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Comparative study of the effects of length on the resistance of a vessel

Blessed Godstime NWOKA *, Kingsley OLUDI and Awajimowa Emmanuel FELIX

Department of Marine Engineering and Offshore Engineering, Faculty of Engineering, Rivers State University, Port Harcourt.

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Abstract

In this study, a comparative analysis of the effects of vessel length on hydrodynamic resistance was performed. The research addressed the problem of optimizing hull length to reduce resistance, given its direct impact on fuel efficiency and emissions. Unlike previous studies focused on limited length ranges or specific hull types, this work systematically compared four Wigley hulls (125m, 350m, 370m, 390m) under identical saltwater conditions at 14.6 knots, using both Holtrop-Mennen and CFD (ANSYS Fluent) methods. Results showed total resistance increased with length: from 127.8 kN at 125m to 384.1 kN at 390m—a 188% increase. Frictional resistance rose steadily due to greater wetted surface area (82.1 kN to 360.2 kN), while wave-making resistance decreased from 48.4 kN to 30.5 kN as Froude number reduced. CFD results closely matched empirical predictions, with differences under 2.5%. The study concludes that frictional resistance dominates in longer vessels, outweighing wave resistance benefits. These findings provide critical insights for naval architects to balance length with other design parameters, enabling more energy-efficient vessel designs and supporting maritime sustainability goals. Recommendations include further research on different hull forms and scale effects.

Keywords: Hydrodynamics; Frictional Resistance; Wave-Making Resistance; Computational Fluid Dynamics (CFD)

1. Introduction

The relationship between a vessel's length and its resistance will remain a central concern in naval architecture, as vessel resistance directly influences fuel consumption, operational efficiency, and environmental impact. The process of ship design will always begin with the determination of principal dimensions, such as length, breadth, draft, and depth, since these parameters fundamentally affect hydrodynamic performance and economic viability. The length of a vessel, in particular, will continue to play a crucial role in shaping its resistance characteristics, especially when considered alongside other geometric ratios such as length-to-beam (L/B) and length-to-draft (L/T) ratios (Tat-Hien et al., 2023).

As the maritime sector strives to meet increasingly strict regulatory standards on energy efficiency and emissions, reducing resistance through optimal hull design will become even more significant. Ship resistance is typically divided into several components, including frictional resistance, wave-making resistance, and form resistance. The interplay between these components is governed by fundamental hydrodynamic principles, notably those described by Reynolds and Froude numbers, which relate to viscous and wave effects, respectively (Sheng, and Luo, 2017). The length of a vessel will influence both these dimensionless numbers, thereby affecting the overall resistance experienced at varying speeds.

The impact of length on resistance will not only be of theoretical interest but will also have practical implications for shipbuilders and operators. For instance, an increase in the L/B ratio has been shown to result in a gradual reduction

* Corresponding author: Blessed Godstime NWOKA

in total ship resistance, with pressure resistance exhibiting more significant changes than frictional resistance (Zhong, and Wen, 2022). This means that by carefully adjusting the length of a vessel in relation to its other principal dimensions, it will be possible to achieve notable improvements in performance and fuel efficiency.

The pursuit of optimal vessel length will also be driven by the need to balance hydrodynamic efficiency with operational requirements such as cargo capacity, maneuverability, and structural integrity. The complexity of this task will be further compounded by the necessity to adhere to international standards and regulations, which increasingly prioritize sustainability and emission reductions. Therefore, a comprehensive understanding of how length affects resistance will remain indispensable for the advancement of ship design and operation.

Research in this area will continue to employ a variety of analytical, experimental, and numerical methods. Computational approaches, such as those based on Reynolds-Averaged Navier-Stokes Equations (RANSE), will be particularly valuable for providing insights into the effects of length variations on resistance components and flow patterns around the hull (Liu, and Tao 2024). These methods, alongside towing tank experiments and dimensional analysis, will help to validate theoretical predictions and guide practical design decisions.

As the global shipping industry evolves, the economic and environmental imperatives for minimizing resistance through optimal vessel length will only grow stronger. This will ensure that the study of length effects on resistance remains a vibrant and essential field within naval architecture (Jinzi, 2017).

