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Optimizing the Performance of different Airfoils at Various Angles of Attack through CFD Simulation

Kazim Ghulam [a,*], Faizan Ali[c], Athar Ali Khan Gorar[a,b]

[a] College of Electrical and Mechanical Engineering, Harbin Engineering University, Harbin, China.

[b] Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Sciences & Technology, Larkana, Pakistan.

[c] Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan.

[*] Corresponding authors

Email addresses: gkazim366@outlook.com, gkazim@hrbeu.edu.cn

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ABSTRACT

This study specifically examines the NACA 0012, NACA 4412, and NACA 2412 airfoil profiles using ANSYS FLUENT. By simulating the flow over these airfoils, we can comprehensively explore the impact of the angle of attack on lift and drag coefficients. Notably, the study reveals that the angle of attack directly influences lift force, with a critical angle beyond which the aircraft may stall. Thus, the research underscores the importance of maintaining an optimal angle of attack to avoid turbulence and optimize aircraft performance. The aerodynamics of airfoil shapes play a crucial role in the performance and safety of aircraft. Understanding airflow characteristics over airfoils, particularly concerning the critical angle of attack, is paramount in achieving optimal lift while avoiding stalling. This paper delves into the shift of the separation point on the upper surface of most airfoil shapes, emphasizing the shift from the trailing edge to the leading edge as the angle of attack increases. Stalling becomes a critical concern beyond the critical angle of attack, necessitating comprehensive research to enhance aircraft performance and safety.

Keywords: Airfoil, Angle of Attack, Lift Coefficient, Drag Coefficient, Simulation Techniques, Turbulence Model, NACA Profiles.

I. INTRODUCTION

There is a correlation between the coefficient of lift and drag and the design of airfoils, as well as the understanding of flow characteristics. As a general rule, a significant number of studies investigated the lift and drag performances of the NACA airfoil. This is due to the fact that the shape of the airfoil is an essential component in the design of wings since the efficiency of wings grows in proportion to the airfoil profile. enhancing the performance of leading-edge slats and trailing-edge flaps, which are essential high-lift devices in general aviation, in order to achieve optimal aerodynamics.

Mr. Mayurkymar Kevadiya et al. [1] studied the NACA 4412 airfoil profile for wind turbine blade analysis. Air geometry was created using GAMBIT 2.4.6. Also, the CFD analysis was performed using FLUENT 6.3.26. Rajat Veer, Kiran Shinde, et al. [2] proposed a report on the coefficient of drag and coefficient of lift with the CFD's help in examining the air tunnel. Although both methods provide almost the same results for the same test phase, the test procedure is costlier and more complex than CFD. Tousif Ahmed et al. analyzed [3] NACA 0012's two-dimensional (2D) flow and confirmed NASA Langley Research Center verification charges. The **k-w** pressure transport model predicts the flow accuracy and magnitude of 1% and 5% input velocity and input pressure, respectively. Villalpando et al [4] studied the NACA 63-415 airfoil profile. They found that the SA model performed better in FLUENT when they used a different turbulence model. Additionally, they looked into the aerodynamics of airfoils at both high and low angles of attack. Modeling aerodynamic flutter on a NACA 4412 airfoil was studied by Ramdenee et al. [5] with a focus on wind turbine blades. The laminar/turbulent transition in airfoil flow was also assessed by Johansen [6]. Drag prediction over two-dimensional airfoils in transitional flow was presented by Bacha et al. [7].

A comparison between the unclear and stressful flow of aerodynamic coefficients and flow signals was made for NACA 2412 airfoil. FEM is used to obtain results. They saw that the SA (Spalart Allmaras) model was better than others. In a study, focused on optimizing leading edge slats and trailing edge flaps, crucial high lift devices in general aviation. Four configurations for each device are analyzed using two-dimensional Computational Fluid Dynamics (CFD) with SolidWorks Flow Simulation. The goal is to maximize the section coefficient of lift. Results show the NACA2412 three-element airfoil as the optimal choice, demonstrating good aerodynamic performance with a 1.09% accuracy for maximum lift coefficient and 0.4% for landing conditions [8, 9].

D.N. Srinath and S. Mittal [10] investigated the flow over a NACA 0012 airfoil at angles of attack (α) of 4° and 12° for Reynolds numbers (Re) up to 500. Optimization studies with various objective functions, including drag minimization, lift maximization, lift-to-drag ratio maximization, and combinations, are conducted. The impact of Reynolds number and objective function definition on the optimization process is explored, revealing diverse geometries at low Re.

Ji Yaoa, Weibin Yuan, et al. [11] discussed that aerodynamic aircraft's aerodynamic performance was an essential basis for aerodynamic design and performance analysis of a wind turbine. The quantitative measurement method used in this paper analyzed the aerodynamic performance of the NACA0018 air turbine airfoil, then discussed the rise and fall of the airfoil value under various trajectory models and compared the experimental data.

Rahbrahim Halil GUZELBEY et al. [12] Wing is significant for marine aircraft and for all airlines regarding aerodynamic performance. One of the most critical stages in designing an airplane wing that works well in the air is the selection of the proper airflow. The analysis was performed on the 2x105 Reynolds number and the angle of attack from -5 to 20 degrees. Izzet et al. studied the lift and drag performances of NACA 0015, and they investigated that the drag and lift coefficient increased with increasing angle of attack [13]. A.L. de Bortoli and R. de Quadros studied [14] an optimization method using Runge–Kutta multi-stage scheme with central spatial discretization, incorporating multigrid and preconditioning techniques. Numerical tests on NACA 0012 and 0009 airfoils, as well as three-dimensional wings based on NACA profiles.

N. Benardet al. [15] proposed an article that Dielectric Barrier Discharge (DBD) is mounted at the leading edge of a NACA 0015 airfoil model. The effects of volatility and instability of elevation and gravitational coefficients are investigated with limited power estimates. The results show that the stable state can be delayed by one or two degrees while the drag value is reduced. Aerodynamic performance is enhanced by the high voltage frequency associated with the frequency of natural vortex dissipation measured here by the time-solved PIV. The last part of the paper works with an occasional interest that enhances the efficiency of the actuation.

