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Aerodynamic Performance and Control of Symmetric Low-Reynolds-Number Airfoils for Small Wind Turbines

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Abstract. This review focuses on symmetric airfoils operating at low Reynolds numbers in small wind turbines. The main purpose of this review is to organize scattered design criteria, optimization results and flow-control concepts into a clear framework. First, this review summaries the characteristic low-Reynolds-number behavior of symmetric section airfoils and claims serval multi-criteria metrics, including lift to drag ratio, stall margin and sensitivity to operating conditions. Next, this review examines the application of symmetric airfoils to small horizontal-axis and H-rotor vertical-axis turbines, highlighting the trade-offs between airfoil choice, rotor solidity and levelized cost of energy. Finally, this review discusses the potential of smart blade which proposes that different tip-speed ratios favor different optimal geometries. It also points out some key research gaps, including integrated optimization of airfoil families, rotor solidity, economic performance and manufacturing constraints. In all, the review concludes compact design trends and organizes design criteria for symmetric airfoils operating at low Reynolds numbers in small-scale wind turbines.

Keywords: Airfoil, Low Reynolds number, Symmetric airfoils, Small wind turbine, Flow control

1. Introduction

The rapid expansion of renewable energy shows society's concerns to climate change, global warming and other environmental issues. Small horizontal-axis and vertical-axis wind turbines (VAWT and HAWT) could be an ideal solution to deal with it. In urban area, especially for remote communities and off-grid applications, small VAWT and HAWT benefits these situations at low wind speeds and with limited rotor diameters. Under such condition, the characteristic Reynolds numbers based on the blade chord typically fall in the range of 10^4~10^6 , where viscous effects, geometric type, and angle of attack can strongly affect the aerodynamic performance of the blades [1,2]. Thus, the design of low-Reynolds-number airfoils with suitable outline become significant for getting reliable and acceptable power output in small wind turbine systems.

Among various airfoils with low Reynolds numbers, symmetric sections like NACA 00-series play a central role. These symmetric profiles are attractive for small horizontal-axis rotors with yaw misalignment and straight-bladed vertical-axis wind turbines, primarily because it's geometrically simple, efficient structure and well-studied to bi-directional inflow. Furthermore, research in recent years for these symmetric airfoils like NACA 0015 have provided a large amount of data in this

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area. For instance, Kassa conducted a comprehensive investigation into the aerodynamic performance of low Re airfoils using numerical analysis and identified the suitable airfoil candidates for small scale wind turbine blade applications using MCDM approach in 2024 [1,2], Buğday specifically analyzed and compared the aerodynamic performance of the NACA 0015 airfoil in 2025 [3], and Tirandaz & Rezaeiha examined the shape parameters of symmetrical wing types in 2021 [4]. This research provides a common basis for validating computational models and comparing flow-control concepts.

Existing research on symmetric low-Reynolds-number airfoils could be grouped into three strands. Firstly, some research focus on the choice and optimum of airfoils for small HAWT [2,5,6]. Secondly, this strand concerns the section of VAWT about the issue of dynamic stall, geometric parameters like thickness, leading edge radius, angle of attack and so on [4,7,8]. The last group is about how to approach flow-control and shape-modification for symmetric airfoils, with the aim of enhancing lift and delaying separation without excessively penalizing drag [9-13].

Despite there is a lot of research on small turbines, the available information on symmetric low-Reynolds-number airfoils remains fragmented. This review aims to gather existing aerodynamic performance trends, geometric optimization strategies and flow-control concepts into symmetric low-Reynolds-number wind turbines design guidelines.

