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Analysis of Submarine Hydrodynamics and NACA Aerofoils Using Ansys Fluent

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Abstract

This study investigates the hydrodynamic behaviour of submerged offshore vehicles, including submarine hull and NACA aerofoils through simulation and fluid flow analysis, using ANSYS Fluent. The study models the interaction between fluid flow and offshore submerged vessels i.e. a Standard Submarine Model and various NACA profiles, simulating pressure distributions and drag forces that affect offshore operational stability. The analysis comprises of the study of multiple mesh profiles required to calculate the drag force and their coefficients in a pressure based solver. The inter-dependency on the variation of one data on the other is also studied with the help of tables and graphs. The error analysis between the data obtained is also investigated in order to ensure the validity of the report. The findings contribute to the optimization of offshore structures, aiding in the design of submerged energy platforms and deep-sea exploration vessels. Concurrence with the data obtained is generally agreed as accepted within the error margin of 10% which is quite within the range.

Keywords: Hydrodynamics, offshore engineering, submarine, computational fluid dynamics (CFD), NACA aerofoils

INTRODUCTION

Hydrodynamic analysis plays a crucial role in offshore engineering, particularly in the design of submerged structures, underwater pipelines, and offshore drilling support systems. The study of flow field around the submarine hull considering rudder interaction has been a topic of great concern for naval architects in order to guarantee that a submarine manoeuvre at an efficient and economical manner at a desired velocity. Computational Fluid Dynamics (CFD) is extensively used in offshore industries to optimize hydrodynamic performance, reduce drag forces on submerged platforms, and enhance the stability of underwater energy storage units. Though extensive discussion and research concerning the flow field around the bare submarine hull have been performed in recent times, the hull-rudder interaction is crucial for accurate prediction of flow especially at stern portion of the submarine. This study applies CFD simulations to analyse submerged offshore structures, drawing comparisons with conventional submarine hydrodynamics to improve offshore operational efficiency [1–4].

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Modelling

A standardized DRDC-STR submarine geometry (hull-sail-tail configuration) reproduced from Mackay M. [1].

Figure 1 depicts a hull-sail-tail (HST) configuration of DRDC's generic standard submarine geometry which is used for all CFD simulations in this report. The submarine comprises of an axisymmetric hull with length to maximum diameter (l/d) ratio of 8.75 and comprises of three profile sections which are as follows:

i. Riegels type D2 nose,

ii. A constant diameter midsection, and
iii. A parabolic tail.

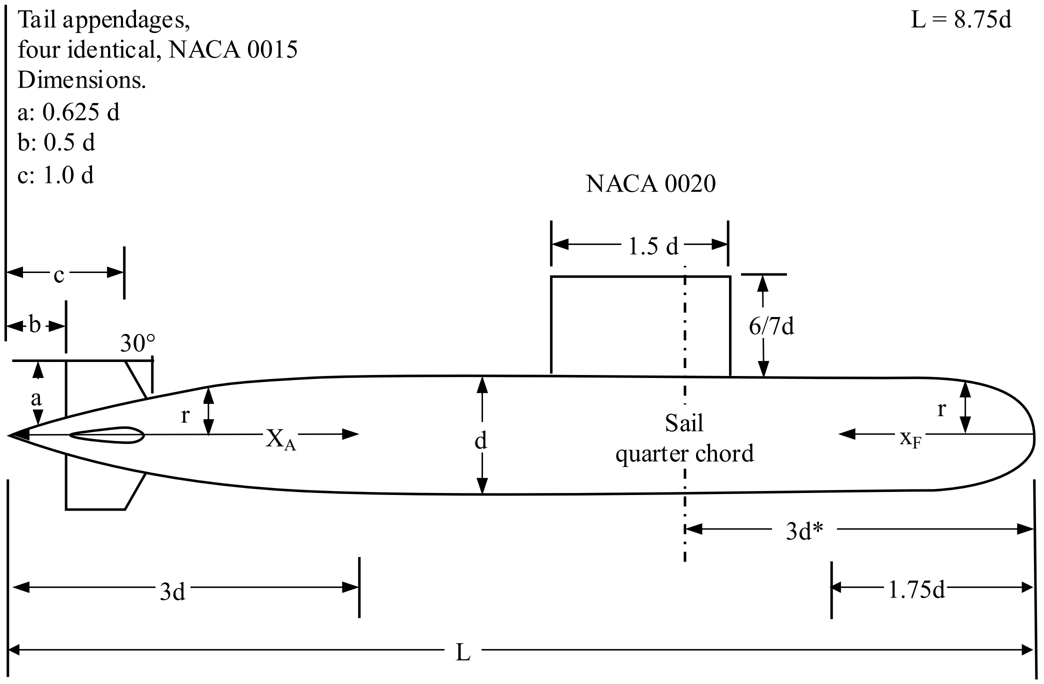

Figure 1. A standardized DRDC-STR submarine geometry.

