hull geometry for better performance and efficiency. If a reduction in beam leads to significant increases in resistance and fuel consumption, designers may reconsider such modifications despite other potential benefits.

MATERIAL AND METHODS

Objective Ship

The tugboat used in this study was initially designed to be 9 meters breadth but measured 8.6 meters after production, resulting in a breadth change of 0.4 meters. Both versions have the same engine power: 2x1018 HP. Table 1 compares the dimensions of both versions, and Figure 1 shows the ship models designed using Maxsurf Modeller.

Table 1. Ship dimensions

Dimensions	B = 9 m	B = 8.6 m	Unit
LOA	28.474	28.474	m
LWL	26.72	26.72	m
LPP	25.5	25.5	m
T	2.5	2.5	m
H	3.62	3.62	m
∇	338.524	322.744	m^3
CB	0.580	0.576	-
CM	0.857	0.857	-
CP	0.680	0.675	-
CWP	0.893	0.890	-
KG	3.371	3.568	m
LCG	12.980	12.912	m from AP
LCB	12.906	12.899	m from AP

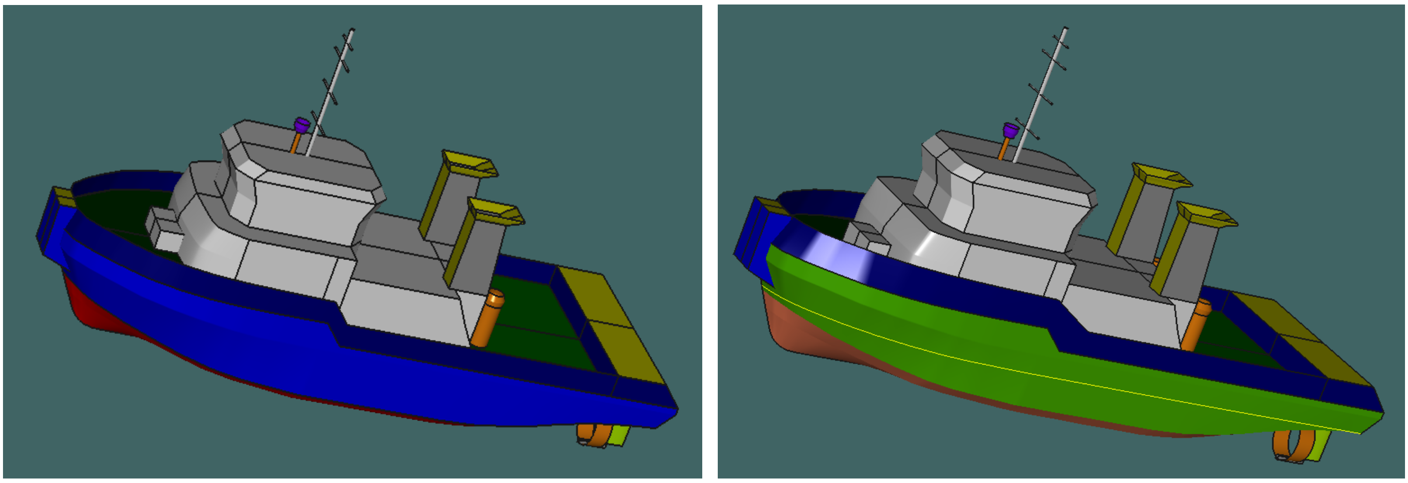

(a). 9 m (b). 8.6 m

Figure 1. Ship Models.

Ship Resistance and Power Estimation

Holtrop Method

The Holtrop method is used to estimate the resistance experienced by the ship through an approximate calculation formula. This method involves several components: Rf (friction resistance), Rapp (additional resistance), Rw (wave resistance), Rb (bulbous bow resistance), Rt (transom resistance), and Ra (model resistance). These components are essential to determine the total resistance (RT) acting on the ship's hull during movement. The detail of calculation using Holtrop method can be found here [15]. The tabulation of calculation result with the speed variation is shown in Table 2.

Table 2. Calculation results of Holtrop method

v (Knot)	9m (KN)	8.6m (KN)
10	70.37	64.18
11	83.84	76.44
12	98.55	89.86
13	114.74	104.67
14	132.23	120.66

Computational Fluid Dynamics (CFD) Method

In this study, the CFD (Computational Fluid Dynamics) method is used. This method has been implemented in various research topics in naval architecture [17]–[19]. This study follows the method that is implemented in the previous research. The analysis, conducted with Ansys 2022 R1 software (Fluid Flow Fluent), aims to simulate fluid flow and determine the drag or resistance when the ship moves on water.

Computational fluid dynamics software solves fluid dynamics behaviour using the Navier-Stokes equation, which is based on the conservation of mass equation (Eq. 1).