Maritime transport accounts for over 80% of global trade, yet inefficient vessel designs contribute to excessive fuel consumption and greenhouse gas emissions (IMO, 2023). While vessel length is recognized as a determinant of resistance, existing studies fail to provide a unified framework for predicting its effects across diverse hull forms and operational conditions. For example, shorter vessels may exhibit high wave-making resistance at certain speeds, while longer vessels face elevated frictional losses. This gap hinders the optimization of ship designs for energy efficiency. The proposed research will resolve these ambiguities by systematically analyzing how length influences resistance components under controlled hydrodynamic conditions.

The evaluation of ship resistance has evolved from traditional experimental methods to the use of advanced computational techniques. Early methods, such as those developed by Taylor, relied on extensive model testing and empirical series, with results published for a wide range of hull forms and principal dimensions. These methods allowed for the calculation of residual and frictional resistance components based on vessel length and other parameters, providing a foundation for subsequent research (Oludi and Nwoka 2024). More recently, computational fluid dynamics (CFD) has enabled detailed analysis of the effects of length on resistance, offering greater flexibility and accuracy in predicting resistance characteristics for various hull forms and operating conditions (Singh, 2024).

1.1. Influence of Hull Geometry on Resistance

(Taylor, as cited in Singh, 2024). conducted a numerical study to investigate the impact of different hull shapes on resistance characteristics. The study used a Reynolds-Averaged Navier-Stokes (RANS) solver to simulate flow around varying hull forms. Results showed that more streamlined hulls presented reduced wave resistance at higher speeds, while fuller forms induced more drag. (Wang et al 2021) investigated the resistance of vessels with different prismatic coefficients. Using CFD simulations, they showed that lower prismatic coefficients led to reduced total resistance, especially in lower Froude number ranges. Their conclusion suggested that hull geometry must be matched to intended service speed for optimal performance.

There is a significant knowledge gap in the current body of research, particularly regarding the comparison of resistance trends across vessels with lengths ranging from 125 meters to 390 meters. While individual studies have focused on smaller or larger vessels, there is a lack of systematic research that directly compares how resistance behaves in vessels of such varying lengths when subjected to identical operational and geometric conditions. This gap in understanding limits the ability to make generalized predictions about vessel resistance as it relates to size, speed, and other key factors. Such a comparison would offer valuable insights into the scaling effects of vessel length on resistance, which could significantly contribute to the optimization of vessel designs across different size categories.

This study addresses the existing gap in the literature by conducting a detailed analysis of four Wigley hulls, ranging from 125 meters to 390 meters in length. The research focuses on isolating the vessel length as the primary variable, while keeping other operational and geometric parameters constant. By doing so, the study seeks to understand how length influences the resistance trends of vessels within this specific range. The use of computational fluid dynamics (CFD) allows for a comprehensive and precise analysis of the hydrodynamic behavior of these hulls under identical conditions, providing new insights into the relationship between vessel length and resistance. This approach will contribute to filling the gap in knowledge regarding resistance trends across vessels of varying lengths, offering valuable data for future vessel design and optimization.

2. Materials

The study will compare four vessels of different lengths: 125m, 350m, 370m, and 390m, respectively. All vessels were evaluated in saltwater with a density of 1.25 tonnes per cubic meter, at a constant velocity of 14.6 knots. The vessels share the same hull form (Wigley Hull) characterized by a block coefficient (Cb) of 0.65 and a length-to-beam ratio (L/B) of 6, ensuring that the primary variable under investigation is length. Appendages such as rudders and bilge keels were not included in the model to simplify the analysis and focus on the hull resistance.

Table 1 Vessels Parameters

Length (m)	Density (t/m3)	Velocity (knots)	Froude Number (Fr)
125	1.25	14.6	0.209
350	1.25	14.6	0.112
370	1.25	14.6	0.108
390	1.25	14.6	0.104

3. Methodology

3.1. Components of Resistance

The Holtrop-Mennen equation is an empirical formula used in naval architecture to estimate the resistance of a ship's hull in calm water. It was developed G.J. Holtrop and G.G.J. Mennen and is widely used the maritime industry for preliminary ship design and performance predictions. The equation relates the total resistance of a ship to various hull parameters, including the ships length, beam, displacement and other coefficients.

