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Effect of Airfoil Thickness on Aerodynamic Performance of NACA Symmetric Airfoils

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ABSTRACT

By altering airfoil designs, scientists have been putting forth endless effort to increase turbine efficiency over the past few decades. These modifications focus on maximizing efficiency specifically for regions with low air velocities, thereby enhancing overall power output. This study focused on varying the thickness of symmetrical airfoils at Reynolds number of 4.6×10^5. Five different NACA-4 series symmetric airfoils are investigated, with maximum thicknesses of 12%, 14%, 16%, 18% and 20% of the airfoil at 30% chord corresponding to NACA0012, NACA0014, NACA0016, NACA0018, NACA0020, respectively. ANSYS FLUENT was used to simulate three-dimensional flows. Numerical analyses indicated a gradual increase in the lift-to-drag ratio (Cl/Cd) with decreasing thickness of airfoils. The airfoil with the lowest thickness (12%), the NACA0012, has the highest Cl/Cd (15.23096). On the other hand, the NACA0020 exhibits the lowest lift-to-drag ratio (11.7848) despite having the largest thickness (20%). The pressure and velocity contour plots of these two airfoils illustrate the distribution of pressure and velocity that contributes to the differences in lift generation. Researchers might find the analysis's conclusions useful in developing future airfoil and turbine designs and improving the accuracy of engineering models.

Keywords: Aerodynamic Performance, Numerical Simulation, Relative Thickness, Lift Coefficient, Drag Coefficient

1. Introduction

As the world relies heavily on energy, primarily from nonrenewable sources (i.e., fossil fuels), the depletion of these resources has resulted in shortages in electricity production. As a result, there is now more demand for renewable energy sources including hydropower, wind, and solar. In 2021, the world's energy consumption is projected to reach 14.21 Gtoe, or approximately 165.26 billion kWh annually [1]. Fig.1 presents the annual power generation from various sources, highlighting the significant dependence on fossil fuels. Currently, fossil fuels, including coal, gas, and oil, provide about 80% of the world's energy supply, with nuclear power contributing an additional 4.22% to global electricity generation [1, 2].

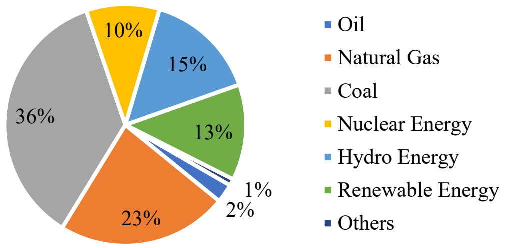

Fig.1 Annual electricity generation by different sources

These non-renewable fuels have a limited quantity and will eventually run out, therefore finding sustainable alternatives is necessary to fulfill the world's rising energy requirements. Globally, renewable resources are expected to contribute around 12.8% of power production in 2021. Among these, solar energy accounts for 6.54% of the total energy, while wind energy contributes 3.62% and other sources account for 2.58% [1]. As observed, wind energy accounts for only a small portion of the world's energy supply and is less studied and developed than other renewable sources, such as biomass, hydropower, and solar (see Fig.2 for details).

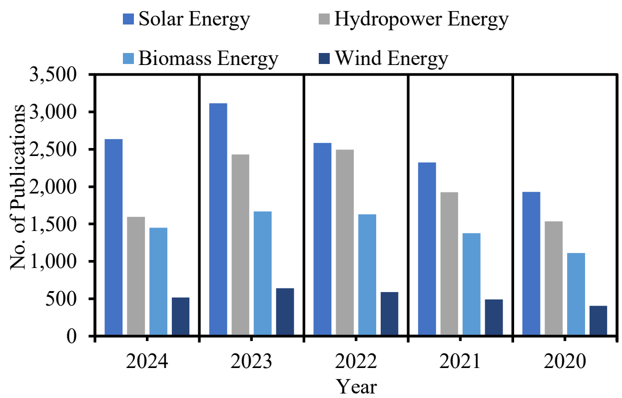

Fig.2 Current research on different renewable energy sources (solar, hydropower, biomass and wind)