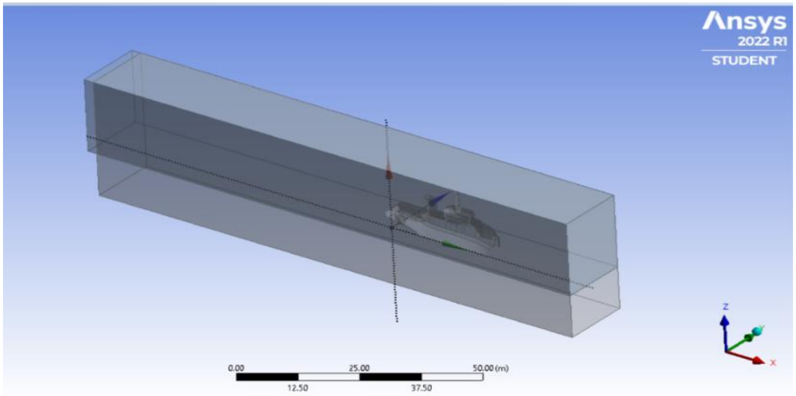
$$\frac{\delta\rho}{\delta t} + \frac{\delta\rho u_i}{\delta x_i} = 0 \tag{1}$$

The Navier-Stokes equations (Eq. 2) control momentum conservation, forces, acceleration, and fluid behaviour. These equations are solved numerically using methods such as finite volume or finite element to calculate fluid velocity and pressure fields.

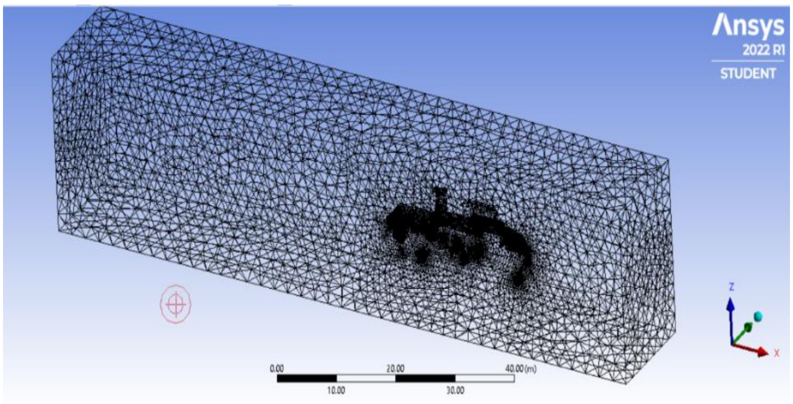
$$\frac{\delta u_i}{\delta t} + u_j \frac{\delta u_t}{\delta x_j} = f_i - (\frac{1}{\rho}\ \frac{\delta_p}{\delta x_j}) + (\frac{1}{\rho}\ \frac{\delta \tau_y}{\delta x_j}) \tag{2}$$

Where u_i is the velocity vector, f_i are the external body forces per unit mass, ρ is the density, p is the pressure and τ_y represents the viscous stress tensor.

To simulate ship resistance, Rhinoceros 6 software helps convert the surface shape from Maxsurf Modeller to a solid surface. The next process is to determine the computational domain which are boundary condition including boundary setting and meshing. The boundary condition has been discussed in the following research [20],[21]. Figure 2 reveals the boundary condition of the model and visualized using the software with respect to the wave contour as displayed in Figure 3. the example of the computational simulation result with respect to the total ship’s resistance has been shown in Table 3.



(a). Boundary setting



(b). Meshing

Figure 2. Boundary condition of ship model.