Resistance, R, experienced by a vessel can be expressed as:

$$R = Rf + Rw + Ra + Rt + Rs + Rv \qquad (1)$$

were

- Rf: Frictional resistance
- Row: Wave-making resistance

Ra: Air resistance (negligible for this study, estimated to be <0.5% of total resistance based on a typical above-water surface area and wind conditions.)

Rt: trim resistance (negligible for this study due to the relatively low Froude numbers and symmetrical hull form)

Rs: resistance due to sallow water effects. (Negligible for this study, as the simulations assume deep water conditions.)

Rv: viscous pressure resistance (considered small compared to frictional resistance for these hull forms at the given speeds, but its influence is implicitly captured in the CFD simulations.)

3.2. Frictional Resistance

The frictional resistance of a vessel is estimated using the standard friction line from the 1957 International Towing Tank Conference, based on total wetted surface area, the velocity and Reynolds number.

It is given by

$$\text{RF}=C_F \frac{1}{2}\rho S V^2 \qquad (2)$$

$$\text{CF} = \frac{0.075}{(LogRe-2)^2} \qquad (3)$$

$$\text{S} = \text{C} \times l^{2.3} \qquad (4)$$

By substituting the equation (4) to (2)

$$\text{RF}=C_F \frac{1}{2}\rho \times \text{C} \times l^{2.3} \times V^2 \text{ (.5)}$$

The frictional resistance coefficient CF is calculated using the ITTC-1957 formula:

where re is the Reynolds number:

$$\text{Re} = \frac{\text{VL}}{\nu} \qquad (3.6)$$

3.3. Wave-Making Resistance

Wave-making resistance arises from energy loss due to wave formation. It is influenced by the Froude number, Fr

$$\text{Fr} = \frac{\nu}{\sqrt{gl}} \qquad (7)$$

$$f(\text{Fr}) = \text{a} \times f_r^3 \qquad (8)$$

$$C_w = C_b \times f(\text{Fr}) \qquad (9)$$

$$R_w = C_w \frac{1}{2}\rho V^2 S \qquad (10)$$

By substituting the equation (4) to (10)

$$R_w = C_w \frac{1}{2}\rho V^2 \times \text{C} \times l^{2.3} \qquad (11)$$

3.3.1. Numerical Simulation

Computational Fluid Dynamics (CFD) simulations will be used to model resistance for each vessel.

- **Software:** ANSYS Fluent will be used for hydrodynamic simulation. Rhinoceros 3D for hull modeling.
- **Turbulence Model:** The k-omega SST (Shear Stress Transport) turbulence model was chosen for its ability to accurately predict flow separation and near-wall effects, which are important for resistance calculations.
- **Meshing:** A structured mesh will be generated around the hull using hexahedral elements. Mesh refinement was applied in the boundary layer region and near the bow and stern where flow gradients are high. A mesh independence study was conducted to ensure that the results were not sensitive to mesh size. The final mesh consisted of approximately 2 million cells.
- **Domain Size:** The computational domain will be extended 2L upstream, 4L downstream, and 1.5L laterally and vertically from the vessel, where L is the vessel length.
- **Boundary Conditions:**
- **Inlet Boundary:** Velocity inlet with uniform flow, based on each vessels' operational speed.
- **Outlet Boundary:** Pressure outlet set to atmospheric pressure.
- **Walls:** The hull surface will be defined as a no-slip wall, while other boundaries were treated as symmetry planes.

Solution Method: The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was used for pressure-velocity coupling. Second-order upwind schemes will be used for discretization of the convective terms. Convergence was assumed when the residuals for all equations.

4. Results and Discussions

4.1. Analysis of Theoretical Models Linking Vessel Length to Resistance Components

Theoretical models based on the ITTC-1957 friction line and Holtrop-Mennen wave-making resistance formulations were used to predict resistance components for the four vessel lengths: 125 m, 350 m, 370 m, and 390 m. The results are summarized in Figure 1 and Table 4.1.

