AERODYNAMIC PERFORMANCE ANALYSIS OF NACA 2412 AND NACA 4412 AIRFOIL PROFILES FOR SMALL-SCALE WIND TURBINES USING CFD

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ABSTRACT

Small-scale wind turbines require airfoil profiles that are able to produce sufficient lift while maintaining low drag under low Reynolds number conditions. This research analyzes the aerodynamic performance of NACA 2412 and NACA 4412 airfoil profiles for small-scale wind turbine blade sections using Computational Fluid Dynamics (CFD). The Reynolds number is fixed at 300,000, with a chord length of 1 m and an inlet velocity of approximately 4.38 m/s. The angle of attack is varied at 0°, 4°, 8°, 12°, and 16°. The analyzed parameters are lift coefficient (Cl), drag coefficient (Cd), and lift-to-drag ratio (Cl/Cd). The NACA 2412 result shows that the maximum Cl occurs at 8°, while the maximum Cl/Cd occurs at 4°, indicating that the highest lift is not necessarily the most efficient operating condition because drag increases significantly at higher angles of attack. The NACA 4412 result shows a higher lift generation tendency due to its larger camber and provides higher Cl/Cd in the low-to-moderate angle-of-attack region, with a maximum Cl/Cd of 50.64 at 8°. Validation against experimental and literature data shows that the numerical trends are consistent with the general aerodynamic behavior of cambered airfoils at low Reynolds number. Based on the Cl/Cd criterion, NACA 4412 provides stronger aerodynamic potential for small-scale wind turbine applications at Re = 300,000, while NACA 2412 remains useful as a more moderate airfoil profile.

Keywords: NACA 2412; NACA 4412; CFD; Reynolds number; small-scale wind turbine; lift coefficient; drag coefficient; lift-to-drag ratio

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INTRODUCTION

The development of renewable energy technology has become an important issue in modern engineering because fossil-based energy resources are limited and produce environmental impacts. Wind energy is one of the renewable energy sources that can be used for electricity generation, especially in areas with sufficient wind availability. Although large-scale wind turbines are commonly used in commercial wind farms, small-scale wind turbines are more suitable for decentralized power generation, household-scale systems, laboratory-scale development, and off-grid areas. In this context, the aerodynamic performance of the blade becomes a central factor because the blade is the component that directly converts wind kinetic energy into mechanical rotation.

Small-scale wind turbines generally operate at lower wind speed than large-scale turbines, causing the airfoil sections of the blade to work at low Reynolds number. At low Reynolds number, viscous effects become more dominant and the boundary layer is more sensitive to separation. Selig et al. (1995) state that low Reynolds number airfoils require careful aerodynamic selection because their lift and drag characteristics may differ significantly from airfoils operating at high Reynolds number. Airfoil performance is commonly represented by lift coefficient (Cl), drag coefficient (Cd), and lift-to-drag ratio (Cl/Cd), where the Cl/Cd ratio represents aerodynamic efficiency. Anderson (2016) explains that angle of attack affects lift and drag simultaneously; therefore, the optimum operating condition should not be determined only from the highest lift value.

NACA 4-digit airfoils are widely used in aerodynamic analysis because their geometry is standardized and can be generated using mathematical equations, making them suitable for numerical simulation and comparison. NACA 2412 and NACA 4412 share the same maximum thickness of 12% chord but different maximum camber (2% and 4% chord, respectively), which affects pressure distribution, lift generation, drag behavior, and stall tendency. Although NACA 4412 is expected to generate higher lift because of its larger camber, higher lift does not automatically mean better performance; both airfoils must therefore be compared using Cl, Cd, and Cl/Cd simultaneously.

Computational Fluid Dynamics (CFD) is used in this research because it enables numerical prediction of airfoil aerodynamic coefficients under controlled operating conditions without requiring a physical wind tunnel test for every case. Menter (1994) introduced the SST k-ω turbulence model, which is commonly used in airfoil simulations because it represents near-wall flow and adverse pressure gradient effects better than simpler turbulence models, making it suitable for the present low Reynolds number analysis. The Reynolds number used in this research is Re = 300,000, which represents a low Reynolds number operating condition relevant to small-scale wind turbine blade sections. The analysis is focused on Cl, Cd, and Cl/Cd, while pressure coefficient (Cp) is not used as a dependent variable.