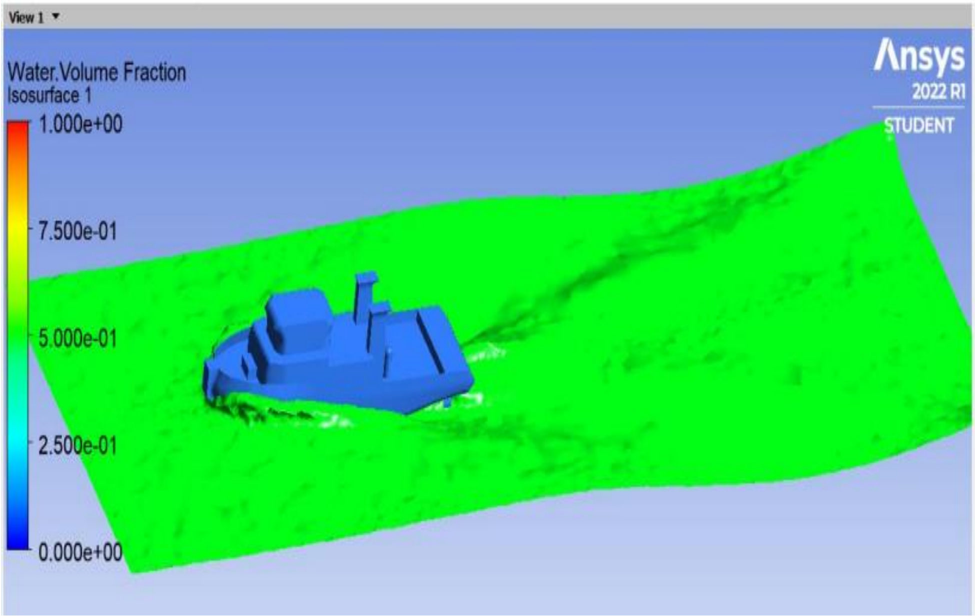


Figure 3. Visualization of wave contour on a ship of 8.6 m at a speed of 10 knots.

Table 3. Comparison of ship dimensions

v (Knot)	9 m (KN)	8.6 m (KN)
10	45.60	36.59
11	63.82	55.67
12	79.50	74.55
13	99.75	95.39
14	121.37	118.64

Fuel Consumption Calculation

Volume and Weight of Fuel

The Fuel weight calculations are carried out with the aim of knowing the volume of the fuel tank on the ship. The Calculation of fuel weight on a ship with a breadth of 9m. carried out are as follows:

S (distance traveled by the ship in nautical miles), namely the ship is planned to sail from Samarinda to Jakarta, where the ship is estimated to sail using a speed of 14 Knots and cover a distance of 819 nautical miles or 1516,788 km, then this distance must be converted into time so that it will An estimate of the travel time required for the ship to reach its destination is obtained by converting the ship's speed (Knots) into km/h so that if the ship sails at a speed of 14 knots, the ship will cover a distance of 25,928 km per hour (km/h). h), so that from this value we get an estimate of the travel time required by the ship to reach its destination in 58.50 hours or 2 days 11 hours. After knowing the ship's travel time per hour, the next step is to calculate the weight of the ship's fuel using Equation 3.

$$W_{FO} = SFR\ X\ BHP_{MCR}\ X\ \frac{S}{V_s\ X\ Sea\ Margine} \quad (3)$$

The next step is calculation of tank volume using the following formula:

$$V_{FO} = \frac{W_{FO}}{0.95} \quad (4)$$

Where SFR atau SFOC = 0.00013471 ton/kW.h (Engine Catalogue), BHP_{MCR} = 1492.36 kW (Power with Holtrop method at 14 Knot). and Sea Margine = 5%.

Fuel Tank Volume

The next step is to match the results of the calculation approach that has been obtained with the tank volume that has been installed on the ship, namely by measuring tank calibration as in Table 4, where tank calibration measurements have been carried out in previous research.

Table 4. Data on Fuel Tank Volume (F.O) on Ships with a Breadth of 9m and Ships with a Breadth of 8.6m for which Tank Calibration Measurements.

Tank	9 m (M^3)	8.6 m (M^3)
FO 1 (P)	17.152	15.979
FO 1 (C)	11.473	11.469
FO 1 (S)	17.152	15.979
D.FO (C)	4.785	4.785
FO 2 (P)	7.944	7.591
FO 2 (S)	7.944	7.591
FO 3 (P)	28.942	27.655
FO 3 (S)	28.942	27.655
Total	124.334	118.704

SFOC

Comparison of SFOC values was carried out to determine the efficiency of fuel consumption on ship engines with a breadth of 9m and ships with a breadth of 8.6m. As a comparison, the author used five variations of engine power, namely engine power with speeds of 10 Knots, 11 Knots, 12 Knots, 13 Knots and 14 Knots on each method. The method used to determine the amount of fuel consumption on a ship is by interpolating the SFOC graph obtained through a trusted website because the engine installed on the ship does not include an SFOC graph. where the steps used are by matching the engine load or (engine load) obtained from the calculated engine power with the SFOC value in Figure 4.