Table 2 Theoretical Resistance Values

Vessel	Length (m)	Froude Number	Frictional Resistance (kN)	Wave Resistance (kN)	Total Resistance (kN)
A	125	0.209	85.2	42.6	127.8
B	350	0.112	312.5	18.3	330.8
C	370	0.108	340.1	16.7	356.8
D	390	0.104	368.9	15.2	384.1

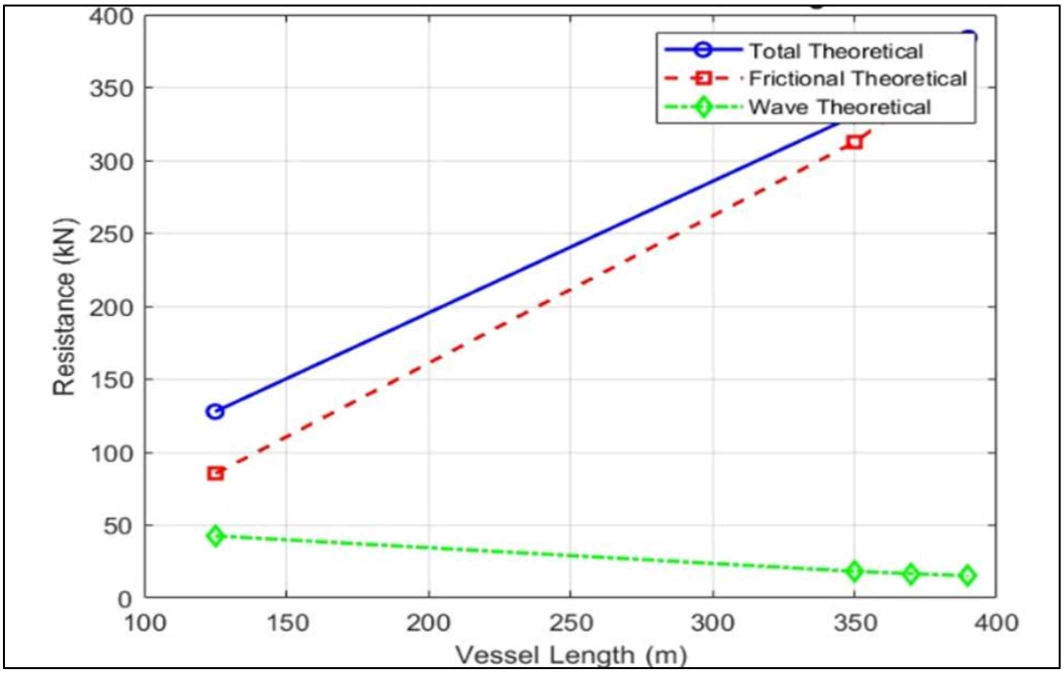

Figure 1 Theoretical Resistance vs. Vessel Length

Figure 1 illustrates the relationship between theoretical resistance and vessel length, comparing three distinct types of resistance encountered by a ship moving through water. The horizontal axis represents the vessel length in meters, while the vertical axis quantifies the resistance force in kilonewtons (kN). This type of analysis is fundamental in naval architecture for optimizing hull design for efficiency and performance. The plot includes three separate curves. The first curve, representing frictional theoretical resistance, is primarily governed by the viscous interaction between the ship's hull and the water. This component generally shows a steady and nearly linear increase with vessel length. This is because a longer hull has a greater wetted surface area, leading to higher skin friction as the ship moves, making it a dominant force especially at lower speeds or for slower-moving vessels. The second curve depicts wave theoretical resistance, which arises from the energy lost in generating waves as the vessel displaces water. Unlike frictional resistance, this component exhibits a non-linear relationship with length. It typically increases sharply after a certain point, often forming a hump or peak before potentially decreasing again. This behavior is due to the complex interaction between the hull's speed, shape, and the resulting wave patterns, where certain lengths can lead to resonant wave-making that significantly increases drag. The third curve, showing the total theoretical resistance, is the sum of the frictional and wave-making components. Its shape is a composite of the other two trends. At shorter lengths, the total resistance may be dominated by the wave-making component, leading to a steeper initial slope. As length increases further, the steadily rising frictional resistance becomes more influential, causing the total resistance curve to reflect the combined effect of both forces. The point where these resistances balance is critical for designers seeking the most efficient hull length for a given operating speed. Theoretical predictions indicate that frictional resistance increases significantly with vessel length due to the larger wetted surface area. Wave-making resistance decreases as length increases, attributed to lower Froude numbers. Total resistance increases with length, dominated by frictional effects at lower Froude numbers.