M.J. Vafaei Rostami al. [16] investigated unsteady and incompressible turbulent flows around stationary and flapping NACA0012 airfoils using the overset grid technique. Three turbulence models—linear Launder–Sharmak–ε, nonlinear Craft–Launder–Sugak–ε, and nonlinear Lien–Chen–Leschziner k–ε model are examined.

R. Azim al. [17] examined the control of transition flow over a 2D NACA 4412 airfoil at higher angles of attack using suction to delay boundary layer separation. The study aims to mitigate energy losses associated with phenomena like local separation, boundary layer transition, turbulence, and shock boundary layer interaction. E. Guilmineau, J. Piquet, P. Queutey [18] they employed CPI finite volume method to simulate the deep dynamic stall of a pitching NACA 0012 aerofoil. Flow sequences are analyzed using the Baldwin–Barth and K–ω SST turbulence models and compared with McAlister et al.'s data.

In an research article presented by Douvi C. Eleni et al. [19], a comprehensive exploration was conducted on the two-dimensional flow characteristics of the National Advisory Committee for Aeronautics (NACA) 0012 airfoil. This investigation involved a range of angles of attack, all while operating within a Reynolds number of 3 × 106. The study involved solving the governing equations of mass and energy conservation to characterize the airflow. This was achieved using one of three turbulence models: Spalart-Allmaras, Realizable, and Shear Stress Transport (SST). The goal was to validate these models by comparing their predictions with measurements taken in open-field conditions.
The focus of this investigation was the meticulous examination of lift and drag coefficients for three distinct airfoil profiles: NACA 4412, NACA 2412, and NACA 0012. This scrutiny extended across a range of angles of attack, specifically 2°, 4°, 8°, 12°, and 16°. The objective was to comprehensively assess the aerodynamic behavior of these airfoils under varying conditions. To facilitate this exploration, the researchers turned to Ansys Fluent 16, a prominent computational fluid dynamics (CFD) software package, for modeling and simulation. Ansys Fluent 16 offers a robust platform for conducting in-depth fluid flow and heat transfer analysis, making it a valuable tool for aerodynamic investigations.

This research employed the Shear-Stress Transport (SST) k-ω turbulence model for simulation purposes. The SST model is widely recognized for its capability to accurately predict turbulence in various flow scenarios, making it a preferred choice in aerospace and aerodynamics studies. The study encompassed an extensive range of angles of attack, reflecting real-world conditions and operational procedures. By delving into the lift and drag coefficients at these various angles of attack, the research contributes valuable insights into the performance characteristics of NACA 4412, NACA 2412, and NACA 0012 airfoils. The findings hold significance for aircraft design, where optimizing lift and minimizing drag are critical factors in enhancing performance and efficiency.

II. METHODS AND MATERIAL

NUMERICAL SIMULATION

For modeling and simulation purposes, ANSYS Fluent 16.0 has been utilized. The geometry, meshing, and model solution design are the simulation phases. ANSYS Fluent Design Modeller was used to design the geometry. The SA (Spalart Allmaras) turbulence model was employed in this investigation. One equation model for the eddy viscosity empirical transport equation is SA.

The spalart-Allmaras model (SA) presented by Spalart and Allmaras is a one-equational model written in modified eddy viscosity. The model uses empiricism and arguments of dimensional analysis; it is independent of y^{+}, but requires the distance to the nearest wall d_w. The turbulent eddy viscosity is developed with the help of model's transport equation:

$$\frac{\partial \tilde{v}}{\partial t} + u_j \frac{\partial \tilde{v}}{\partial x_j} = C_{b1}[1 - f_{t2}]\tilde{S}\tilde{v} + \frac{1}{\sigma}\left\{ \frac{\partial}{\partial x_j} \left[(v + \tilde{v}) \frac{\partial \tilde{v}}{\partial x_j} \right] + C_{b2} \frac{\partial \tilde{v}}{\partial x_j} \frac{\partial \tilde{v}}{\partial x_j} \right\} \quad (1)$$

$$- \left[C_{w1} f_w - \frac{C_{b1}}{K^2} f_{t2} \right] \left(\frac{\tilde{v}}{d} \right)^2 + f_{t1} \Delta U^2$$

G_v , D_v *and* P_v are production term, diffusion term and destruction term respectively and expressed as:

$$G_v = C_{b1}[1 - f_{t2}]\tilde{S}\tilde{v} \quad (2)$$

$$D_v = \frac{1}{\sigma}\left\{ \frac{\partial}{\partial x_j} \left[(v + \tilde{v}) \frac{\partial \tilde{v}}{\partial x_j} \right] + C_{b2} \frac{\partial \tilde{v}}{\partial x_j} \frac{\partial \tilde{v}}{\partial x_j} \right\} \quad (3)$$

$$\boldsymbol{P_v = \left[C_{w1} f_w - \frac{C_{b1}}{K^2} f_{t2} \right] \left(\frac{\tilde{v}}{d} \right)^2} \quad (4)$$

where the production term is developed with the help of norm of vorticity $|\Omega|$. The diffusion terms are naturally connected with spatial derivatives of $\tilde{v}$. The destruction term arose from dimensional analysis. f_{t1} and f_{t2} are transition functions, that provide control over the laminar and turbulent regions. Values of model constraints are $C_{b1} = 0.1355$, $C_{b2} = 0.622$, $\tilde{v} = \frac{2}{3}$.

The Spalart-Allmaras framework is a comparatively easy as one-equation frame that figures out a transport equation for the kinematic eddy (turbulent) viscosity. This represents a relatively fresh form of one-equation frames in which it is unnecessary to find a section scale related to the localized shear layer wideness. The Spalart-Allmaras frame was planned generally for aerospace regions affecting the motion of flows that are bounded by walls and show to provide neat events for boundary layers dependent on adverse pressure gradients.

Table 1 Reference values computed from the inlet.