As can be seen from Fig.2, there are comparatively less research on wind power in comparison to other renewable energy sources. Wind speed has a significant impact on the power generated by wind turbines. Even a small decrease in wind speed significantly lowers the wind turbines' power production. The wind speed as it gets closer to the turbine blades is directly proportional to the power output of the wind turbine [3]. Therefore, to capture as much energy as possible in areas with low wind speeds, appropriate wind turbine modifications are needed. To enhance turbine blade efficiency, numerous studies on designs, materials, and

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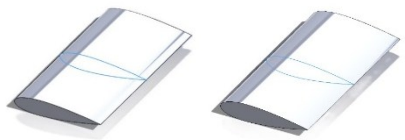
manufacturing processes have been conducted, with a strong focus on increasing the lift coefficient of airfoils, as its efficiency relies on a higher lift-to-drag ratio. The study by Kang et al. (2015) found that oscillation frequency and amplitude significantly boost lift, creating vorticity around the airfoil and maintaining a low-pressure distribution on the upper surface [4]. Debbache et al. (2018) demonstrated that, depending on the airfoil type, the lift coefficient increases with airfoil thickness up to a certain value [5]. According to Bai et al.'s (2011) analysis of the S809 and FX60-100 airfoils, the vortex diffuser at the blade tip raises the pressure coefficient of the vortex core and boosts blade efficiency [6]. In another study, Bangga et al. (2021) demonstrated that the turbine power coefficient increases with airfoil thickness up to 25–30% before decreasing due to trailing edge separation [7]. Lee et al. (2011) examined the impact of Gurney flaps on the aerodynamics and wake characteristics of a NACA0015 airfoil, finding increased lift, drag, and pitching moment [8]. According to the study of Seo et al. (2016) the form of the grooves on the airfoil surface greatly enhances the aerodynamics of wind blades, increasing the lift to drag ratio by 15.3% in some circumstances while sustaining these gains at particular Reynolds numbers and angles [9]. Ghose et al. (2024) stated in their paper that unsymmetrical airfoils exhibit the highest lift-to-drag ratio, with the maximum achieved at a 5-degree angle of attack [10].

It is evident that very few studies have focused on varying the thickness of wind turbine blades to enhance efficiency. The goal of this research is to ascertain how altering the thickness of NACA 4-digit symmetric airfoils impacts the lift-to-drag ratio and, in turn, the wind turbine blades' overall efficiency.

2. Methodology

Five single-blade symmetric airfoil geometries for NACA0012, NACA0014, NACA0016, NACA0018 and NACA0020 were constructed in SolidWorks software for this study. The airfoils feature different thicknesses: 12% for NACA0012, 14% for NACA0014, 16% for NACA0016, 18% for NACA0018, and 20% for NACA0020. Each blade was designed with a chord length (C) of 0.20 m and a span of 0.40 m. The geometry of all five blades is illustrated in Fig.3.

(a) NACA 0012 (b) NACA 0014 (c) NACA 0016



(d) NACA 0018 (e) NACA 0020

Fig.3 Single-blade geometries of VAWT blade configurations considered in this study

A total of three domains were created using ANSYS Design Modeler software to facilitate the computation. The illustration is provided in Fig.4, and the domain sizes are listed in Table 1.

Table 1 Domain sizes

Domain 1		Domain 2		Domain 3	
H1	1m	H5	0.5m	H9	0.2m
H2	2m	H6	1.2m	H10	0.6m
V3	0.35m	V7	0.2m	V11	0.08m
V4	0.35m	V8	0.2m	V12	0.08m