2. Low-Reynolds-number airfoils for small-scale wind turbines

2.1. Low-Reynolds-number aerodynamics and performance metrics

Within the range where chord-based Reynolds number from 5×10^4 to a few 10^5, the airfoils normally work in strong laminar flow to transition-dominated flow state. In this state, it's easy to form laminar separation bubbles and experiences premature and relatively mild stall. And the lift to drag ratio would be significantly lower than the conditions under high Reynold number. In this situation, the aerodynamic characteristics of airfoils can be significantly sensitive to Reynolds number, roughness of surface and geometric changes [1,2]. Thus, the way to design a high Reynolds number of airfoils just based on its maximum lift-to-drag ratio cannot be reliable, which means it needs to consider several indicators, including maximum lift, the drag within the main working range, C_L/C_D within the limited angle of attack window, the stall margin, and the robustness to changes in Reynolds number [1]. From the research about parametric and multi-criteria analysis to 51 low-Reynold-number airfoils, Kassa indicated that it would weaken stall safety margin and performance, when selecting solely just based on the peak value of C_L/C_D[1]. Koning also claimed in his research of optimization of Martian rotorcraft airfoils that acceptable efficiency must be balanced against robustness to uncertainties in transition location and freestream turbulence intensity [5].

Compilation data could clearly indicate the negative influence of low Reynolds number on cross-sectional performance. Fig 1 from Koning's research shows that the change of maximum C_L/C_D with different chord length Reynolds number: in the range around R_{e_c}~10^5, smooth airfoils achieve much lower values than at higher Reynolds numbers, rough airfoils perform even worse, and a Schmitz flat plate maintains only modest lift-to-drag levels across the low-Re range [5]. Fig 2 indicates the change of minimum section drag coefficient $C_{d,min}$ with different R_{e_c}. The laminar separated shear layer results in flow destabilization, and the separated shear layer remains detached only at sufficiently low Reynolds numbers. These results shows that the poor working performance

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of small turbines under typical Reynolds number range, which indicates the importance of optimizing symmetric low-Reynolds-number airfoils with a multi-criteria design framework.

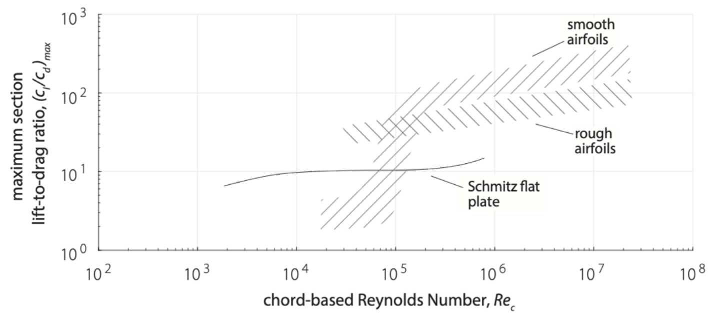

Figure 1. Maximum section lift-to-drag ratio maximumC_L/C_Das a function of chord-based Reynolds number$R_{e_c}$for smooth and rough airfoils, compared with a Schmitz flat plate, adapted from McMasters and Henderson as reported by Koning [5]

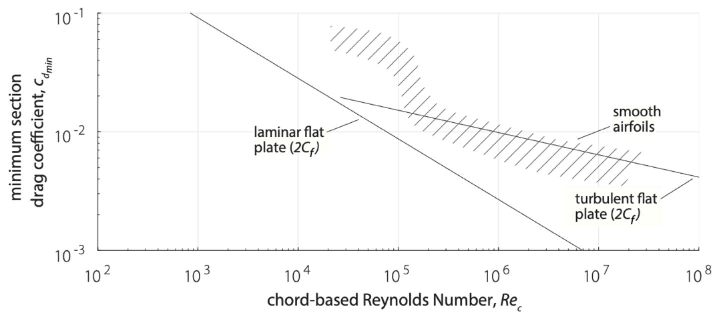

Figure 2. Minimum section drag coefficient$C_{d,min}$as a function of chord-based Reynolds numberR_{e_c} for smooth airfoils and flat plates, after McMasters and Henderson, reproduced from Koning [5]

2.2. Symmetric low-Re airfoils in small-scale wind turbine applications

For small-scale turbines with typical power output under a few tens of kilowatts, rotor diameter from 0.5 to 1 meter, wind speed from 4 to 8 meter per second, their blade chord Reynolds numbers are mainly in the range of 10^4~10^5 . It shows their total efficiency can be sensitive to geometric change [2]. The result of Yossri's 3D CFD study (Table 1) indicates that airfoils NACA 4412 performed best under same wind speed of 4 meter per second and different rotor diameters. For instance, airfoils NACA 4412 reached 34.576 W and about 11.0 W/m^2 for $RD = 1.0\ m$[6]. For straight-bladed vertical-axis turbines, same symmetric airfoils experience a wide range of angles of attack and Reynolds numbers during each revolution. Data simulation shows that thinner airfoils benefit to achieve higher peak efficiency at higher tip-speed ratios. And thicker one is good at starting torque at low tip-speed ratios [8]. Thus, for low-Reynolds-number airfoils, symmetric series like NACA00-series are always selected to be used in small HAWT and H-rotor VAWT design for its simple geometry and abundant aerodynamic data [3].