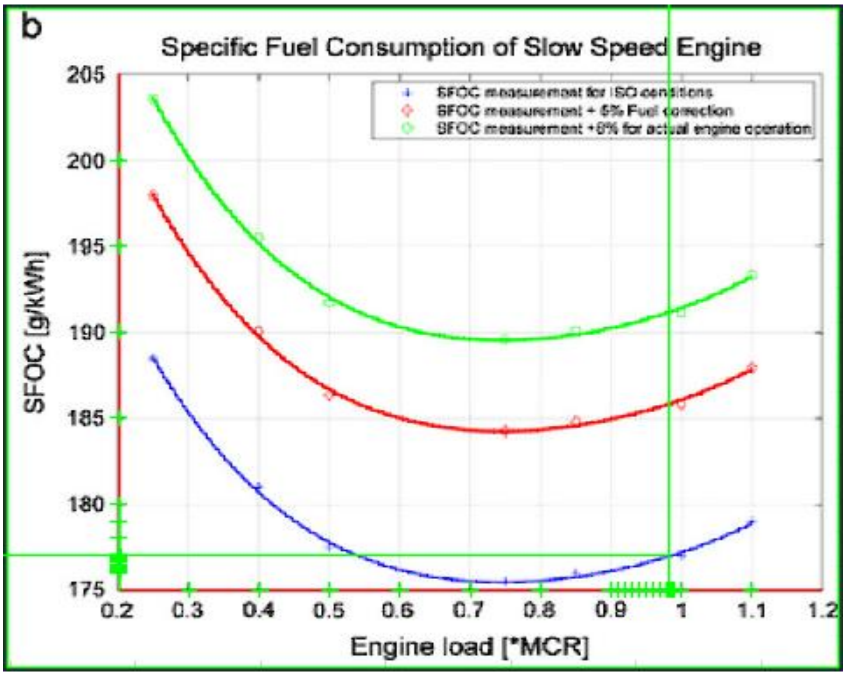


Figure 4. SFOC Interpolation on a Ship with a Breadth of 9m with Engine Load at a Speed of 14 Knots and Using the Holtrop Method.

RESULTS AND DISCUSSION

Ship Resistance

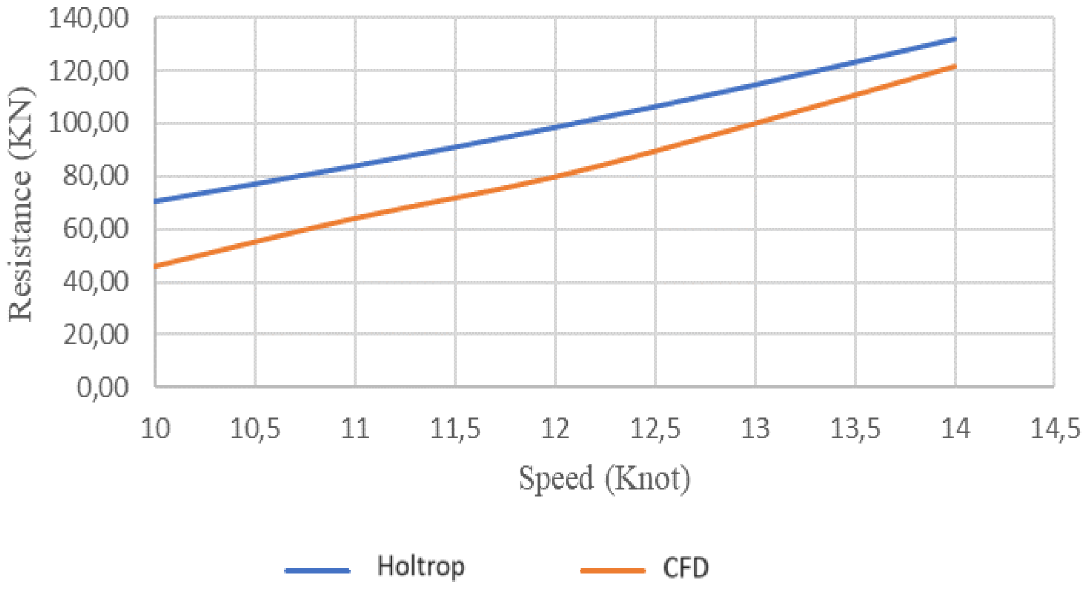


Figure 5. Comparison of Resistance on a 9m breadth Ship Using the Holtrop and CDF Methods.