A full-scale length of l=30 m is contemplated for this report. The sail comprises of a NACA0021 profile which has a rectangular profile with a flat tip. The tail is a cruciform ('+') configuration with four identical NACA0015 tail planes of flat tips (Figure 1).

The NACA 4-digit aerofoil specification is as follows:

The NACA aerofoil series is controlled by four digits which designate the camber, position of the maximum camber and thickness. Considering an aerofoil number as NACA MPXX, the following specifications may be considered:

- M is the maximum camber as percentage of the chord.
- P is the distance of maximum camber from the aerofoil leading edge in tenths of the chord.
- XX is the maximum thickness of the aerofoil as percent of the chord.

All the appendages have NACA four digit aerofoil profiles defined by the following equation:

$$\frac{y_t}{c} = \pm\left[1.4845\sqrt{\frac{x}{c}} - 0.6300\frac{x}{c} - 1.7580\left(\frac{x}{c}\right)^2 + 1.4215\left(\frac{x}{c}\right)^3 - 0.5075\left(\frac{x}{c}\right)^4\right]$$

Where,

c: The chord length,
t/c: The maximum thickness to chord ratio,
$x = 0$: The leading edge, and
$x = c$t: The trailing edge, which has non-zero thickness.

The numerical simulations in this study utilize standard hydrodynamic principles applied in offshore engineering, particularly in designing submerged offshore structures and vehicles exposed to strong ocean currents. The results of this study can be used to optimize the shape and positioning of submerged offshore components (Table 1) [5–7].

Table 1. Types of meshing.

Type	Sphere of Influence		Relevance	Vertex Sizing	Element Shape
	Radius	*Element Size*		*Element Size*	
A	-	-	+100	-	Tetrahedron
B	1 m	0.01 m	0	-	Tetrahedron
C	1 m	0.01 m	+100	0.001 m	Tetrahedron

MESHING RESULTS AND DISCUSSIONS

The mesh generation procedure used for this report was trial and error complemented by what could be learned with the help of various iterations. The mesh should be fine enough to yield grid independent solutions but coarse enough to have a decent computational time.

This balance is achieved by completing a mesh sensitivity analysis. Fundamentally, a mesh sensitivity analysis is an iterative process of refining the mesh and checking the results until the results no longer vary by an appreciable amount. An analysis of mesh sensitivity was carried out on the various sections of the submarine hull. Initially, the nose section of the submarine hull is considered, followed by the mid-hull section and finally the complete cross-section. Three different mesh was introduced along with three different velocities i.e. 50, 30 and 20 m/s [8, 9].

The pressure drag analysis of the submarine hull and NACA aerofoils provides valuable insights into the design of submerged offshore structures and vehicles. Offshore submerged vessels and underwater research stations can benefit from optimized hull shapes that minimize drag and enhance hydrodynamic stability under varying ocean currents. The simulation results suggest that the NACA profiles used in this study can be further adapted for offshore hydrodynamic applications, such as underwater oil storage systems and deep-sea marine exploration vehicles.

Following the mesh convergence, we obtained three values of C_d (Coefficient of Drag) and Pressure Drag Force. These values were compared with their respective theoretical values and their percentage error calculated [10].

The three types of meshing used for the computation of the submarine hull are as follows:

1. *Type A:* A system default mesh with +100 relevance and fine relevance centre.
2. *Type B:* A vertex sizing mesh with sphere of influence of 1 m and element size 0.01 m with patch conforming tetrahedron method.
3. *Type C:* A vertex sizing mesh with sphere of influence of 1 m and element size 0.01 m and edge sizing with size 0.001 m with patch conforming tetrahedron method.