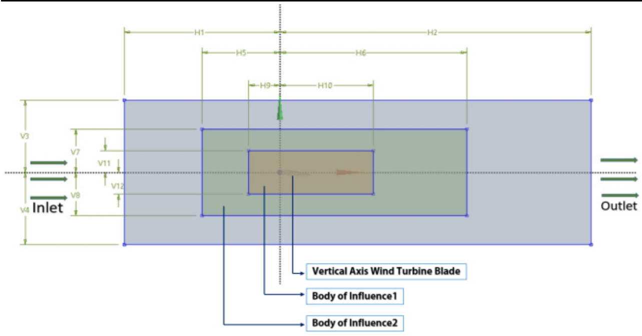
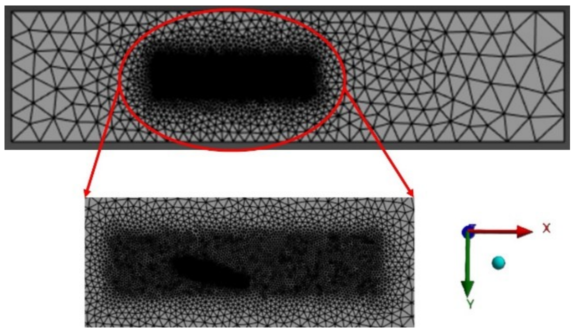
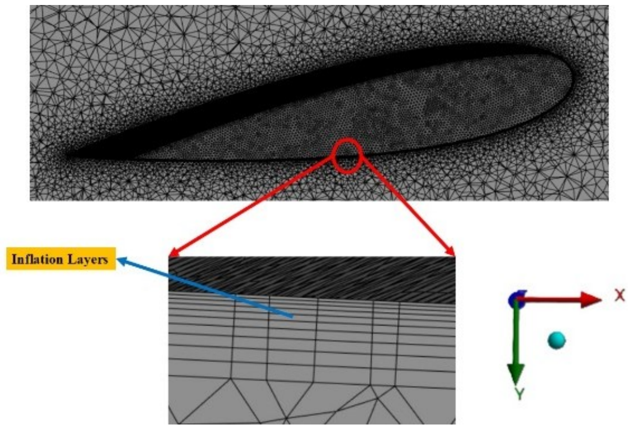


Fig.4 Computational Domain

Two stages of the body of influence were incorporated within the computational domain, with element sizes of 7×10^{-3}m and 8×10^{-2}m, respectively. Fig.5 indicates the illustration of the final used mesh.



(a)



(b)

Fig.5 (a) Final mesh quality and (b) Mesh with inflation layers

The targeted skewness for finally used mesh was 0.09 and the numerical were solved using viscous k $-\varepsilon$ model in ANSYS Fluent software environment. All data were computed from the inlet with a fluid velocity of 7 ms^{-1}. The technical data for meshing and parameters for the numerical setup are presented in Table 2.

Table 2 Overview of the key parameters of numerical investigation

Parameter	Value Type	Parameter	Value Type
Edge sizing	7×10^{-4}m	Viscous Model	SST k-omega
Face sizing	1×10^{-3}m	Fluid density	1.205kgm^{-3}
Body sizing 1	7×10^{-3}m	Fluid viscosity	1.82e-05kgm^{-1}s^{-1}
Body sizing 2	8×10^{-2}m	Velocity	7ms^{-1}
Inflation (first layer thickness)		Reference values	Compute from inlet Area- 0.08m^2 Length- 0.2m
First layer height	4×10^{-5}m	Viscous Model	SST k-omega
Maximum layers	10	Fluid density	1.205kgm^{-3}

3. Results & discussion

We verified that the selected mesh size is suitable after doing a mesh dependency analysis because a coarser mesh yielded comparable results (Fig.6). This guarantees our simulation's precision and dependability.

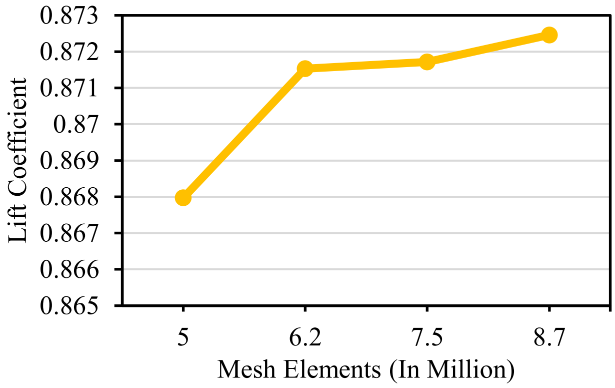
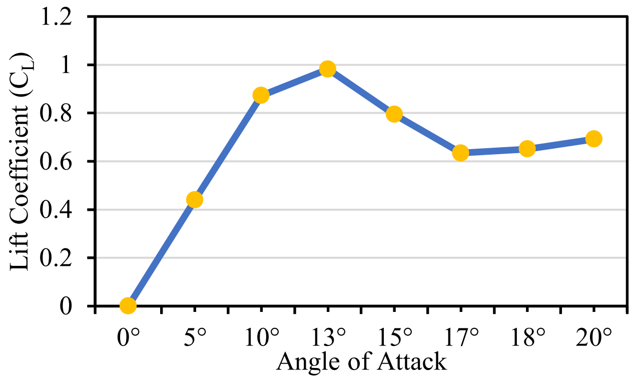
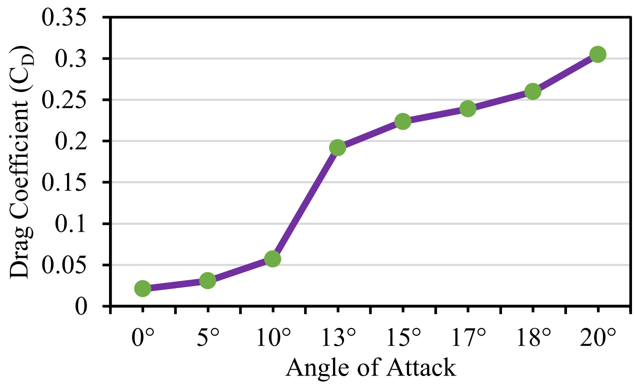