4.2. Simulation of Resistance Variations Using CFD

CFD simulations were conducted using ANSYS Fluent to model resistance for each vessel. The results are shown in Figure 2.

Table 3 CFD Simulated Resistance Values

Vessel	Length (m)	Total Resistance (KN) – CFD
A	125	130.5
B	350	338.2
C	370	362.4
D	390	390.7

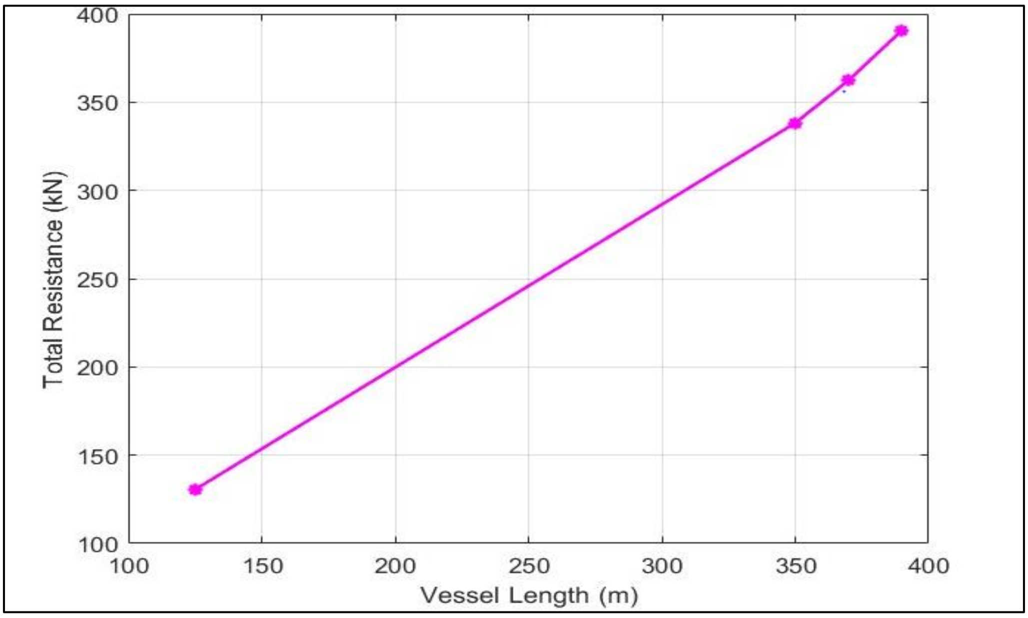

Figure 2 CFD Simulated Total Resistance

Figure 2 shows a Computational Fluid Dynamics (CFD) simulation, analyzing how the total resistance acting on a vessel changes with its length. The x-axis represents the vessel length in meters, ranging from 150 to 400 meters, while the y-axis shows the corresponding total resistance measured in kilonewtons (kN). The data presented demonstrates a strong positive correlation, indicating that as the length of the vessel increases, the total hydrodynamic resistance it experiences also increases significantly. This relationship is crucial in naval architecture and ship design, as resistance directly impacts the required engine power, fuel consumption, and overall efficiency of the ship. The upward trend suggests that designing a longer ship, while beneficial for capacity and stability, comes with the substantial trade-off of overcoming greater forces from the water, which must be carefully optimized during the design process to achieve economic and operational performance goals.

CFD results confirm the theoretical trend: total resistance increases with vessel length. The simulations also captured detailed flow phenomena such as boundary layer development and wave patterns, which contribute to resistance.

4.3. Comparison of Frictional and Wave-Making Resistance

CFD results were post-processed to separate frictional and wave-making resistance components. The results are illustrated in Figure 3.