Based on this background, the present study is directed to answer three questions: (1) how do NACA 2412 and NACA 4412 airfoil profiles affect aerodynamic performance; (2) how does the angle of attack from 0° to 16° affect Cl, Cd, and Cl/Cd for each profile; and (3) which airfoil profile provides the most favorable aerodynamic efficiency for small-scale wind turbine applications based on Cl/Cd. Accordingly, the objectives of this research are to analyze the aerodynamic performance of NACA 2412 and NACA 4412 at Re = 300,000, to evaluate the effect of angle of attack on Cl, Cd, and Cl/Cd, and to determine the airfoil profile and operating angle that provide the best aerodynamic efficiency for small-scale wind turbine blade sections.

RESEARCH METHOD

Research design and object

This research is a quantitative numerical study using Computational Fluid Dynamics to analyze the aerodynamic performance of NACA 2412 and NACA 4412 airfoils at Re = 300,000. Both airfoils have a chord length of 1 m and a maximum thickness of 12% chord; the key geometric difference is the maximum camber, which is 2% for NACA 2412 and 4% for NACA 4412, both located at 40% chord. The independent variables are airfoil profile and angle of attack (0°, 4°, 8°, 12°, 16°); the dependent variables are Cl, Cd, and Cl/Cd; and the control variables are Reynolds number, chord length, air properties, turbulence model, mesh strategy, and convergence criteria.

Reynolds number and inlet velocity

The inlet velocity is calculated using V = Re·μ / (ρ·c). Substituting Re = 300,000, dynamic viscosity μ = 1.7894 × 10^{-5} kg/m·s, air density ρ = 1.225 kg/m^3, and chord length c = 1 m gives an inlet velocity of V ≈ 4.38 m/s. This value is used as the velocity inlet to ensure that the simulation operates at the intended Reynolds number.

Computational domain, mesh, and solver settings

The computational domain is arranged to provide sufficient space for the flow to develop around the airfoil without being strongly affected by the outer boundaries. The inlet is defined as a velocity inlet (4.38 m/s), the outlet as a pressure outlet (0 Pa gauge), and the airfoil surface as a no-slip wall, while the upper and lower boundaries represent the far-field region. The mesh is refined near the airfoil surface, leading edge, trailing edge, and wake region so that the first layer height keeps y^+ near or below 1 for the SST k-ω model, and a mesh-independence check is applied to ensure that the results are not strongly dependent on the number of elements.

Figure 1. Boundary mesh of the computational domain

The simulation uses a pressure-based, steady, incompressible solver with the SST k-ω turbulence model, SIMPLE pressure-velocity coupling, least-squares cell-based gradient, and second-order schemes for pressure, momentum, turbulent kinetic energy, and specific dissipation rate. Convergence is monitored from residual decrease and a stable Cl/Cd value. After the simulation data are obtained, Cl and Cd are arranged based on airfoil type and angle of attack, and Cl/Cd is calculated by dividing Cl by Cd; the optimum angle is determined from the maximum Cl/Cd value rather than the maximum Cl value alone.

Validation method

Validation is conducted by comparing the coefficient results with experimental or literature data at Re = 300,000 or at the closest available low Reynolds number condition, using Cl and Cd because both parameters directly determine Cl/Cd. The percentage error is calculated using Error (%) = |Result − Experimental| / Experimental × 100%.

RESULTS AND DISCUSSION

Aerodynamic coefficients of NACA 2412 and NACA 4412

Table 1 and Table 2 present the aerodynamic coefficients of NACA 2412 and NACA 4412 at Re = 300,000 for angles of attack of 0°, 4°, 8°, 12°, and 16°.

Table 1. Aerodynamic coefficients of NACA 2412 at Re = 300,000

AoA (°)	Cl	Cd	Cl/Cd
0	0.2305	0.0150	15.37
4	0.6045	0.0221	27.35
8	0.7959	0.0479	16.62
12	0.7896	0.1018	7.76
16	0.7710	0.1720	4.48

Table 2. Aerodynamic coefficients of

NACA 4412 at Re = 300,000

AoA (°)	Cl	Cd	Cl/Cd
0	0.3958	0.0145	27.30
4	0.8400	0.0170	49.41
8	1.1900	0.0235	50.64
12	1.3700	0.0395	34.68
16	1.3350	0.0730	18.29

For NACA 2412, the lift coefficient increases from AoA 0° to 8° but the lift gain becomes less effective after 8°, while the drag coefficient increases continuously with angle of attack. This combination causes Cl/Cd to reach its maximum at AoA 4° (27.35), not at the angle with the highest Cl. This agrees with the aerodynamic concept explained by Anderson (2016), where the most efficient angle is often located before the high-angle region because drag begins to increase more rapidly as the airfoil approaches separation. Beyond AoA 8°, Cd rises sharply—from 0.0479 at 8° to 0.1018 at 12° and 0.1720 at 16°—so that Cl/Cd drops to less than one-third of its maximum value, indicating a strong drag penalty consistent with an approaching separated-flow regime.