Fig.6 Mesh dependency analysis for NACA 0012 (10 degree AoA)

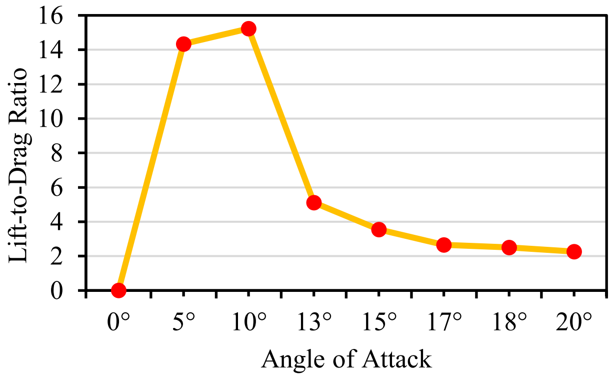
Fig.7 displays the numerical analysis results of the selected symmetric NACA 4 series airfoils. The analysis indicates that the NACA 0012 airfoil, with the lowest thickness (≈12%), achieved the highest lift-to-drag ratio among the five studied airfoils. It reached a maximum lift coefficient (≈0.9818) at a 13-degree angle of attack (AoA), identifying this as the stall angle. This authors numerically investigated the aerodynamic performance of the NACA 0012 airfoil and identified the stall angle at 14° AoA, compared to 13° AoA in the present study [11]. Although, the lift coefficient (C_L) increased gradually up to the stall angle and then began to decrease, the drag coefficient (C_D) consistently rose with increased AoA. The maximum lift-to-drag ratio (C_L/C_D) for NACA 0012 was achieved at 10 degrees AoA (≈15.231), which is 29.24% higher than the minimum C_L/C_D value (≈11.7848) observed for the NACA 0020 airfoil. This clearly shows that the C_L/C_D ratio decreases with increasing airfoil thickness. Consequently, the NACA 0012 airfoil is expected to generate more power than the NACA 0020 airfoil.



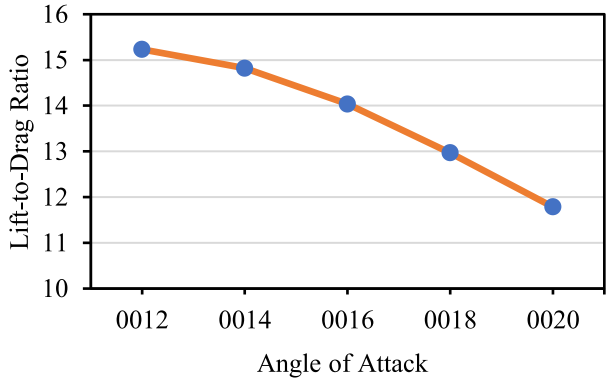
(a) Lift Coefficient vs Angle of Attack (NACA0012)



(b) Drag Coefficient vs Angle of Attack (NACA0012)



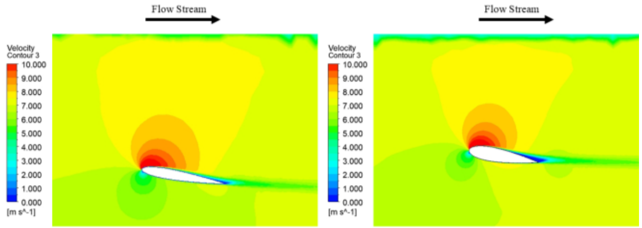
(c) Lift to Drag Ratio vs Angle of Attack (NACA0012)