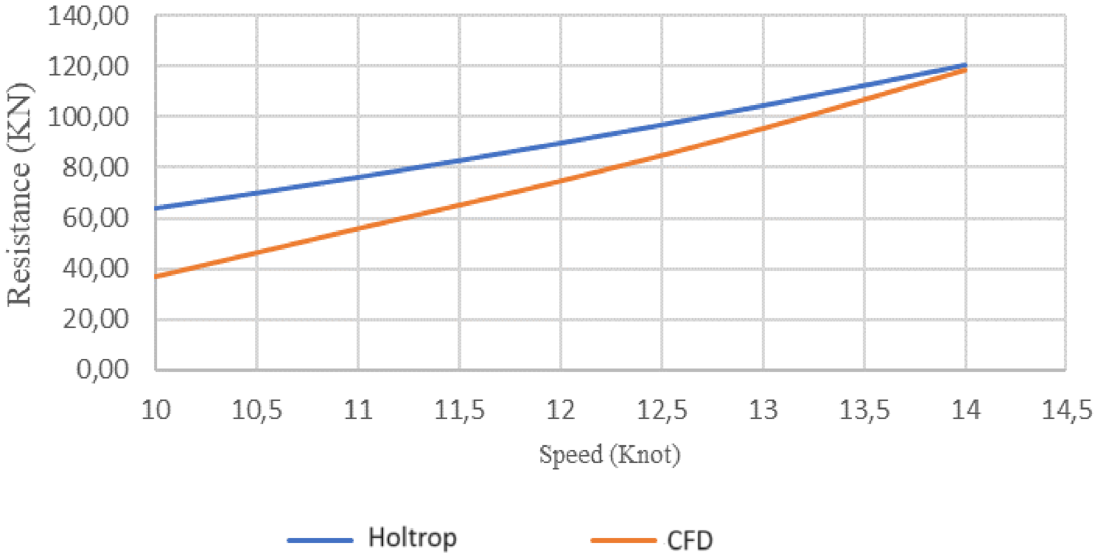


Figure 6. Comparison of Resistance on 8.6m breadth Ships Using the Holtrop Method and CFD.

In Figures 5 and 6, the resistance values for ships with breadths of 9m and 8.6m vary depending on the method used. For a 9m ship, the smallest resistance difference between the Holtrop and CFD methods is 10,865 KN at 14 knots, while the largest is 24,771 KN at 10 knots. For an 8.6m ship, the smallest difference is 2,015 KN at 14 knots, and the largest is 27,590 KN at 10 knots.

Power Engine Estimation

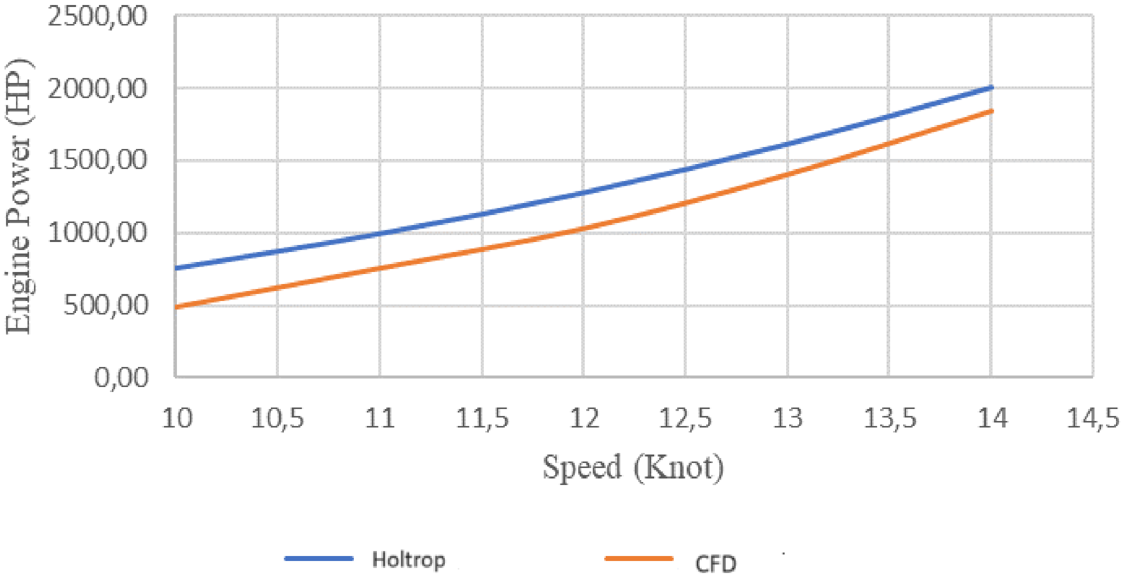


Figure 7. Comparison of engine power on a 9m breadth ship using the Holtrop method and CFD.