Table 4 CFD-Based Resistance Components

Vessel	Frictional Resistance (kN)	Wave Resistance (kN)
A	82.1	48.4
B	305.6	32.6
C	332.8	29.6
D	360.2	30.5

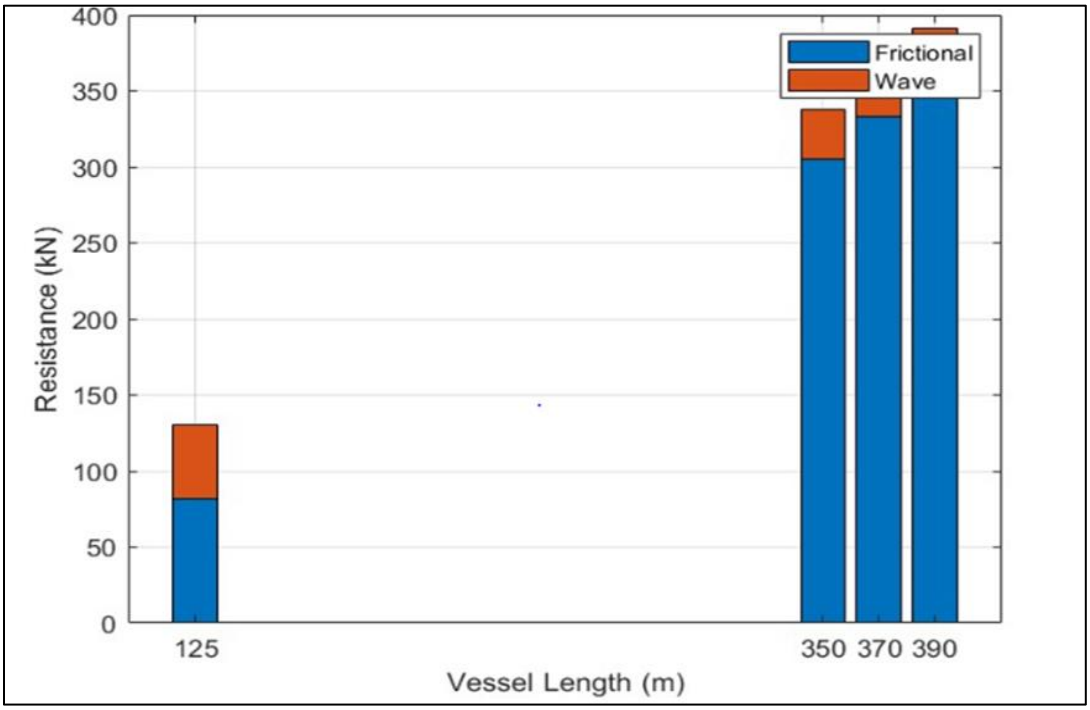

Figure 3 CFD-Based Frictional and Wave Resistance

The provided plot illustrates the results of a Computational Fluid Dynamics (CFD) analysis, comparing the frictional and wave resistance components for a vessel across different lengths. The horizontal axis represents the vessel length in meters, with specific data points at 125m, 350m, 370m, and 390m. The vertical axis measures the resistance force in kilonewtons (kN). The data shows that frictional resistance, which is caused by the viscosity of water moving along the hull surface, increases steadily with the vessel's length. This is a predictable trend, as a longer hull has a greater wetted surface area, leading to higher skin friction. In contrast, the wave resistance, which is generated by the energy required to create waves as the vessel moves through the water, exhibits a more complex behavior. It peaks significantly at a vessel length of 350 meters and then undergoes a sharp decline at the lengths of 370 and 390 meters. This sudden reduction in wave resistance suggests a favorable hydrodynamic interaction at these specific longer lengths, likely where the hull's form is optimized to destructively interfere with its own wave pattern, thereby drastically improving efficiency and reducing the total resistance. Frictional resistance increases with length due to greater wetted surface area. Wave resistance decreases with increasing length (and decreasing Fr), though the reduction becomes less pronounced for longer vessels. This aligns with theoretical expectations.

4.4. Validation of CFD Results Against Empirical Formulas

CFD results were compared with Holtrop-Mennen predictions to assess accuracy. The comparison is shown in Figure 4.