INLET VALUES

Density (kg/m³)	1.225
Area (m²)	1
Depth (m)	1
Enthalpy (J/kg)	0
Length (m)	1
Pressure (Pa)	0
Temperature (K)	288.16
Velocity (m/s)	20
Viscosity (kg/ms)	1.7894×10^{-5}
Ratio of specific Heats	1.4

Mesh around NACA 0012, NACA 4412, and NACA 2412 is shown below:

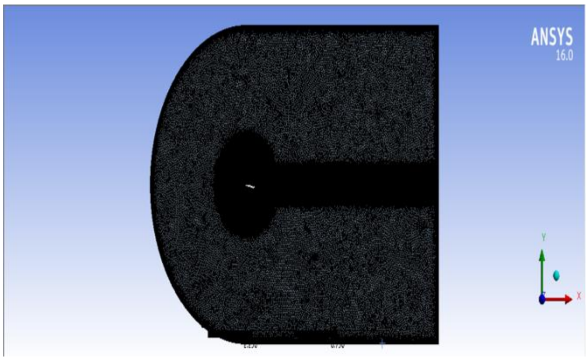

Figure 1a Unstructured mesh

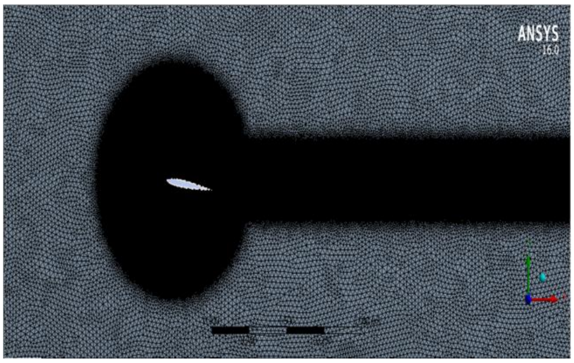

Figure 1b Close view of Meshing

An independent study was performed to verify that the solution will not change with subsequent additional refinements.

Table 2 Grid Number for Airfoils

S.NO.	AIRFOIL	NODES, ELEMENTS
1	NACA 0012	157158
2	NACA 2412	237657
3	NACA 4412	253201

III. RESULTS AND DISCUSSION

In this research, numerical analysis was performed for various NACA Series airfoils. The lift and drag co-efficient were calculated for multiple NACA series airfoils at 20 m/s wind velocity and 2°, 4°, 6°, 12°, and 16°degree angle of attack. Lift and drag co-efficient were obtained numerically with ANSYS Fluent 16.0.

SA (Spalart Allmaras) turbulence model was used in this work. The 1500 iterations were given for NACA 0012, and the solution was converged at 1300 (figure 2a). For NACA 4412, 1000 iterations were shown, and the solution was converged at 750 iterations (figure 2b). For NACA 2412, 1000 iterations were given, and the solution was converged at 950 iterations (figure 2c).

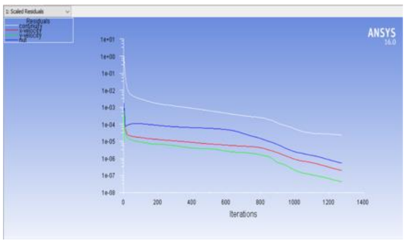

Figure 2a Residual Convergence NACA 0012

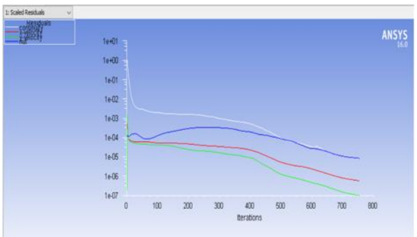

Figure 2b Residual Convergence NACA 4412

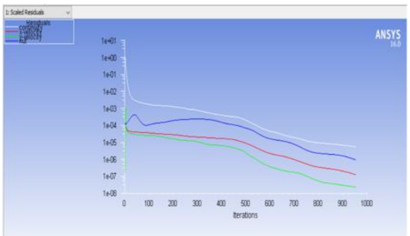

Figure 2c Residual Convergence NACA 2412

The results obtained numerically in ANSYS Fluent 16.0 are shown in Table 3, table 4, and table 5.

Table 3 Lift and Drag coefficient for NACA 0012

NACA 0012	(2° AOA)	4° AOA	8° AOA	12° AOA	16° AOA
DRAG COEFFICIENT	0.0107	0.0126	0.0159	0.409	0.442
LIFT COEFFICIENT	0.2107	0.417	0.829	1.387	1.47

Table 4 Lift and Drag coefficient for NACA 4412

NACA 4412	(2° AOA)	4° AOA	8° AOA	12° AOA	16° AOA
LIFT COEFFICIENT	0.629	0.851	0.948	1.356	1.721
DRAG COEFFICIENT	0.0123	0.0154	0.0479	0.0433	0.157

Table 5 Lift and Drag coefficient for NACA 2412

NACA 2412	(2° AOA)	4° AOA	8° AOA	12° AOA	16° AOA
LIFT COEFFICIENT	0.405	0.589	0.958	1.239	1.55
DRAG COEFFICIENT	0.0140	0.0142	0.0219	0.033	0.139

The pressure and velocity contours are shown in the following figures:

NACA 0012

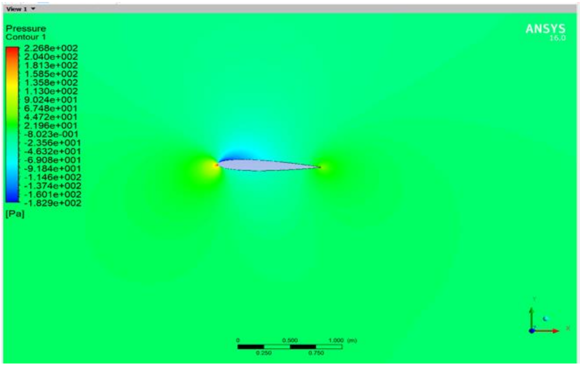

Figure 3 Pressure contour NACA 0012 (2° AOA)