(d) Lift to Drag Ratio vs Types of Airfoils (10˚ AoA)

Fig.7 Variation of (a) lift coefficient (C_L), (b) drag coefficient (C_D), (c) lift-to-drag ratio (L/D) with the angle of attacks of a selected airfoil (NACA0012) and (d) Lift to Drag Ratio (L/D) vs Types of Airfoils (10˚)

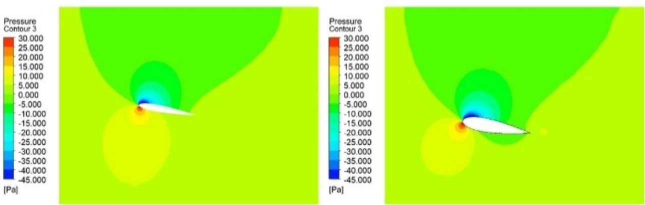
Fig.8 displays velocity contour plots for the airfoils with the best and worst lift-to-drag ratios among those analyzed in this study, using the blade's midplane. NACA0012 (Fig.8(a)) airfoil shows a greater overall velocity distribution compared to the NACA0020. In contrast, the NACA0020 (Fig.8(b)) airfoil has a higher velocity on the lower surface, leading to lower pressure and, consequently, reduced lift generation. For the NACA0012 airfoil, the lower velocity on the lower surface (Fig.8(a)) suggests an area of increased pressure, contributing to a higher lift force relative to the other configurations. Therefore, out of the five airfoils, the NACA 0012 airfoil with the least thickness exhibits effective velocity distribution and achieves the highest lift-to-drag ratio.



(a) (b)

Fig.8 Velocity contour of turbine blades at 10-degree AoA (a) NACA 0012 (b) NACA 0020

Fig.9 displays the pressure contour map for NACA0012 and NACA0020, which illustrates the pressure distribution throughout this core region. As shown in Fig.9(a), the NACA0012 blade has a greater region of negative pressure distribution along the suction surface than the other five blade types. The blade's lift is increased by an upward push caused by a greater pressure differential between the upper and lower surfaces. As a result, among the blades, NACA0012 (Fig.9(a)) generates the most lift, whereas NACA0020 (Fig.9(b)) produces the least.



(a) (b)

Fig.9 Pressure Contour of turbine blades at 10-degree AoA (a) NACA 0012 (b) NACA 0020

To ensure their accuracy and reliability, the results have been validated. The findings are consistent, as they closely align with those reported in other sources [12].

4. Conclusion

This paper investigated the effect of blade thickness on the aerodynamic performance of NACA 4-digit symmetric airfoils. Five different 4-digit symmetric airfoils (NACA0012, NACA0014, NACA0016, NACA0018, NACA0020) were numerically analyzed with varying thickness of 12%, 14%, 16%, 18% and 20% of the airfoil at 30% chord, respectively. The results indicate that NACA0012 achieves the highest lift-to-drag ratio (≈15.23) at a 10° angle of attack among the selected airfoils. The highest lift coefficient for NACA0012 reaches approximately 0.982 at a stall angle of 13°. Despite a gradual increase in drag coefficient with rising angles of attack, the optimal angle for NACA0012 was determined to be 10 degrees. NACA0020 provided the lowest lift-to-drag ratio (≈11.7848) at the optimal angle, which was 29.24% lower than that of the NACA0012. This demonstrates that as the thickness of symmetric 4-digit airfoils increases, the lift-to-drag ratio decreases. It highlights the advantage of using thinner airfoils, such as NACA0012, for lift-based wind turbine applications. Additionally, velocity and pressure contour plots at the cross-sectional plane are provided in this paper to enhance understanding. In order to obtain optimal power production and good aerodynamic performance, researchers and decision-makers will find this study useful in choosing appropriate turbine blades for lift-type VAWT applications.

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NOMENCLATURE

Gtoe : Gigatonne of Oil Equivalent
NACA : National Advisory Committee for Aeronautics
VAWT : Vertical-Axis Wind Turbine