

# **Numerical Investigation of NACA4412 Aerofoil Aerodynamics for Wind Turbines in Bangladesh Using RANS SST Model**

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## **Abstract**

This study presents a numerical investigation of the aerodynamic behavior of the NACA4412 aerofoil for small wind turbine applications operating in Bangladeshi wind conditions. A steady Reynolds Averaged Navier Stokes (RANS) approach using the Shear Stress Transport (SST)  $k-\omega$  turbulence model was used in ANSYS Fluent to evaluate the lift, drag, and moment characteristics of the aerofoil at a velocity of 7 m/s, corresponding to a Reynolds number of  $4.8 \times 10^5$ . The analysis considered  $-8^\circ$ ,  $-4^\circ$ ,  $0^\circ$ ,  $4^\circ$ , and  $8^\circ$  angles of attack to represent low to moderate operating conditions relevant to small horizontal axis wind turbines in Bangladesh. Additionally, a C type mesh was generated to ensure proper boundary layers. The numerical results show a linear increase in lift to  $8^\circ$ , minimal drag near zero, and the highest aerodynamic efficiency occurring between  $4^\circ$  and  $8^\circ$ , indicating that the NACA 4412 aerofoil is suited for low wind regions like Bangladesh's coastal area. The findings support preliminary aerodynamic design decisions for small wind turbines and provide a reference dataset for future transient analysis.

## **Keywords**

NACA4412, Aerofoil Aerodynamics, RANS SST Model, Bangladesh Wind Condition.

## **1. Introduction**

Wind energy has become an essential part of modern renewable energy research for developing countries seeking energy diversification. Bangladesh has showed significant potential for small to medium scale wind power establishment in the coastal and island regions where average wind speeds typically range between 5 to 7 m/s (Islam et al., 2021; Habib & Asgar, 2025). These moderate wind conditions demand aerofoils with high aerodynamic efficiency at relatively low Reynolds numbers to ensure meaningful power extraction from horizontal axis wind

turbines (HAWTs). As turbine performance at low wind speeds is strongly influenced by the aerodynamic properties of the aerofoil section, selecting an appropriate aerofoil profile is a critical design step.

### 1.1 Focus on NACA4412 Aerofoil

The NACA4412 is a cambered aerofoil characterized by maximum camber located at the chord and a 12% thickness to chord ratio (Drela & Giles, 1987; Jacobs et al., 1932). For its ability to generate high lift at lower angles of attack, stable stall behavior, and predictable low Reynolds number performance; it has been adopted in small HAWT blade designs (Heffley & Treuren, 2007; Portela et al., 2025). The NACA4412 typically offers good lift to drag ratios in moderate wind environments, and it makes them suitable for Bangladesh, where the available wind speed is below global average.

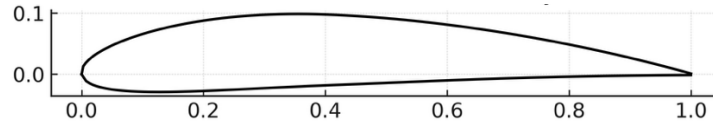


Figure 1. Geometry of NACA4412

The NACA4412 aerofoil profile, illustrated in Figure. 1, supports the efficient boundary layer behavior, reduces drag at lower Reynolds numbers and enables good lift to drag ratios for maximum energy extraction in low wind conditions (Manjunath et al., 2020). Modern applications have explored its performance under variable inflow turbulence, laminar separation bubble formation, and flow reattachment patterns, all of which influence power production in low-wind regions (Abobaker et al., 2017). So, understanding the detailed aerodynamic behavior of this aerofoil under specific wind condition is essential.

### 1.2 CFD based Numerical Aerodynamic Analysis

Currently the Computational Fluid Dynamics (CFD) has significantly enhanced the ability to analyze aerofoil aerodynamics under realistic wind turbine conditions. The Reynolds Averaged Navier Stokes (RANS) formulation, in combination with turbulence models such as the Shear Stress Transport (SST)  $k-\omega$ , has showed its effectiveness for calculating aerodynamic behavior in both attached and separated flows at low to moderate Reynolds numbers for small wind turbines (Younoussi & Ettaouil, 2024; Rahman et al., 2025). CFD tools allow researchers to resolve flow physics more accurately than simplified analytical methods, providing detailed insights into pressure distribution, boundary layer development, and stall characteristics. Moreover, the virtual wind tunnel platforms such as the Armfield C15 system used by (Madha et al., 2025) have become valuable for interpreting lift, drag, and moment trends in educational and research environments.