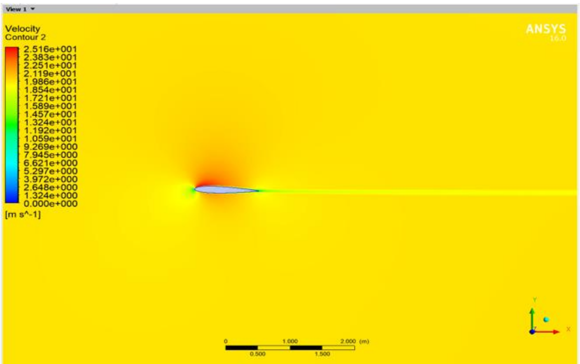

Figure 4 Velocity contour NACA 0012 (2° AOA)

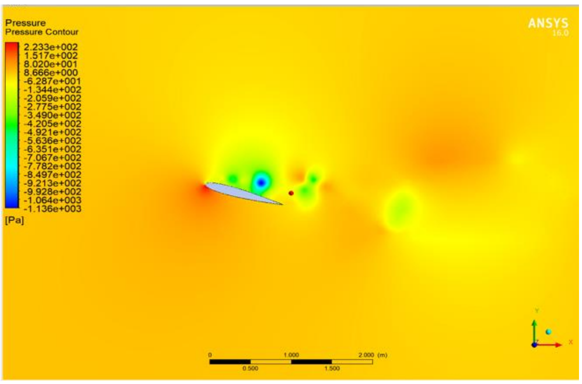

Figure 5 Pressure contour NACA 0012 (16° AOA)

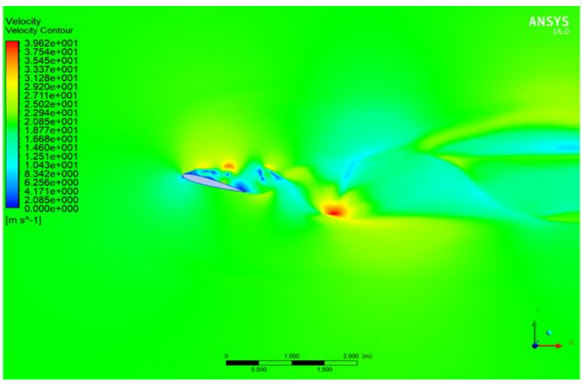

Figure 6 Velocity contour NACA 0012 (16° AOA)

Figure 3 displays pressure contours, where the blue hue on the upper surface indicates lower pressure. In Figure 4, velocity contours are showcased, with red showing higher velocities on the upper surface. Increasing the angle of attack leads to heightened drag forces and elevated pressure on the airfoil's lower side, consequently lowering the lift coefficient. Figures 5 and 6 illustrate the flow at a 16° angle of attack, revealing an increase in turbulence that can lead to a stalling condition.

NACA 4412

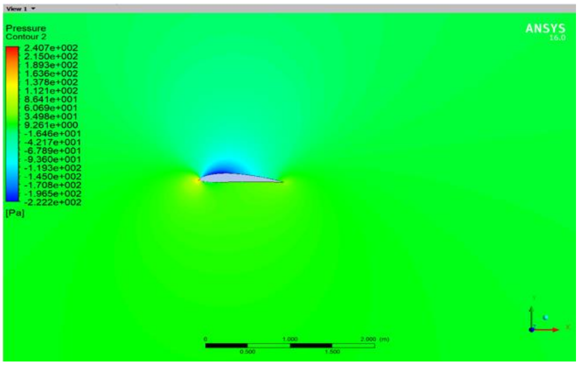

Figure 7 Pressure contour NACA 4412 (2° AOA)

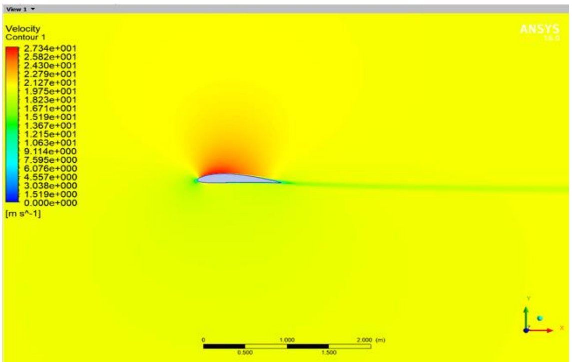

Figure 8 Velocity contour NACA 4412 (2° AOA)

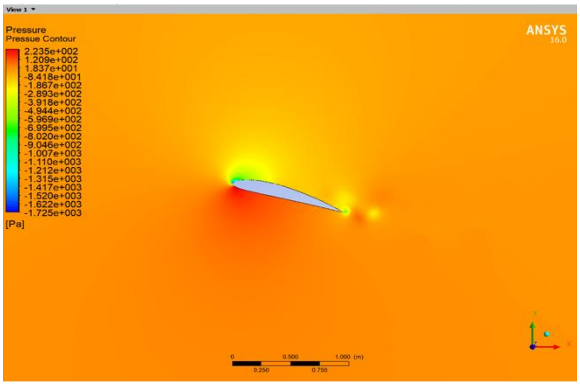

Figure 9 Pressure contour NACA 4412 (16° AOA)

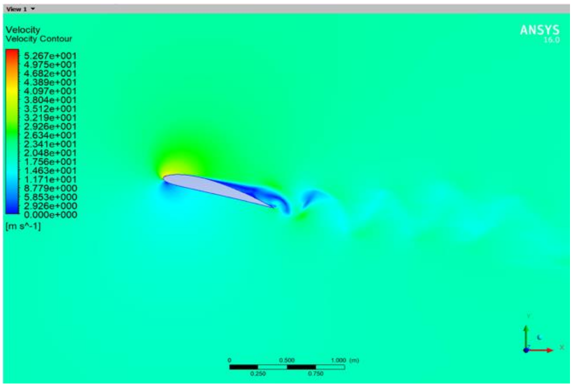

Figure 10 Velocity contour NACA 4412 (16° AOA)

In Figure 7, we observe pressure contours, where the color blue on the upper surface signifies lower pressure levels. Meanwhile, Figure 8 provides velocity contours, with red indicating elevated velocities on the upper surface. This observation is crucial as it signifies the complex interplay between pressure and speed in aerodynamics.