Boundary Condition

- A boundary condition was set at the inlet with the inlet velocity profile set as 10, 30 and 50 m/s for the three cases respectively.
- Density of water: 998.2 kg/m^3
- Temperature of water (Operating Temperature): 298.15 K
- Dynamic viscosity of water: 0.001003 N-s/m^2
- Density of material of construction of submarine: 2719 kg/m^3
- The equation used to calculate the theoretical value of drag force is given by:

$$F_D = \frac{1}{2} \times C_D \times \rho \times A \times v^2$$

- The simulated values of coefficient of drag are calculated by FLUENT using the formula stated below:

$$c_d = \frac{1}{\rho v^2 A} \int_S \ dA(p - p_0)(\hat{n} \cdot \hat{\imath}) + \frac{1}{\rho v^2 A} \int_S \ dA(\hat{t} \cdot i)T_w$$

- The boundary condition set as inlet velocity for the simulation of the NACA profiles was set as 50 m/s.

ANALYSIS AND DISCUSSION

The flow characteristics over the submarine hull are studied in terms of pressure contours and velocity profiles. Firstly, we took into consideration the C_d vs. Iteration curve simulated by the software. The iterations were done till the solution i.e. C_d value and their subsequent values of drag force calculated by the system converged. Furthermore, the most frequently occurring value of C_d i.e. the mode is perceived, from which we analytically calculated the value of drag force. Finally, the error between the system generated value and analytically calculated value of drag force is calculated and compared.

The pressure contour and velocity profiles are also studied such that we can understand the hydrodynamics of each section of the submarine hull. The data is calculated for three different velocity profiles i.e. 10, 30 and 50 m/s corresponding to which three different mesh structures are used.

The submarine is divided into three sections, namely the nose, mid-hull and the tail. The simulation is firstly proceeded taking into account only the nose section, followed by the combination of nose and mid-hull section which also includes the sail and finally the whole submarine hull.

Similarly, the flow characteristics over the seven NACA Profiles are also studied by firstly taking into consideration the C_d vs. Iteration curve and finding the values of C_d as the graph converged and their subsequent value of drag force were calculated by the system. Secondly, the mode value of C_d is found out along with its subsequent value of drag force analytically and finally error is calculated.

RESULT

On selective meshing and iterating the parts of the submarine hull, the pressure drag force and coefficient of drag at the hull section at 50 m/s was found to be 4609168.59 N and 0.0627 respectively. When compared with the theoretical values which was 4531308.936 N, an error of 1.718% was concurred which is well within the acceptable range.

Similarly, the following NACA Aerofoils were iterated and simulated in a velocity profile of 50 m/s and the following results were obtained. When compared with the theoretical values, the maximum error found out was 1.95%, which is well within the acceptable range (Table 2).

In Figure 4, the curve formed by thickness vs. drag force seems to almost coincide with the Power Curve ($y = ax^n + c$). Hence by using MATLAB, an equation or relation between thickness of NACA Profile and Pressure Drag Force at 50 m/s velocity is obtained through the Curve Fitting Process (Figures 2–4 and Table 2).

Table 2. Table for the NACA Profiles along with their respective thickness, C_d and drag forces.

NACA Series	Thickness (m)	C_d	Pressure Drag (N)	Theoretical Value (N)	% error
NACA 0008	0.41143	0.02099	19013.33	18640.8204	1.95
NACA 0010	0.51429	0.0298	32464.35	32036.48684	1.32
NACA 0015	0.77143	0.0611	97267.79	98117.694	0.87
NACA 0018	0.92572	0.0735	143264.26	144318.22	0.74
NACA 0020	1.02857	0.0919	186648.67	185498.7876	0.62
NACA 0024	1.23429	0.1162	301262.82	298604.44	0.88
NACA 0030	1.54286	0.1472	479604.85	478255.1883	0.28

The equation thus obtained can be written as:

$$F = 173078.95t^{2.4175} \tag{1}$$

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Where,
'F' is the Pressure Drag Force (N), and
't' is the Thickness of the NACA Profile (m).