For NACA 4412, the larger camber produces a higher Cl than NACA 2412 at every evaluated angle. Cl increases continuously up to AoA 12° (1.3700), while the highest Cl/Cd (50.64) occurs at AoA 8°, not at the angle of maximum Cl. This again confirms that the highest lift does not correspond to the highest aerodynamic efficiency. At AoA 16°, Cl decreases slightly while Cd increases significantly to 0.0730, so Cl/Cd falls to 18.29, indicating that the airfoil begins to lose efficiency as the flow approaches separation.

Comparison of Cl, Cd, and Cl/Cd

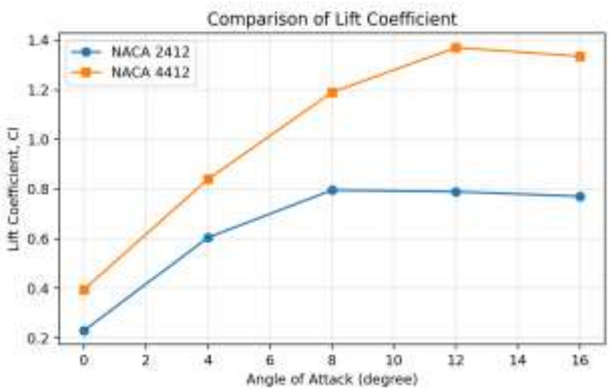

Figure 2. Comparison of lift coefficient (Cl) between NACA 2412 and NACA 4412

The lift coefficient comparison shows that NACA 4412 produces a higher Cl than NACA 2412 at all evaluated angles of attack, consistent with its larger camber (4% versus 2%), which produces stronger circulation and pressure difference around the airfoil. At AoA 0°, Cl of NACA 4412 is 0.3958 compared with 0.2305 for NACA 2412, and at AoA 8° the values are 1.1900 versus 0.7959, respectively.

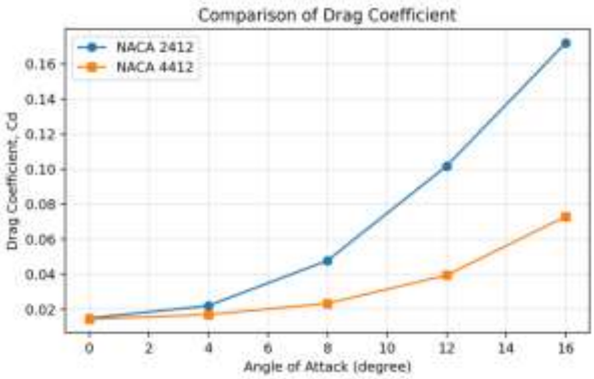

Figure 3. Comparison of drag coefficient (Cd) between NACA 2412 and NACA 4412

The drag coefficient increases with angle of attack for both airfoils, which is expected because a higher angle of attack strengthens the adverse pressure gradient and increases the tendency of flow separation. NACA 2412 shows a particularly strong drag increase after AoA 8°, rising from 0.0479 at 8° to 0.1720 at 16°, whereas NACA 4412 shows comparatively lower Cd values across the same range although its drag also increases at 12° and 16°.

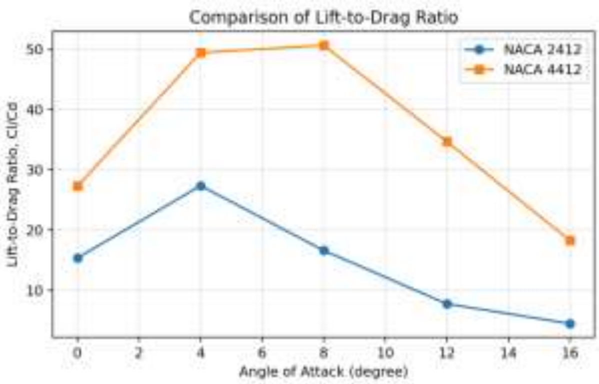

Figure 4. Comparison of lift-to-drag ratio (Cl/Cd) between NACA 2412 and NACA 4412

The Cl/Cd comparison is the most important part of the aerodynamic analysis because it represents efficiency. NACA 2412 reaches its maximum Cl/Cd at AoA 4° (27.35) and decreases afterward because drag increases faster than lift. NACA 4412 reaches a higher maximum Cl/Cd of 50.64 at AoA 8°, indicating stronger aerodynamic efficiency at Re = 300,000. From a small-scale wind turbine perspective, the favorable operating range is around 4°–8° for NACA 4412 and around 4° for NACA 2412, while operation at 12° and 16° is less efficient for both profiles.