NACA 2412

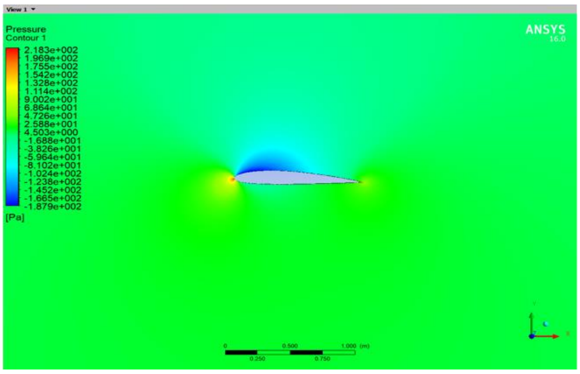

Figure 11 Pressure contour NACA 2412 (2° AOA)

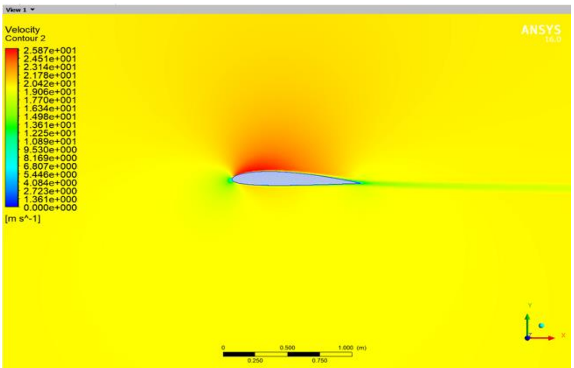

Figure 12 Velocity contour NACA 2412 (2° AOA)

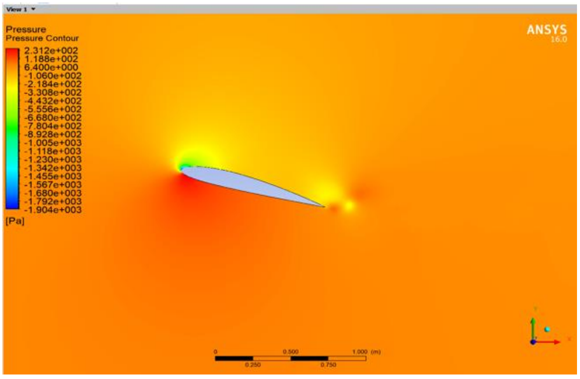

Figure 13 Pressure contour NACA 2412 (16° AOA)

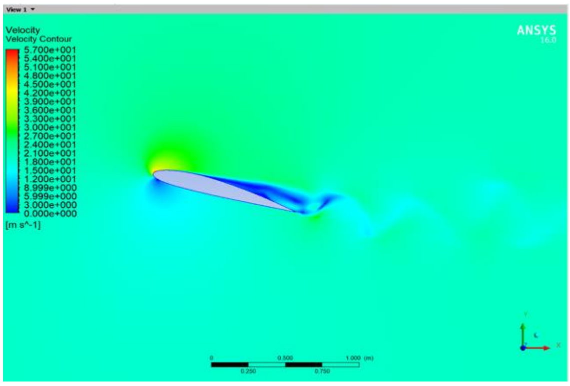

Figure 14 Velocity contour NACA 2412 (16° AOA)

In Figure 11, pressure contours are depicted, and a distinct pattern emerges. The blue color signifies areas of low pressure, evident on both the upper and lower camber surfaces. Conversely, the airfoil's leading edge is prominently marked by the red color, indicating high pressure areas. This pressure distribution is critical in understanding airfoil behavior as it directly influences lift and drag forces.

Figure 13 highlights a noteworthy phenomenon: flow separation. This separation occurs as the angle of attack increases, leading to adverse changes in the airflow patterns around the airfoil. Flow separation can adversely impact an airfoil's performance and is critical in aerodynamics and aircraft design. Understanding these pressure and flow patterns is pivotal for optimizing airfoil design and enhancing overall aircraft efficiency.

The CL vs. α curve reveals a linear relationship up to an angle of attack (AOA) of 16 degrees. This AOA marks the point of optimal lift coefficient (CL). However, beyond this point, with a further increase in AOA, the curve displays a significant deviation as stalling occurs. This aerodynamic phenomenon leads to an abrupt decrease in the lift coefficient. The linear region indicates a favorable operating range where increased AOA corresponds to an increase in lift until the stalling threshold is reached. Understanding this relationship is crucial in aircraft design and operation, as it defines the limits within which an airfoil can maintain steady lift generation before encountering stalling conditions.

COMPARISON

As the angle of attack increases, a significant trend becomes evident. The drag force intensifies, and the airfoil's lower side has a notable pressure surge. This increase in lower-side pressure, combined with the drag force, leads to a consequential reduction in the lift coefficient. This phenomenon is of great significance in understanding the aerodynamic behavior of airfoils at varying angles of attack. It underscores the intricate relationship between pressure, velocity, and lift characteristics and informs engineering decisions related to airfoil design and performance.