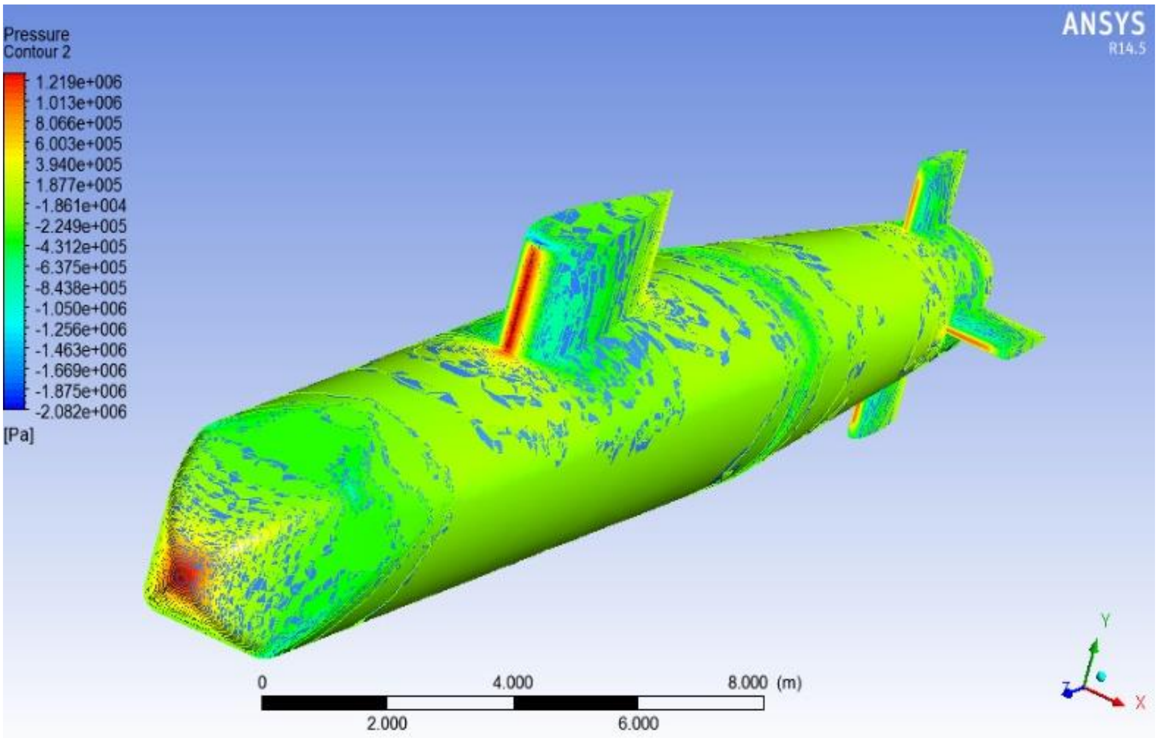

Figure 2. Pressure contour over submarine hull at velocity of 50 m/s with Type C meshing.