### 1.3 Research Gap and Objective of the Study

Although many studies have examined aerofoil aerodynamics for general wind applications, there remains a clear research gap in Bangladesh specific assessments that focus on local wind speeds, low Reynolds numbers, and small scale turbine performance, illustrated in Figure. 2. For regions where the average wind speed is approximately 5 to 7 m/s and designers require proper aerodynamic data for cambered aerofoils like the NACA4412 for the blade element momentum (BEM) analysis, starting behavior evaluation, and operational optimization. Existing studies show either to focus on generic performance curves or rely on wind speeds not representative of Bangladesh's wind conditions.

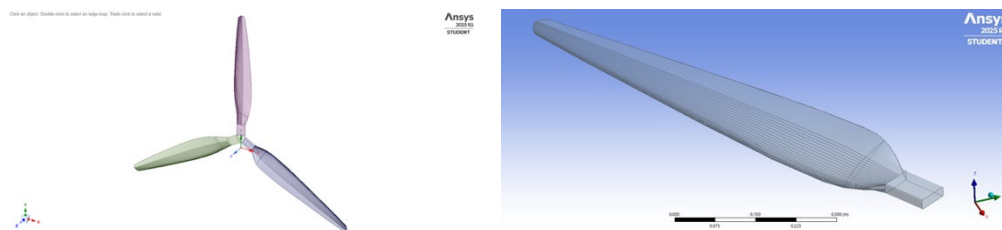


Figure. 2. Small Wind Turbine Blade Design with NACA4412 Aerofoil

To address this gap, the present study performs a numerical analysis of the NACA4412 aerofoil using the RANS SST  $k-\omega$  model at 7 m/s, the  $-8^\circ$ ,  $-4^\circ$ ,  $0^\circ$ ,  $4^\circ$ , and  $8^\circ$  angles of attack. The outcomes include the lift coefficient, drag coefficient, moment coefficient, and aerodynamic efficiency. This dataset supports wind turbine blade design and provides a foundation for future transient aerodynamic studies relevant to Bangladesh's wind energy development.

## **2. Literature Review**

### **2.1 Overview of Aerofoil Aerodynamics for Wind Turbine Applications**

Aerofoil selection portrays as a critical role in determining the aerodynamic performance and energy conversion efficiency of small and medium horizontal axis wind turbines (HAWTs). The aerodynamic behavior of an aerofoil shows lift generation, drag losses, stall characteristics, and power coefficient distribution along the blade span. Modern wind turbine aerodynamics research elaborates the need for aerofoil profiles with high lift to drag ratios, stable performance across low to moderate Reynolds numbers, and predictable pressure distribution suitable for boundary-layer control (Selig & McGranahan, 2004; Vaquero et al., 2010). These characteristics become quite important for regions with modest wind resources like Bangladesh, where turbines often operate below optimal wind speeds. As a result, research continues to focus on evaluating aerofoil profiles and designing modifications for enhanced performance under region specific inflow conditions.

### **2.2 Reynolds Averaged Navier Stokes (RANS) Using $k-\omega$ SST Turbulence Model**

Computational Fluid Dynamics for numerical analysis has become a standard tool for analyzing turbine aerofoils which offers a detailed flow field insight. The Reynolds Averaged Navier Stokes (RANS) framework captures the mean flow behavior while turbulence effects, which is widely used for aerodynamic simulations across wind energy applications (Lomax et al., 2002). Among various turbulence models, the Shear Stress Transport (SST)  $k-\omega$  model has showed accuracy in predicting aerodynamic coefficients for attached and mildly separated flow conditions (Younoussi et al., 2024). Recent studies have validated SST based predictions against wind tunnel measurements for aerofoils operating at Reynolds numbers between  $2 \times 10^5$  and  $8 \times 10^5$ , confirming its reliability for small HAWT analysis (Fadaei et al., 2023; Rahman et al., 2025).