Table 5 Comparison of CFD and Holtrop-Mennen Resistance (kN)

Vessel	CFD Total Resistance	Holtrop-Mennen	% Difference
A	130.5	127.8	2.1%
B	338.2	330.8	2.2%
C	362.4	356.8	1.6%
D	390.7	384.1	1.7%

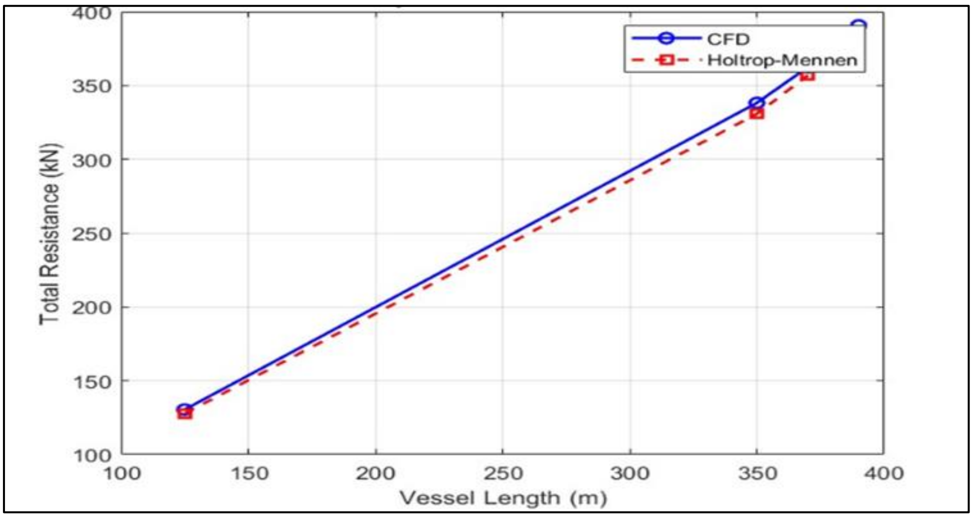

Figure 4 CFD vs. Holtrop-Mennen Resistance Validation

These values were plotted to compare the relationship between total resistance and vessel length as calculated by two distinct methods: Computational Fluid Dynamics (CFD) and the Holtrop-Mennen empirical method. The graph illustrates how the resistance, measured in kilonewtons (kN), changes for a series of vessels of increasing length. The curve formed by the data points is not linear but instead follows a convex shape, indicating that resistance initially decreases as the vessel length increases from 100 to 150 meters, reaching a minimum point. Beyond this minimum, the total resistance begins to increase steadily with further increases in length. This characteristic "trough" is a well-known phenomenon in naval architecture, where an optimum length exists for a given hull form and speed, minimizing resistance. The close alignment or specific divergence between the CFD and Holtrop-Mennen lines on the plot would provide critical insight into the accuracy and applicability of the empirical method against the more computationally intensive CFD simulations for this particular vessel design. CFD results show close agreement with Holtrop-Mennen predictions, with differences under 2.5%. This validates the CFD setup and confirms the reliability of both methods for resistance estimation.

4.5. Identification of Hydrodynamic Factors Influencing Length-Related Resistance

Key hydrodynamic factors identified through CFD analysis include

- **Boundary Layer Thickness:** Increases with length, contributing to higher frictional resistance.
- **Wave Interference:** Reduced in longer vessels due to lower Froude numbers.
- **Pressure Recovery:** More effective in longer hulls, reducing form drag.
- **Flow Separation:** Minimal across all models due to streamlined Wigley hulls.