NACA 0012

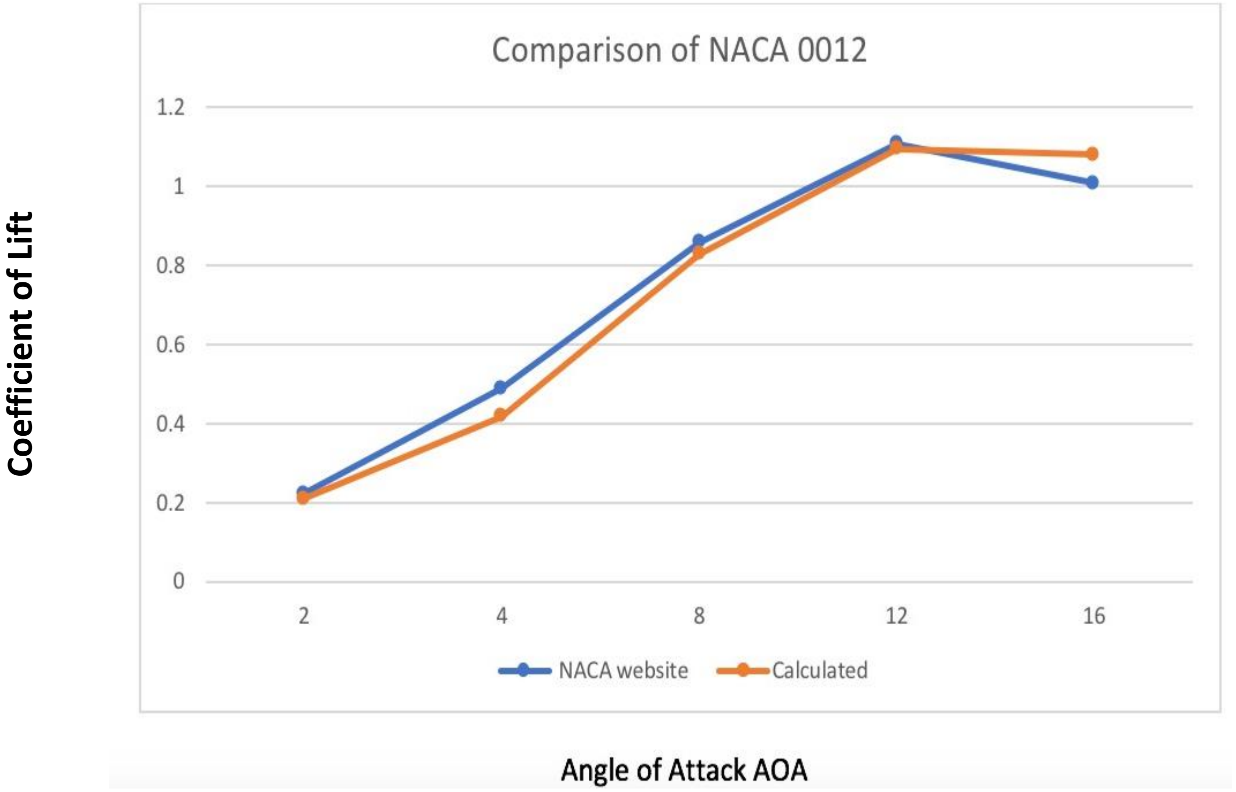

Figure 15 Comparison of NACA 0012

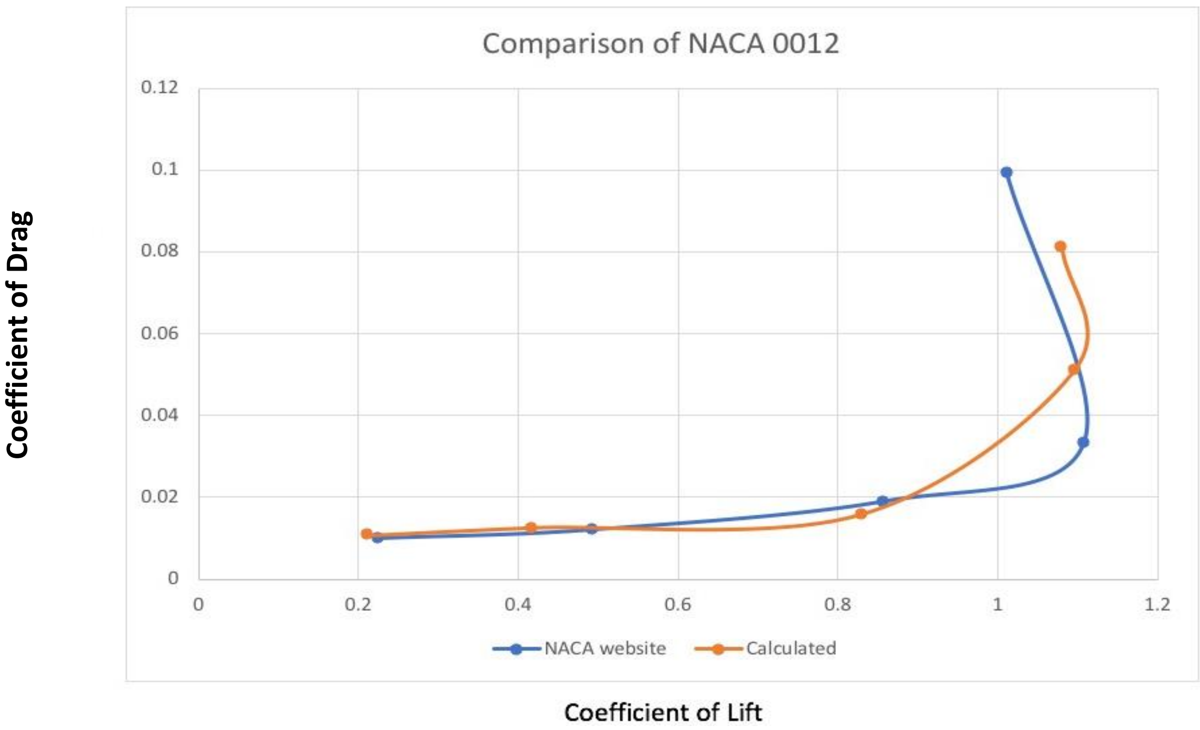

Figure 16 Comparison of NACA 0012. (Cd vs Cl)

NACA 4412

For NACA 4412, the graph is linear. But when the AOA increases above 12º, the lift coefficient decreases, resulting in stalling.