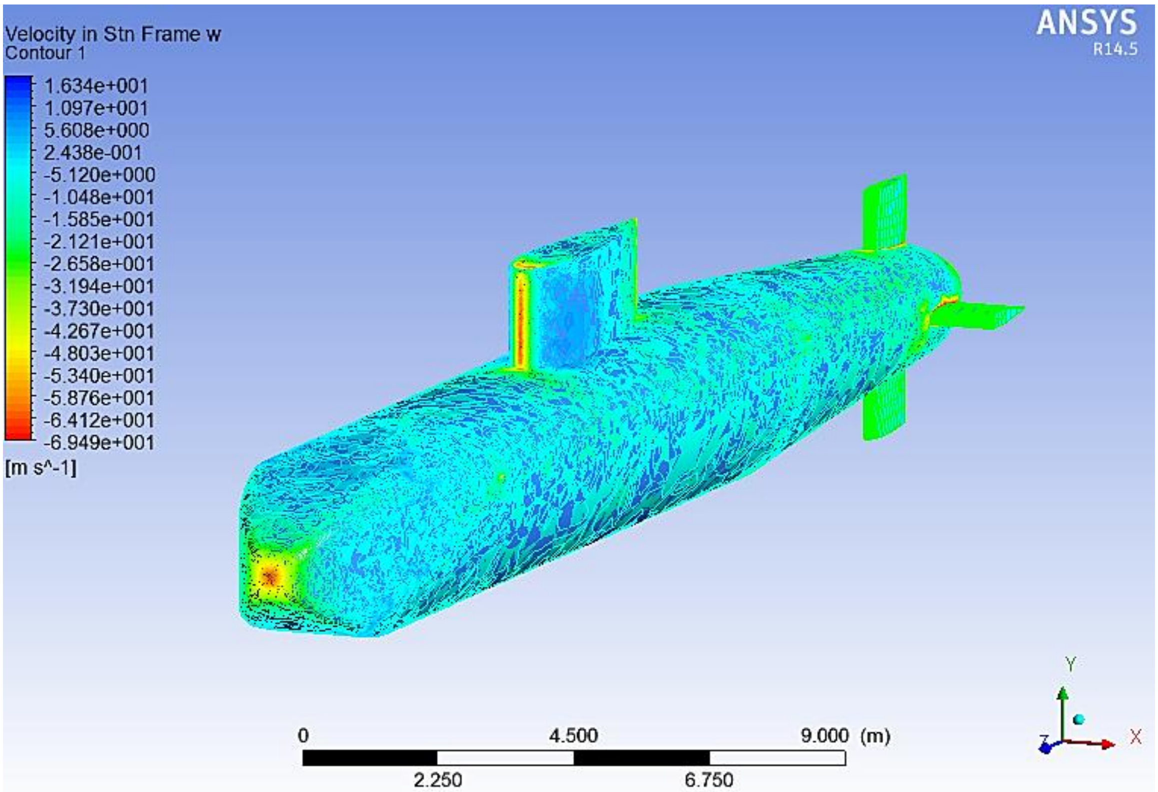

Figure 3. Velocity contour over submarine hull at velocity of 50 m/s with type C meshing.

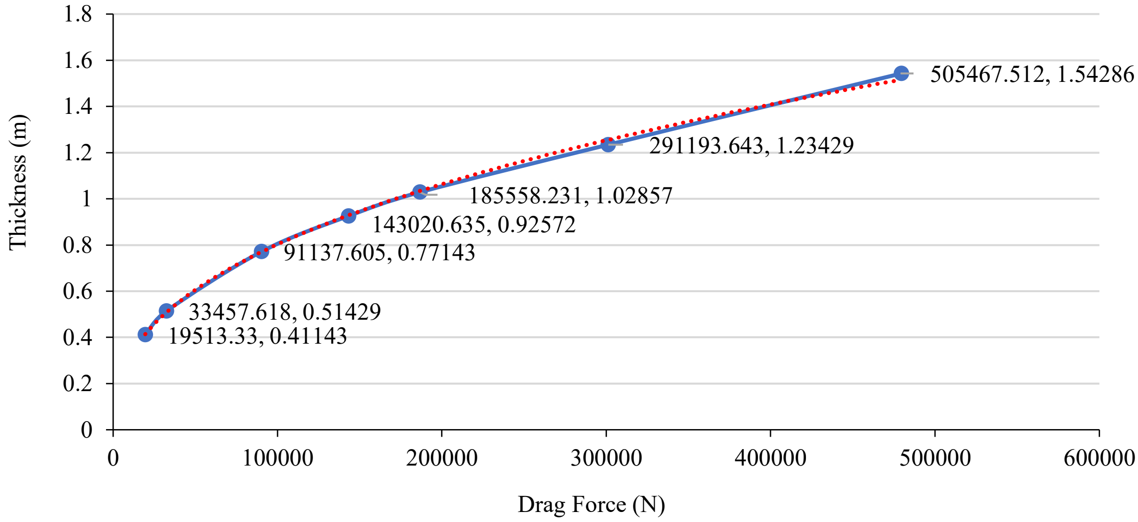

Figure 4. Thickness vs. drag force for various NACA profiles.

Table 3. Table for the NACA Profiles along with their respective drag forces and errors with respect to Eq. (1).

NACA Profile	Thickness (m)	Simulated Drag Force Values (N)	Calculated Value (N) (using Eq. (1))	Error (%)
NACA 0008	0.41143	19513.331	20072.95	2.7879
NACA 0010	0.51429	33457.618	32464.35	3.0596
NACA 0015	0.77143	91137.605	90267.785	0.9636
NACA 0018	0.92572	143020.635	143264.26	0.1701
NACA 0020	1.02857	185558.231	186648.67	0.5842
NACA 0024	1.23429	291193.643	301262.82	3.3423
NACA 0030	1.54286	505467.512	479604.85	5.3925