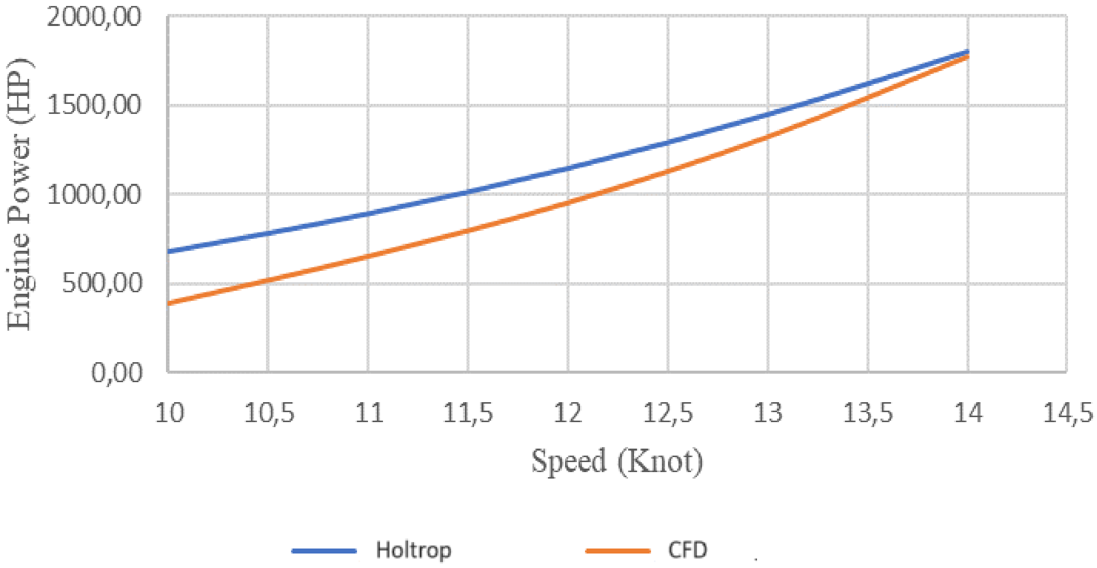


Figure 8. Comparison of engine power on a 8.6m breadth ship using the Holtrop method and CFD.

In Figures 7 and 8, each method shows a variation in engine power values for the same type of ship. For a 9m breadth ship, the Holtrop and CFD methods have the smallest power difference at 14 knots (164,437 HP) and the largest at 10 knots (267,784 HP). For an 8.6m breadth ship, the smallest power difference at 14 knots is 30,104 HP, and the largest at 10 knots is 294,428 HP.

Fuel Consumption

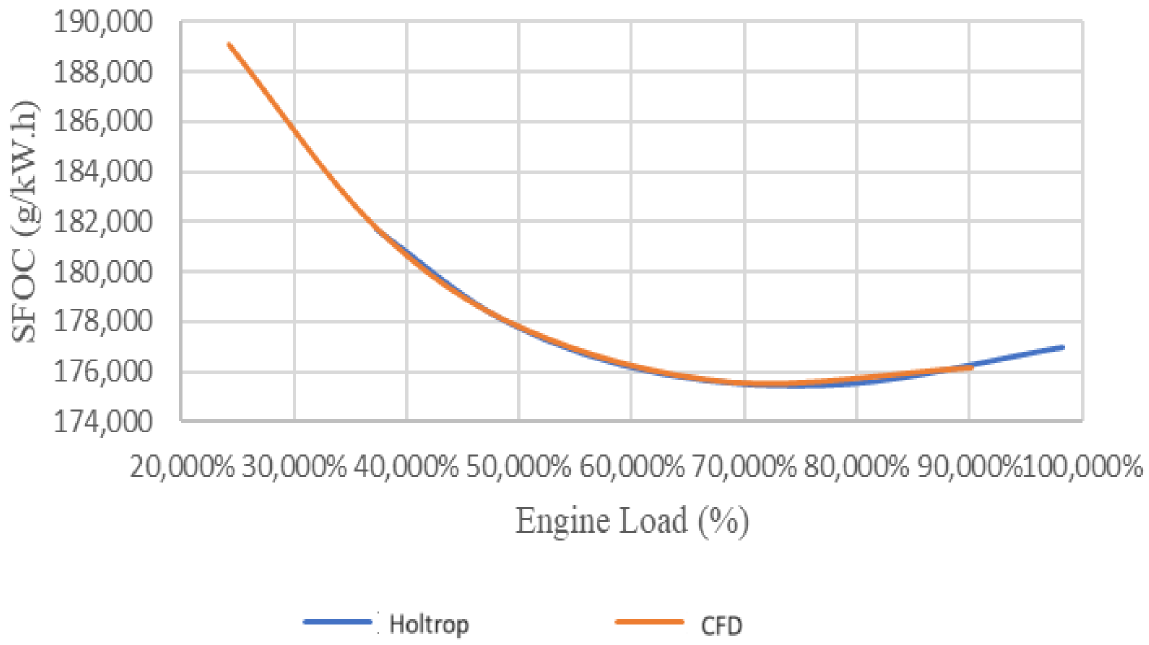


Figure 9. Graph of SFOC Value on a 9m breadth Ship Using the Holtrop Method and CFD.