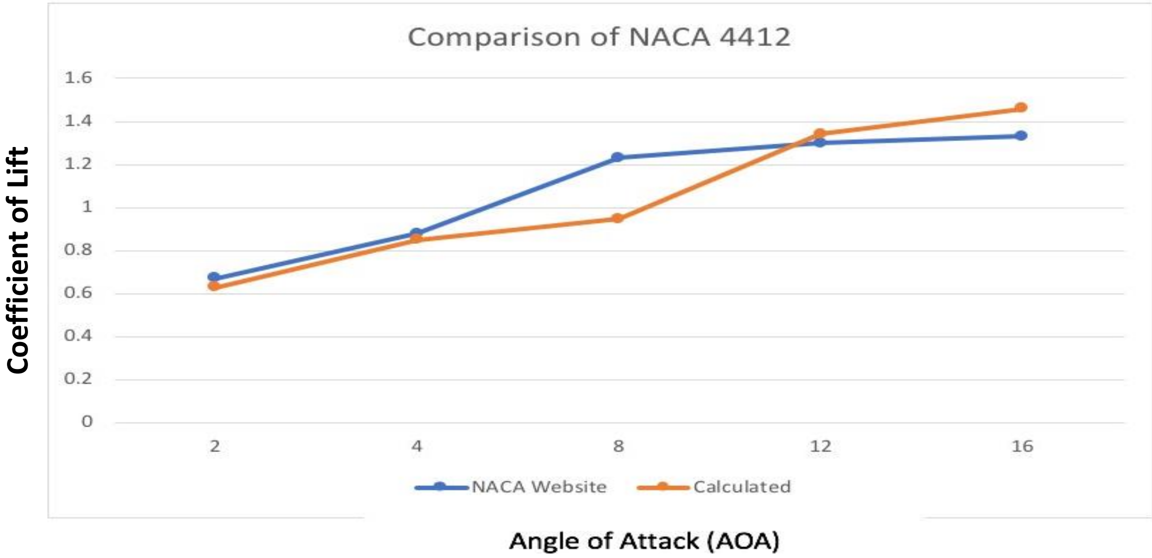

Figure 17 Comparison of NACA 4412

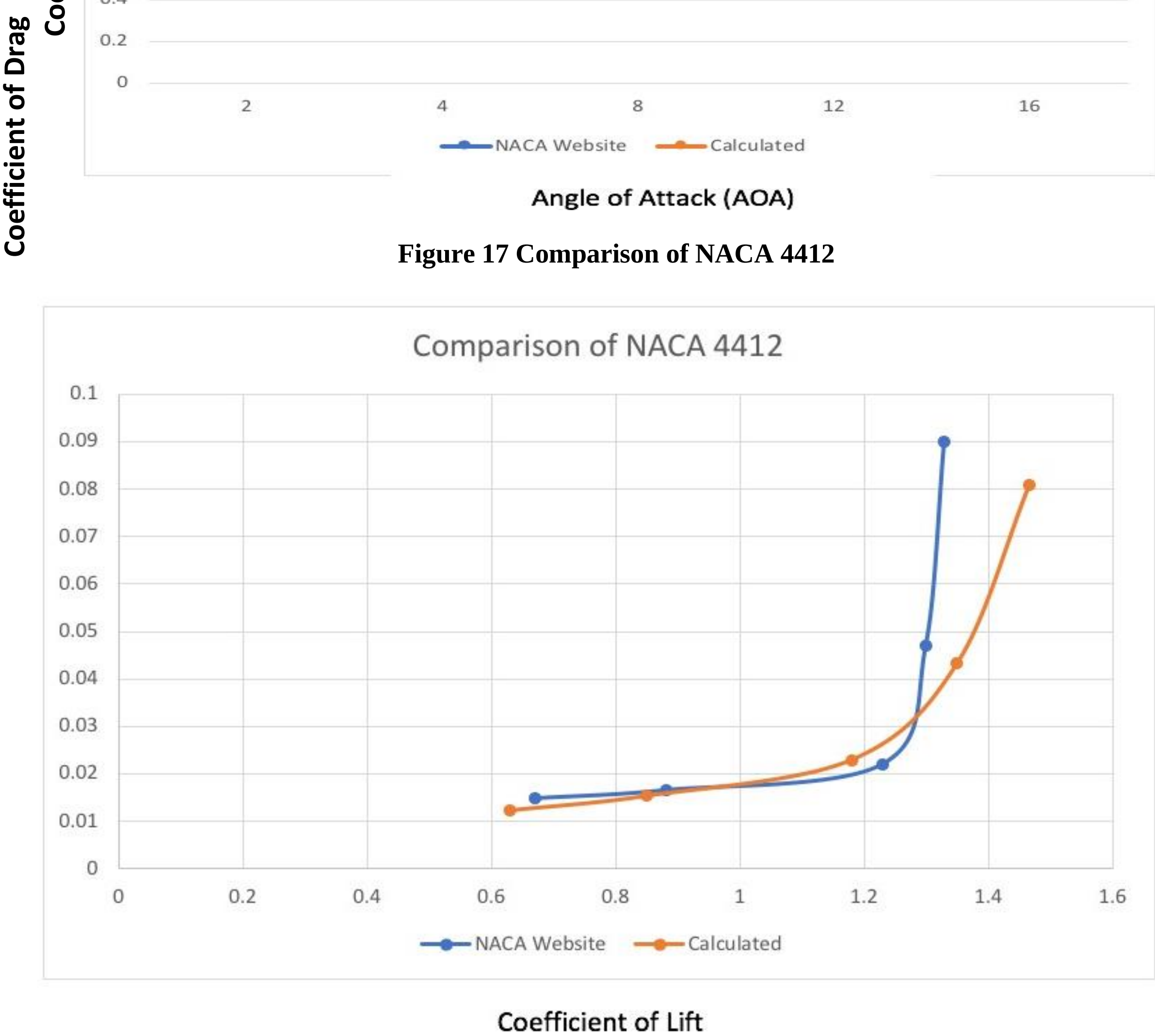

Figure 18 Comparison of NACA 4412 (Cd vs Cl)

NACA 2412

The graph between C_L and *alpha is* linear and the optimum value is obtained at 16^{o} AOA. Further increase in AOA results in stalling.