On the other hand, it also provides flexibility in mesh design and windowing C type and O type structured grids by optimizing the near wall refinement ( $y^+ \approx 1$ ), and explores the domain size on far field points. These capabilities show the good simulation of laminar to turbulent transition behavior and stall onset phenomena that directly affect turbine performance (Campobasso et al., 2008; Munduate & Ferrer, 2009).

### **2.3 Use of Virtual Armfield C15 Wind Tunnel and Experimental Validation**

Virtual wind tunnel, Armfield C15 system have become a valuable tool for validating CFD predictions in academic environments. This platform allows controlled testing of aerofoil sections at different angles of attack, enabling the extraction of lift, drag, and moment coefficients that support the benchmarking of numerical simulations (Madha et al., 2024). Recent educational and research of virtual wind tunnels have demonstrated strong agreement between computational results and laboratory measurements across low speed aerodynamic conditions (Feng et al., 2015; Bachant & Wosnik, 2016). Validation remains crucial for ensuring that numerical outcomes are meaningful and applicable to real world turbine designs.

### **2.4 Wind Resource Assessments for Bangladesh**

Bangladesh's wind energy potential has portrayed significant attention, with several studies identifying coastal and offshore regions as promising locations for small wind turbine setups. Research by Islam et al. (2021), Habib et al. (2025), and Karim et al. (2021) has shown that average wind speeds between 5 to 7 m/s average at hub heights relevant to rural electrification and power systems. These findings highlight the necessity of examining aerofoil performance at moderate Reynolds numbers. Furthermore, the lack of extensive experimental wind tunnel studies within the country, highlights the need for computational investigations that focus on region specific wind conditions.

## **3. Methodology and Numerical Approach**

A numerical investigation was carried out to evaluate the aerodynamic characteristics of the NACA4412 aerofoil under flow conditions of small wind turbine applications in Bangladesh. The study employed a steady state Reynolds Averaged Navier Stokes (RANS) formulation with the Shear Stress Transport (SST)  $k-\omega$  turbulence model. This model was selected due to its established accuracy in predicting boundary layer separation, adverse pressure effects,

and near wall behavior at low to moderate Reynolds numbers results in small scale wind energy systems. The simulations were conducted in ANSYS Fluent 2025 R1, using a structured C type mesh and wall refinement to capture viscous effects.

### 3.1 Use of 7 m/s Wind Speed (Bangladesh Context)

The decision to conduct simulations at a 7 m/s free stream velocity was based on the wind resource characteristics of the coastal and offshore regions of Bangladesh. It includes Cox’s Bazar, Kuakata, and Saint Martin’s Island. Numerous wind assessments indicate that these regions exhibit average wind speeds between 5 to 7 m/s at 30-50 m hub heights, making small wind turbines viable for energy production.

The 7 m/s operating point is therefore selected because:

1. It shows near average wind conditions during the pre-monsoon and monsoon seasons.
2. It fits within the efficiency range for most small HAWTs.
3. It provides a benchmark for Bangladesh’s community about wind energy projects.

### 3.2 Computational Domain and Aerofoil Geometry

The numerical domain is consisted of a C type structure with enclosed NACA4412 aerofoils Boolean. The aerofoil geometry was generated using standard coordinate definitions with a chord length of 1m. The far field boundaries were positioned to minimize the blockage effects are given below in Table 1.:

Table 1. Solution Domains

Boundaries	Domain Setup
Upstream	15c
Downstream	20c
Upper and Lower	15c

This domain size ensures minimal influence of outer boundaries on pressure distribution, illustrated in Figure. 3.

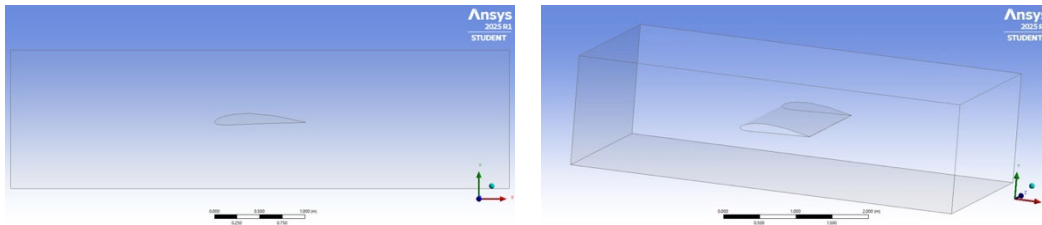


Figure. 3. Solution Domain Setup

### 3.3 Mesh Generation and Near Wall Refinement

A high quality C type mesh was generated around the aerofoil to properly capture the flow gradients, with clustering near the leading and trailing edges (Table 2- Table 4). The boundary layer region wall distance is  $y^+ \approx 1$ , ensuring compatibility with the SST k- $\omega$  model, shown in Figure. 4. The elements remained 120,000 - 150,000 and the layer height calculated by:

$$y = \frac{y^+ \mu}{\rho U_\infty}$$

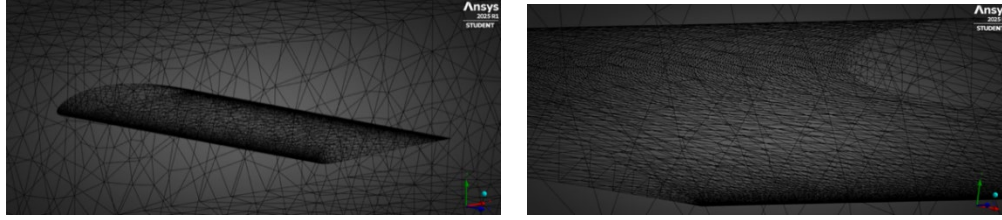


Figure. 4. Mesh Generation and Wall Refinement

### 3.4 Governing Equations for the Analysis

#### 3.4.1 Continuity Equation

For incompressible steady state flow:

$$\nabla \cdot u = 0$$

#### 3.4.2 RANS Momentum Equation

$$\rho(u\nabla)u = -\nabla p + \nabla[(\mu + \mu_t)(\nabla u + \nabla u^T)]$$

#### 3.4.3 SST k- $\omega$ Turbulence Model Equation

For the turbulent kinetic energy:

$$\frac{\partial k}{\partial t} + u\nabla k = P_k - \beta * k\omega + \nabla[(\mu + \sigma_k\mu_t)\nabla k]$$

For specific dissipation rate:

$$\frac{\partial \omega}{\partial t} + u\nabla \omega = \alpha \frac{\omega}{k} P_k - \beta \omega^2 + \nabla[(\mu + \sigma_\omega\mu_t)\nabla \omega]$$

The SST model blends the k- $\epsilon$  in the free stream with k- $\omega$  near walls, making it suitable to predict aerofoil aerodynamics.

### 3.5 Boundary Conditions and Angle of Attack Implementation

Table 2. Setup Conditions

Conditions	Implementation
Velocity Inlet ( $U_\infty$ )	7 m/s,
Turbulence Intensity	1%
Pressure Outlet ( $p$ )	0 Pa
Aerofoil Wall	No slip, stationary
Angles of Attack	-8°, -4°, 0°, 4°, 8°

### 3.6 Solver Configuration in ANSYS Fluent

Table 3. Boundary Setup

Configuration	Implementation
Solver	Pressure based
Formulation	Steady State
Pressure - Velocity Coupling	Simple
Spatial Discretization	Pressure: Second Order
	Momentum: Second Order Upwind
	Turbulence Equation: Second Order Upwind
Convergence Criteria	Residuals $< 10^{-5}$
Angles of Attack	Monitored Stabilization of $C_l$ and $C_d$

After implementing the solver configurations in ANSYS, the simulation initiated which is illustrated in Figure. 5.

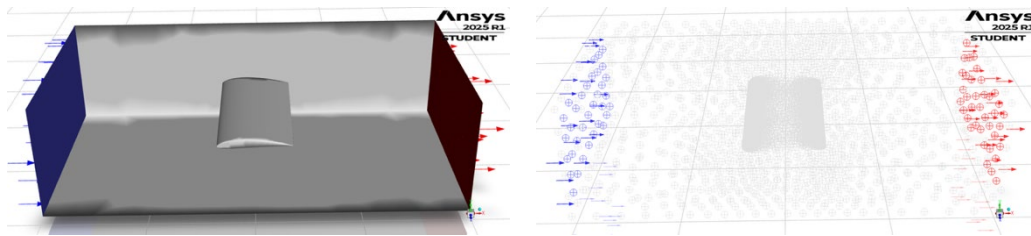


Figure. 5. Solver Configuration

### 3.7 Aerodynamic Coefficients Computation

To calculate the Dynamic Pressure:

$$q = \frac{1}{2} \rho U_{\infty}^2$$

For the Lift Coefficients:

$$C_l = \frac{L}{qA}$$

For the Drag Coefficients:

$$C_d = \frac{D}{qA}$$

For the Moment Coefficients:

$$C_m = \frac{M_c}{qcA}$$

For the Reference Area:

$$A = c \times 1m$$

The coefficients will be extracted using ANSYS Fluent's Force Coefficient reporting tool.