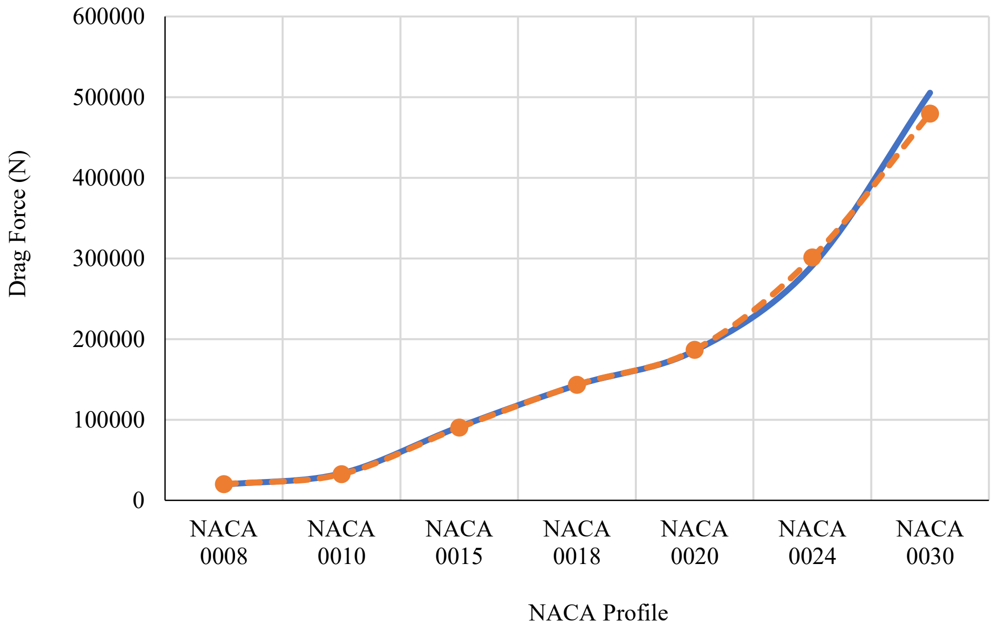

Figure 5. Comparison between simulated and calculated drag force values for various NACA profiles.

CONCLUSION

This study was conducted to establish a flow analysis around a standard submarine hull while in motion with the help of ANSYS Fluent along with a comparative study of various NACA aerofoils.

A DRDC-STR model was simulated to find the coefficient of drag over the submarine nose and hull; and thus calculate the drag force. The calculated force was compared with the reference value and a 2.8% error was conquered which is quite under the acceptable range. This proved that the design geometry and meshing can be considered optimum for further research.

The simulation is then performed with three different types of meshing which allowed us to bring about a linear relation between Velocity, Pressure, Coefficient of Drag and Drag force; and an exponential relationship between Drag force and Cd. Another calculation was carried out taking into consideration the whole submarine body and similarly compared with a theoretical value with resulted in an error of 1.718% which is also quite under the acceptable range.

The velocity and pressure contours over the submarine hull were also examined which showed that the velocity increases from the nose to the top-hull and then slightly decreases as it approaches the mid-hull. Exponential decrease of pressure from the nose tip is observed. Similarly, exponential decrease in the results can be seen on the sail in case of both velocity and pressure.

Regarding the NACA Aerofoils, seven standard aerofoils were considered namely NACA 0008, NACA 0010, NACA 0015, NACA 0018, NACA 0020, NACA 0024 and NACA 0030. They were simulated to find out their respective C_d and drag force values. This allowed us to bring about a relationship between Thickness vs. C_d and Thickness vs. Drag Force. A comparison between the Simulated and Theoretical Value of Drag Force was also drawn with the help of graph resulting in almost coincidental lines.

The Thickness vs. Drag Force curve seemed to almost replicate a Power Curve i.e., $y = ax^n + c$. Thus, Curve Fitting was done using MATLAB to obtain an equation which would give the relation between Thickness and Drag Force of NACA Profiles of length 5.14285 m travelling through water at a velocity of 50 m/s. The values obtained from this equation almost coincides with the simulated values of drag force with maximum error of 5.39%, which is well under acceptable range suggesting that the equation thus obtained can be considered valid.

The findings from this study contribute to the optimization of submerged offshore structures and vehicles, reducing hydrodynamic drag and improving stability under oceanic conditions. The CFD-based approach used in this analysis provides a framework for enhancing the performance of offshore platforms and deep-sea exploration systems. Future studies can expand on these results by incorporating wave-current interaction and multi-body hydrodynamics for offshore applications.

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