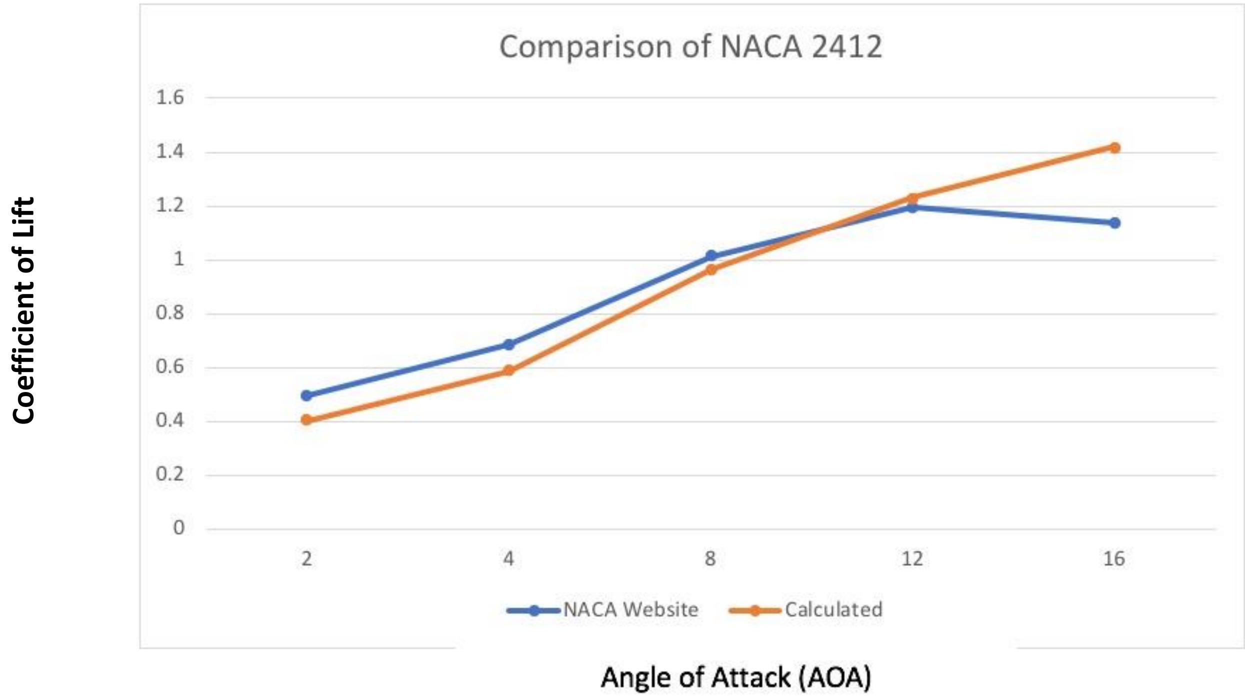

Figure 3 Comparison of NACA 2412

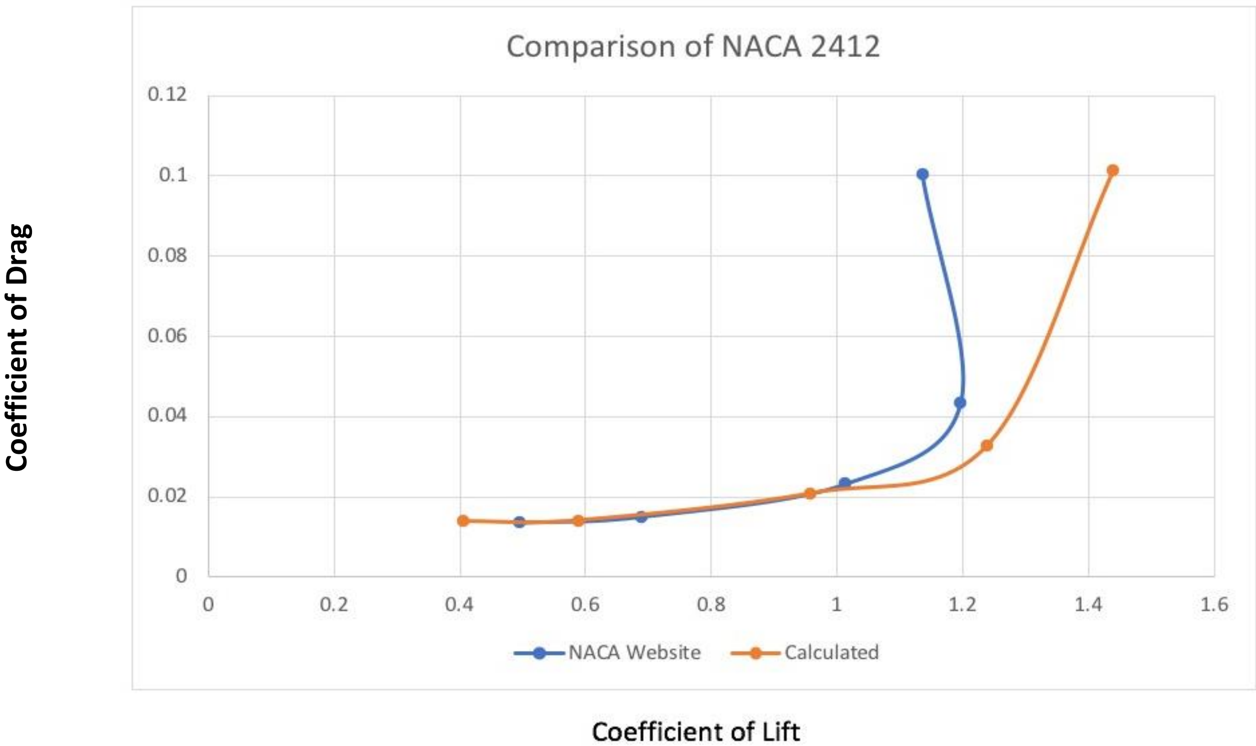

Figure 20 Comparison of NACA 2412 (Cd vs Cl)

IV.CONCLUSION

The investigation encompassed an in-depth examination of NACA 0012, NACA 4412, and NACA 2412 airfoils utilizing ANSYS FLUENT. This computational approach allows for comprehensive simulations of NACA airfoil flows tailored to user-defined parameters, rendering it a versatile and cost-effective tool for aerodynamic studies. The pivotal findings revolved around the influence of the angle of attack on lift and drag coefficients. Notably, NACA 0012 and NACA 4412 airfoils exhibited their maximum lift coefficients at approximately 14 degrees of angle of attack. Beyond this point, the lift coefficients experienced a diminishing trend. Contrastingly, the NACA 2412 airfoil reached its peak lift coefficient at 16 degrees AOA, albeit this higher lift coefficient came at the expense of increased drag coefficients. This observation underscores the intricate trade-off between lift and drag coefficients, which is essential in airfoil optimization and aircraft design. Moreover, the computational approach in ANSYS FLUENT offered a cost-effective alternative to physical testing, streamlining the analysis of airfoil performance.

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