#### 4. Numerical Analysis and Data Extraction

The aerodynamic coefficients of the NACA4412 aerofoil were evaluated at  $-8^\circ$ ,  $-4^\circ$ ,  $0^\circ$ ,  $4^\circ$ , and  $8^\circ$  angles of attack under a velocity of 7 m/s, which represents the general wind speed conditions in Bangladesh’s coastal regions. The computed lift coefficient, drag coefficient, moment coefficient, and aerodynamic efficiency provides the insight into aerofoil behavior under low to moderate Reynolds number conditions, illustrated in Figure. 6.

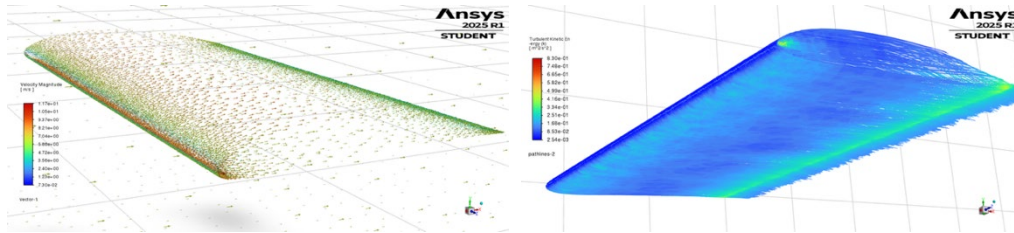


Figure. 6. Resulted Velocity and Kinetic Turbulent Contour

The overall results exhibit the aerodynamic results with cambered aerofoils: linear lift increase with angle of attack, minimal drag near zero, and improving lift to drag ratio up to moderate positive angles. These outcomes validate the suitability of the NACA4412 profile for small wind turbine blades operating in moderate wind conditions.

#### 4.1 Aerodynamic Coefficient Data

The Table 4 summarizes the aerodynamic coefficients collected from the simulations. These values serve as the core dataset for analyzing aerodynamic behavior under Bangladeshi wind conditions.

The lift coefficient increases nearly simultaneously with angles of attack, while drag remains low at small angles and rises gradually with increasing angles. The moment coefficient becomes more negative as angle of attack increases, which is expected due to the cambered geometry, shown in Figure. 7.

Table 4. Aerodynamic Coefficients for NACA4412 at ( $U_\infty = 7 \frac{m}{s}$ )

Angles of Attack	$C_l$	$C_d$	$C_m$	$\frac{C_l}{C_d}$
$-8^\circ$	-0.663	0.0127	-0.05	-52.2047
$-4^\circ$	-0.251	0.0084	-0.06	-29.8810
$0^\circ$	0.234	0.0086	-0.11	27.2093
$4^\circ$	0.681	0.0121	-0.13	56.2810
$8^\circ$	1.121	0.0137	-0.14	81.8248

The cambered geometry resulted velocity magnitude and pressure impacts shown in the following Figure. 7.

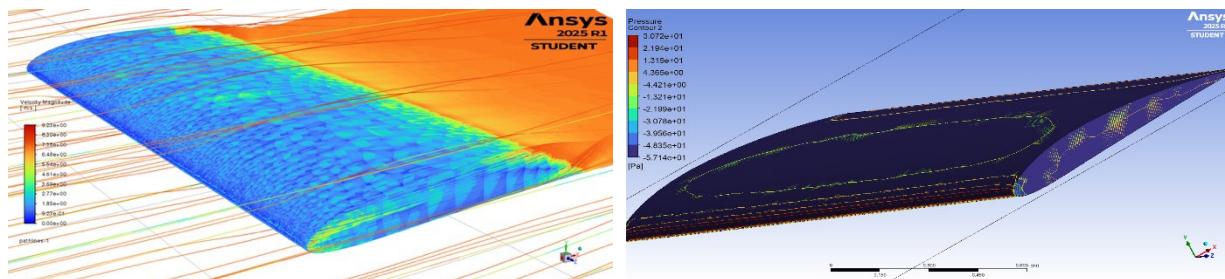


Figure. 7. Resulted Velocity Magnitude and Pressure Impacts upon Aerofoil

## 4.2 Lift Curve Characteristics

Figure. 8 plots the variation of lift coefficient with angle of attack. The curve shows a near linear behavior from  $-8^\circ$  to  $8^\circ$ , like the NACA4412 aerofoil theory.