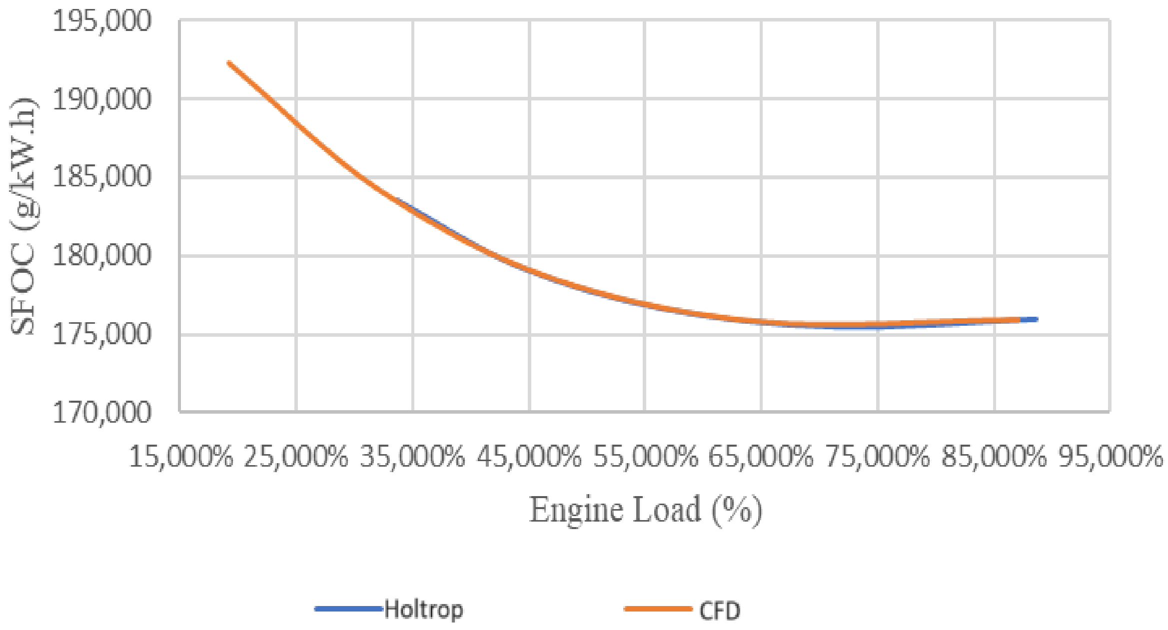


Figure 10. SFOC on a 8.6m breadth Ship Using the Holtrop Method and CFD.

Figures 9 and 10 show that ships with breadths of 9m and 8.6m have varying engine load and SFOC values depending on the method used. For 9m ships, the Holtrop and CFD methods show the smallest differences at 14 knots, with an 8.078% engine load difference and 0.847 g/kW.h SFOC difference. The largest differences occur at 10 knots, with 13.155% engine load and 7.354 g/kW.h SFOC. For 8.6m ships, the smallest differences at 14 knots are 1.479% engine load and 0.098 g/kW.h SFOC, while the largest at 10 knots are 14.463% engine load and 8.727 g/kW.h SFOC.

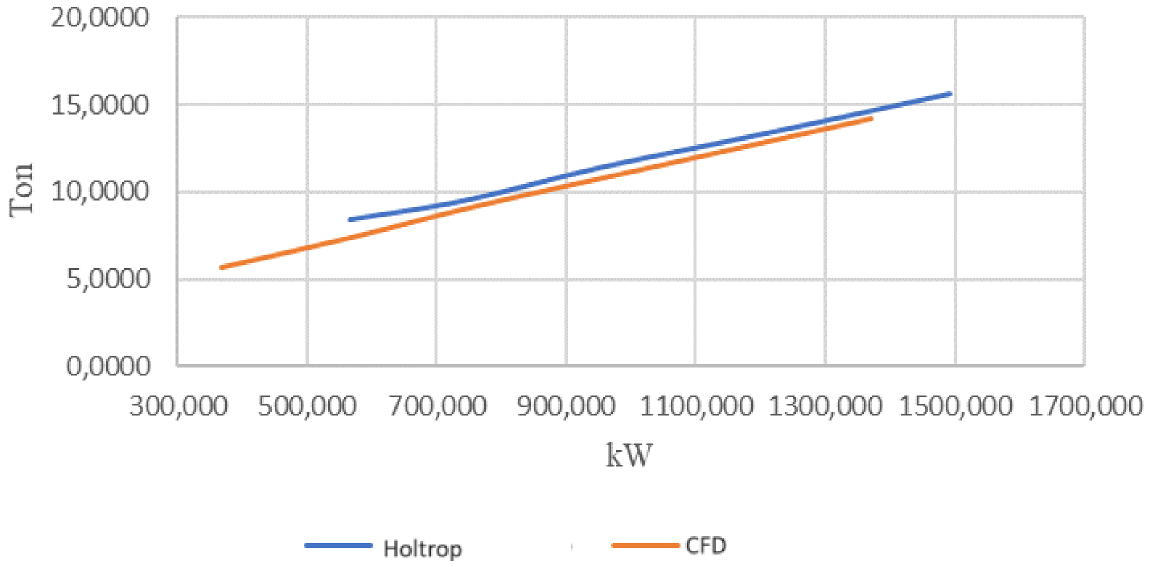


Figure 11. Comparison of Fuel Consumption on a 9m Breadth Ship Using the Holtrop Method and CFD Method.