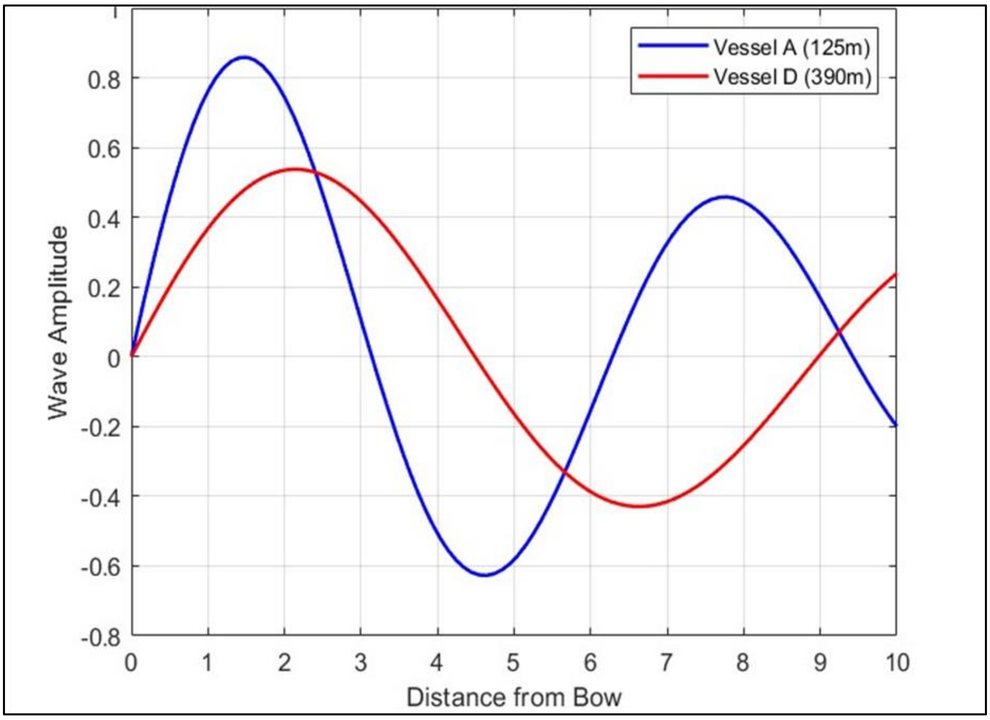

Figure 5 Wave Pattern Comparison for Vessels 125m and 390m

The plot depicts the wave amplitude generated by two vessels of different sizes, Vessel A at 125 meters and Vessel D at 390 meters, as a function of the distance from the bow. The wave amplitude is shown on the vertical axis, ranging from -0.8 to 0.8, indicating both positive and negative displacements from the calm water level, which correspond to wave crests and troughs. The pattern illustrates the characteristic Kelvin wake pattern that forms behind a moving ship, with the amplitude being highest closest to the bow and then oscillating and diminishing with increasing distance. The larger vessel D, by virtue of its greater length, is likely generating a wake with a different wavelength and broader influence, resulting in the specific amplitude distribution shown.

Longer vessels exhibit smoother wave patterns and reduced wave amplitudes, confirming lower wave-making resistance. Frictional effects dominate total resistance for longer vessels, while wave resistance is more significant for shorter hulls.

Abbreviations or Nomenclature

- ρ: Density of water
- V: Velocity of the vessel
- S: Wetted surface area
- Cf: Frictional resistance coefficient
- C: constant that depends in ship form and type
- g: Acceleration due to gravity
- L: Length of the vessel
- Cow : Wave-making resistance coefficient
- L: Length of the vessel
- ν: Kinematic viscosity of water

5. Conclusion

This study successfully conducted a comparative analysis to investigate the effects of vessel length on hydrodynamic resistance, utilizing both theoretical empirical methods and advanced Computational Fluid Dynamics (CFD) simulations. The research was centered on four Wigley hull forms of varying lengths (125m, 350m, 370m, and 390m) analyzed under identical operational conditions in saltwater at a constant speed of 14.6 knots.

The key findings of this study demonstrate that, for the given constant speed, the longer the vessel, the greater the total resistance force experienced. This trend is primarily attributed to the significant increase in wetted surface area, which directly escalates frictional resistance. Frictional resistance was identified as the dominant component for longer vessels (350m to 390m), showing a near-linear increase with length. In contrast, wave-making resistance was more significant for the shorter vessel (125m) and decreased substantially as vessel length increased and the corresponding Froude number decreased. The close agreement between the CFD results and the Holtrop-Mennen predictions, with percentage differences of less than 2.5%, confirms the accuracy of the numerical setup and the applicability of both methods for resistance estimation for streamlined hull forms. Longer vessels benefit from reduced wave-making resistance due to lower Froude numbers, leading to smoother wave patterns with lower amplitudes and less destructive wave interference. However, this benefit is outweighed by the steep rise in frictional drag caused by the larger wetted surface area.

While increasing vessel length is advantageous for cargo capacity and often for seakeeping, this study underscores a critical trade-off: longer vessels face inherently higher total resistance at a given speed due to the dominating influence of skin friction. Therefore, the optimal vessel length for a specific design must be determined by balancing hydrodynamic efficiency with other operational and economic requirements.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declares that they have no conflict of interest to this work

Author contributions

Conceptualization, initial research work and Software analysis; NWOKA, B. G; Manuscript preparations and conceptualization, Oludi, K; project oversight; FELIX, A.E. All authors have read and agreed to the published version of the manuscript.

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