And the key findings are:

- i. Negative lift occurs at negative attacks because the camber shifts the zero lift angle to approximately  $-4^\circ$ .
- ii. Peak lift within the tested range occurs at  $+8^\circ$ , with  $C_l = 1.121$ .

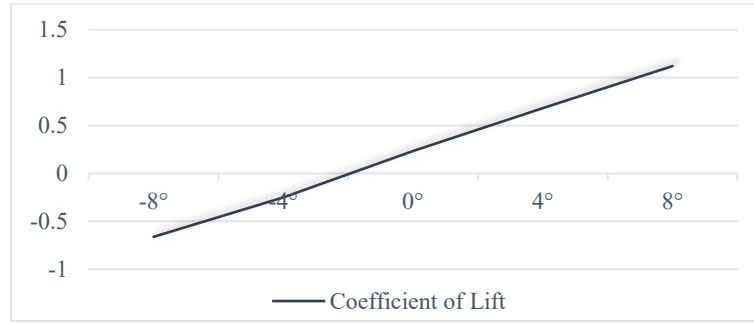


Figure. 8. Lift Coefficient Curve

## 4.3 Drag Behavior and Boundary Layer Effects

Figure. 9 shows the variation of drag coefficient with angles of attack. The drag behavior reflects the boundary layer performance at a moderate Reynolds number:

- Minimum drag occurs between  $-4^\circ$  and  $+4^\circ$ , with  $C_d \approx 0.0084$ .
- $C_d$  increases at larger positive and negative angles due to stronger pressures & mild leading edge separation.
- The drag rise between  $+4^\circ$  and  $+8^\circ$  is smooth, indicates delayed stall characteristics which is beneficial for small turbine blades.

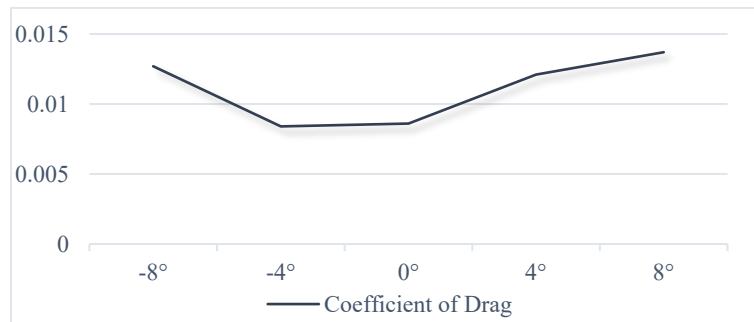


Figure. 9. Drag Coefficient Curve

## 4.4 Aerodynamic Efficiency

The lift to drag ratio is a critical metric for wind turbine blade design. The key findings here:

- i. Maximum efficiency occurs at  $+4^\circ$  to  $+8^\circ$  with  $\frac{C_l}{C_d} \approx 56.2810$  to  $81.8248$ , shown Figure. 10 Curve
- ii. Efficiency drops sharply for negative angles due to unfavorable pressure distribution.
- iii. Moderate positive angle of attack offers optimal turbine operation under Bangladesh's wind condition.

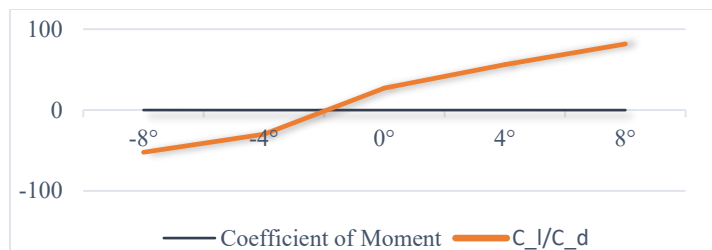


Figure. 10.  $C_m$  to  $C_l/C_d$  ratio

This range should be used as the basis for selecting aerodynamic pitch and blade elements.