Validation of aerodynamic coefficients

Table 3 summarizes the validation results against experimental/literature data. For NACA 2412, the Cl error is relatively small at AoA 4° and 8° (2.50% and 7.45%, respectively) and increases to 19.43% at AoA 12°, which is expected because the high-angle region is more sensitive to separation and turbulence-model prediction; the Cd error ranges between approximately 5% and 8%. For NACA 4412, the Cl error is very small from AoA 0° to 12° (below 2.5%) and increases to 6.80% at AoA 16°, while the Cd error reaches 14.12% at the same angle, consistent with the greater difficulty of predicting separated flow noted by Menter (1994). Overall, both profiles follow the expected aerodynamic trend—Cl increases initially before stagnating or decreasing at high AoA, while Cd increases continuously—supporting the interpretation that NACA 4412 provides better Cl/Cd potential than NACA 2412 in the evaluated range.

Table 3. Validation of Cl and Cd against experimental/literature data

AoA	Cl 2412	Err. Cl 2412	Cl 4412	Err. Cl 4412	Cd 2412	Err. Cd 2412	Cd 4412	Err. Cd 4412
0	0.2305	7.80%	0.3958	1.05%	0.0150	7.14%	0.0145	3.57%
4	0.6045	2.50%	0.8400	2.33%	0.0221	5.24%	0.0170	5.56%
8	0.7959	7.45%	1.1900	0.83%	0.0479	6.44%	0.0235	9.62%
12	0.7896	19.43%	1.3700	0.74%	0.1018	7.16%	0.0395	12.22%
16	0.7710	12.39%	1.3350	6.80%	0.1720	7.50%	0.0730	14.12%

Aerodynamic recommendation

Based on the comparison of Cl, Cd, and Cl/Cd, NACA 4412 provides stronger aerodynamic performance than NACA 2412 at Re = 300,000, producing higher Cl at all evaluated angles and reaching a higher maximum Cl/Cd. NACA 2412 remains useful as a more moderate profile, with its best efficiency at AoA 4° (Cl/Cd = 27.35), but its efficiency decreases sharply after AoA 8°. The recommended profile for the evaluated small-scale wind turbine condition is therefore NACA 4412, particularly near AoA 8°, using the maximum Cl/Cd criterion as the most direct indicator of aerodynamic efficiency. In blade design, the local pitch or twist should be arranged so that the airfoil section operates near its efficient angle range during normal wind turbine operation.

CONCLUSION

Based on the aerodynamic analysis of NACA 2412 and NACA 4412 at Re = 300,000, several conclusions can be drawn. First, with air density of 1.225 kg/m³, dynamic viscosity of 1.7894×10^{-5} kg/m·s, and chord length of 1 m, the required inlet velocity is 4.38 m/s. Second, NACA 2412 produces its highest Cl at AoA 8°, but its highest Cl/Cd occurs at AoA 4°, proving that maximum lift is not the same as maximum aerodynamic efficiency; NACA 2412 also experiences a strong drag increase at AoA 12° and 16°, so its efficient operating angle is located around AoA 4°. Third, NACA 4412 produces higher Cl than NACA 2412 at all evaluated angles because of its larger camber, with the highest Cl/Cd occurring at AoA 8°, showing that the profile is efficient in the low-to-moderate angle-of-attack region. Finally, based on the Cl/Cd criterion, NACA 4412 provides better aerodynamic potential for small-scale wind turbine blade sections at Re = 300,000. Future research is recommended to test additional angles of attack with smaller intervals (especially between 4° and 10°), to include three-dimensional blade modeling so that tip loss, spanwise flow, and blade rotation effects can be evaluated, to perform experimental wind tunnel testing for direct validation, and to compare both profiles with airfoils specifically designed for small wind turbine applications.

NOMENCLATURE

Cl lift coefficient [-]

Cd drag coefficient [-]

Cl/Cd lift-to-drag ratio [-]

Re Reynolds number [-]

α angle of attack [°]

c chord length [m]

V inlet velocity [m/s]

ρ air density [kg/m^3]

μ dynamic viscosity [kg/m·s]

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