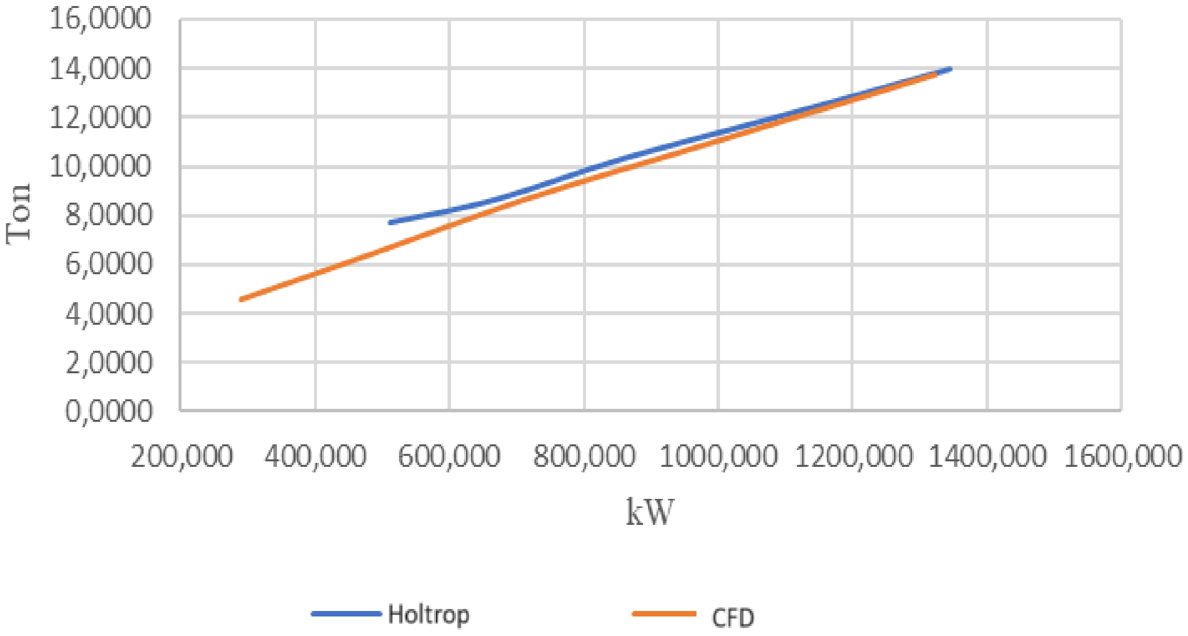


Figure 12. Comparison of Fuel Consumption on 8.6m breadth Ship Using the Holtrop Method and CFD Method.

From Figures 11 and 12, it is evident that ships with a breadth of 9m show significant differences in fuel consumption at each speed when comparing the Holtrop and CFD methods. The smallest fuel consumption difference at 14 knots is 1.3489 tons, while the largest is 2.7535 tons at 10 knots. For ships with a breadth of 8.6m, the largest difference at 10 knots is 3.0955 tons, and the smallest at 14 knots is 0.2407 tons.

CONCLUSION

In this study, resistance analysis of ships with breadths of 9m and 8.6m was conducted using both the Holtrop and CFD methods. The Holtrop method showed the smallest resistance difference at 10 knots (6,190 KN) and the largest at 14 knots (11,577 KN). Conversely, the CFD method found the largest difference at 10 knots (9,009 KN) and the smallest at 14 knots (2,727 KN). Engine power differences were smallest at 10 knots (56,544 kW) using Holtrop and largest at 14 knots (148,144 kW), while the CFD method showed the smallest difference at 14 knots (47,972 kW) and the largest at 10 knots (76,413 kW). Specific Fuel Oil Consumption (SFOC) analysis revealed the smallest difference using Holtrop at 13 knots (0.040 g/kW.h) and the largest at 10 knots (1,819 g/kW.h), while the CFD method had the smallest at 14 knots (0.255 g/kW.h) and the largest at 10 knots (3,192 g/kW.h). Fuel consumption differences were smallest at 10 knots (0.7663 tonnes) using Holtrop and largest at 14 knots (1.6266 tonnes). The CFD method showed the smallest difference at 14 knots (0.5184 tonnes) and the largest at 10 knots (1.1083 tonnes). Comparing the methods, the smallest fuel consumption difference at 14 knots was 1.3489 tonnes for the 9m ship and 0.2407 tonnes for the 8.6m ship, with the largest at 10 knots being 2.7535 tonnes and 3.0955 tonnes, respectively. This analysis highlights the impact of breadth and speed on ship resistance, engine power, SFOC, and fuel consumption.

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