## 5. Reported Aerodynamic Results and Discussion

### 5.1 Interpretation of Aerodynamic Behavior

The aerodynamic coefficients obtained from numerical simulation demonstrate that the NACA4412 aerofoil shows highly predictable and stable aerodynamic behavior within the tested angles of attack range. The lift growth observed from  $-8^\circ$  to  $+8^\circ$  confirms that the aerofoil operates well under a Reynolds number of approximately  $4.8 \times 10^5$ . This behavior is advantageous for small wind turbines, which experiences fluctuating wind inflow and require good aerodynamic stability to ensure smooth power output.

Drag levels remain low at near zero and rise gradually with increasing angles of attack, indicating that boundary layer attachment is maintained throughout the simulated range. This is shown by the pressure and streamline plots, which show no evidence of large separation bubbles or abrupt flow detachment. These results suggest that the NACA4412 maintains an efficient aerodynamic profile even at moderate and favorable conditions for power extraction at low wind speeds characteristic of Bangladeshi coastal regions.

### 5.2 Lift to Drag Ratio and Turbine Performance Implications

The lift to drag ratio is a critical parameter in determining rotor efficiency which directly influences the torque available for power generation. The numerical results show that  $(C_l/C_d)$  reaches peak values between  $4^\circ$  and  $8^\circ$ , corresponding to aerodynamic efficiencies of approximately 56.2810 to 81.8248. This efficiency range aligns well with the operational angles commonly used in small HAWT blades designed for moderate wind conditions.

For low wind regions like Bangladesh, where turbines often operate under transitional wind speeds, this ratio is essential. The observed performance indicates that turbine blades with the NACA4412 aerofoil should be used to operate within this angle of attack to optimize energy capture. This observation is highly relevant for rural and coastal installations where resource is limited, and turbine setup is critical for long term deployment.

### 5.3 Suitability for Bangladesh's Coastal Wind Regime

Given that Bangladesh's coastal regions normally experience average wind speeds around 7 m/s, and the results obtained in this study directly correspond to real world turbine operating conditions, visualized in Figure. 11. The aerodynamic coefficients reflect how the aerofoil would behave throughout the year with the inflow characteristics. This aerodynamic understanding enables more accurate predictions for annual energy production (AEP), and design optimization under practical environmental conditions.

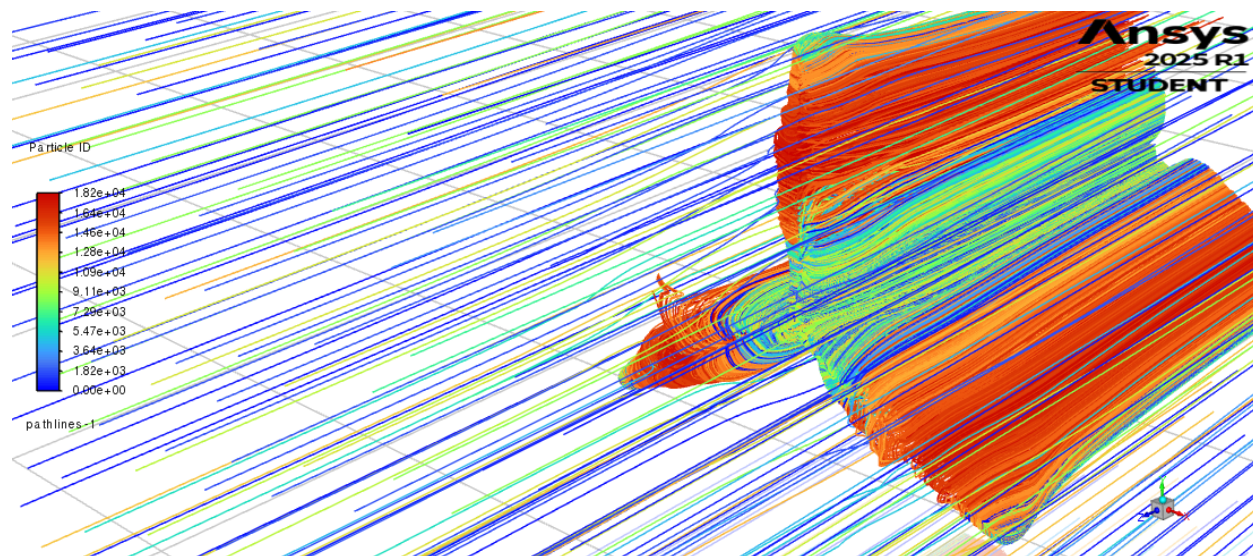


Figure. 11. Wind Pressure Impacts on Turbine Blade Design with NACA4412 Aerofoil

Overall, the NACA 4412 demonstrates strong aerodynamic potential for deployment in small scale community energy projects by emphasizing efficiency, and minimal to moderate Reynolds number variations.