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Table 1. Power output of various airfoil profiles at different rotor diameters [6]

SSWT size (RD)	Airfoil profile	Steady-state torque (Nm)	Power (W)	Power density (W/m²)
Small (0.5m)	NACA 0012	0.0906	1.897	2.401
Small (0.5m)	NACA 4412	0.0930	1.947	2.465
Small (0.5m)	NACA 0015	0.0905	1.895	2.339
Small (0.5m)	NACA 4415	0.0900	1.881	2.381
Medium (0.75m)	NACA 0012	0.4780	10.004	5.652
Medium (0.75m)	NACA 4412	0.5020	10.506	5.935
Medium (0.75m)	NACA 0015	0.4680	9.795	5.534
Medium (0.75m)	NACA 4415	0.4540	9.502	5.368
Large (1m)	NACA 0012	1.5740	32.944	10.492
Large (1m)	NACA 4412	1.6520	34.576	11.011
Large (1m)	NACA 0015	1.5420	32.974	10.501
Large (1m)	NACA 4415	1.4940	31.269	9.958

3. Application-oriented optimization and modification of symmetric low-Re airfoils

3.1. Performance and economic trade-offs at turbine level

In small-scale wind turbine design, airfoils selection cannot be based on aerodynamic coefficients alone. Engineers also care about power coefficient, start-up behaviors, structural strength and manufacturing cost [2]. Jafari's work shows that different airfoils can yield similar mean power coefficients but noticeably different levelized costs of energy because of blade mass and manufacturing complexity [7]. Thus, optimization of symmetric low-Re airfoils should be coupled with rotor solidity, size and economic metrics, rather than targeting maximum C_p in isolation [7].

3.2. Passive modification and flow control for symmetric airfoils

In the situation of low Reynolds number, symmetric airfoils could be improved by modifying local geometry while keeping overall shape same. Studies on Gurney flaps indicates that small trailing-edge devices can significantly increase lift by changing wake vortex structures [11]. Thakur et al. added dimples and trailing-edge modifications to symmetric blades in straight-bladed VAWTs and obtained higher torque and power coefficient at low tip-speed ratios [9]. Gikenyi et al. combined static-extended trailing edges and Gurney flaps on a NACA 0012 airfoil, increasing lift-to-drag ratio and widening the effective angle-of-attack range under low-Re wind-turbine conditions [12]. Liu et al. proposed new Gurney-flap layouts for H-rotor turbines and achieved higher power coefficient near the design tip-speed ratio while preserving structural feasibility [13]. These results indicate that passive trailing-edge devices provide a practical way to enhance low-Re performance of small wind turbines without abandoning symmetric airfoils.

3.3. Smart blades and emerging design trends

In recent years, some studies have transformed their direction from fixed airfoils toward smart blades that adapt to operating conditions. Tirandaz et al. indicate that the optimal symmetric airfoil

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has different thickness, maximum-thickness position and leading-edge bluntness at different tip-speed ratios. This result shows that a single airfoil cannot always be optimal for all situations. Small turbines would improve their efficiency by using a family of complementary symmetric profiles or equivalent geometries [10].

4. Conclusion

This review indicate that symmetric airfoils must be assessed with a multi-criteria framework instead of single lift to drag ratio or C_p metric in low-Reynolds-number turbines. When choosing symmetric airfoils profiles to small turbines, solidity, size and levelized cost of energy should be taken into consideration. Passive trailing-edge devices and local shape modifications can significantly enhance low-Re performance without losing the structural benefits of symmetric airfoils, while recent smart-blade studies suggest that future work should optimize airfoil families and control strategies together.

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