## 6. Conclusion

This study investigated the aerodynamic characteristics of the NACA4412 aerofoil using a steady RANS SST  $k-\omega$  model at a wind speed of 7 m/s, compared to Bangladesh's wind speed in the coastal region. Numerical simulations were performed across a range of angles of attack from  $-8^\circ$  to  $+8^\circ$ , with a comprehensive assessment of lift, drag, moment behavior, and flow. The results show that the aerofoil climbs linear lift growth within the tested angles of attack, minimal drag near zero, and high aerodynamic efficiency between  $4^\circ$  and  $8^\circ$ , aligning well with the operational requirements of small horizontal axis wind turbines in moderate wind regions like Bangladesh. The pressure, velocity, and streamline visualizations confirm that the flow remains attached up to  $8^\circ$ , with no significant separation or stall. This stability is particularly advantageous for turbines deployed in coastal regions of Bangladesh, where seasonal wind variation requires reliable performance in these types of conditions. The aerodynamic behavior captured in this study demonstrates that the NACA4412 is a strong candidate for small turbine blade design, offering good performance, and favorable efficiency under typical local wind conditions.

## 7. Future Work

Future work may extend the analysis to three dimensional blade modeling, tip vortex evaluation, transient turbulence modeling, and full rotor simulations incorporating Blade Element Momentum (BEM) theory. Additionally, integrating site specific wind data and structural load analysis could further enhance turbine design accuracy for coastal and rural regions of Bangladesh.

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## Biographies

**Anika Nawar (Outstanding Student Awardee 2023, IEOM Society International)** studied and worked on research at both Institute of Education and Research, University of Dhaka, and Department of Mechatronics Engineering, World University of Bangladesh. She was the 1<sup>st</sup> Runner-up of the KYAU National Hackathon 2023. She was the Former Secretary of IEOM Society World University of Bangladesh Chapter till 2023 and Former President of Mechatronics Club, World University of Bangladesh. He was a Joint Champion of IEOM Green Technology and Innovation Contest 2019 by World University of Bangladesh.

**Jowad Md Madha (Professional Member and Outstanding Student Awardee 2023, IEOM Society International)** is studying in Automotive Systems Engineering at Heilbronn University in Germany. He also studied and worked on research at both Institute of Education and Research, University of Dhaka and Department of Mechatronics Engineering, World University of Bangladesh. He was a participant at prestigious 2025 Tsinghua-Princeton-CI Summer School on Combustion Energy jointly by Tsinghua University from China and Princeton University of USA. He was the 1<sup>st</sup> Runner-up of the KYAU National Hackathon 2023. He was the Former President of IEOM Society World University of Bangladesh Chapter till 2023 and Former Vice President of Mechatronics Club, World University of Bangladesh. He was a Joint Champion of IEOM Green Technology and Innovation Contest 2019 by World University of Bangladesh and was the 1<sup>st</sup> Runner-up of 9th National Astro Olympiad 2014, Bangladesh.

**Wenbo Yang (Mater Student Member of the Chinese Society of Engineering Thermophysics)** is a student doing research in the Institute of Engineering Thermophysics, Chinese Academy of Sciences. He also studied in School of Space exploration (formerly the School of Aeronautics and Astronautics), University of Chinese Academy of Sciences. Focus on Structural Design of Aero-derivative Gas Turbine Combustor, Hypersonic Propulsion and Numerical Simulation of Turbulent Combustion. He participated in the Undergraduate Scientific Innovation Program of the Chinese Academy of Sciences. He was a participant at the prestigious 2025 Tsinghua-Princeton-CI Summer School on Combustion Energy jointly by Tsinghua University from China and Princeton University of USA.