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# Modeling and aerodynamic analysis of small scale, mixed airfoil HAWT blade: A Review

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**Abstract -** *Wind Energy is an indirect form of Solar Energy. About 1% of the total solar radiation that reaches earth is converted into energy of wind. Wind Energy is one of the most economical and exploitable renewable source of energy which can be harnessed for generation of power. The application of wind energy has several advantages like low gestation period, no raw-material cost, non-polluting etc. In this review paper the design and selection procedure of airfoil sections for small scale Horizontal Axis Wind Turbine (HAWT) blades is done. The most important component of wind energy converter is rotor, which rotate and produces electricity. The objective of this paper is to design the rotor blade for low Reynolds number i.e. for 100,000, a review. Design procedure consists of selection of suitable airfoil and pros of mixed airfoil over simple airfoil. Aerodynamic analysis is performed through Blade Element Momentum (BEM) theory which gives optimizes torque and power.*

***Key Words***: **HAWT, Airfoil, Reynolds number, Blade Element Momentum theory.**

## 1. INTRODUCTION

Growing awareness of rising levels of greenhouse gases [1], global warming and increasing prices of fossil fuels have led to a shift towards investing into low-cost small wind turbines. Simple structured, compact in design, portable and low noise [2], the small wind turbines are now vital wind power extracting devices in the rural, suburban and even in the populated city areas where installation of large scale wind turbines would not be accepted due to space constraints and generation of noise. Small wind turbines achieve power coefficients of 0.25 or greater in comparison to large turbines which have Cp values around 0.45 [3]. Small wind turbines have been integrated on domestic house roof tops, farms, remote communities and boats [4]. In contrast to larger horizontal axis wind turbines (HAWTs) that are located in areas dictated by optimum wind conditions, small wind turbines are required to produce power without necessarily the best of wind conditions [4-6]. A small wind turbine is one that relies on aerodynamic forces to start-up and has a tail vane for passive yawing. Small wind turbines are categorized as micro (1 kW), mid-range (5 kW) and mini wind turbines (20 kW+) [7]. A more detailed description of micro wind turbines is given by Cooper as being rated less than 2.5 kW and commercially produces power in the range of 0.4 kW – 1.5 kW at 12.5 m/s wind speed [1, 8].

Low Re airfoils operate below Re = 500,000 [10, 13] where the flow across the upper surface of the airfoil is predominantly laminar. Airfoils within this Re range suffer from laminar separation bubble and are susceptible to laminar flow separation that occurs when the laminar separated flow does not reattach to the surface, resulting in a loss in aerodynamic performance. Laminar separation bubble is a phenomenon associated with low Reynolds number where laminar flow separates before it can transit to turbulent flow as a result of adverse pressure gradient (APG)[11] .The separated laminar flow gets re-energized and reattaches back to the surface as turbulent flow forming the so-called separation bubble. The separation bubble leads to an increase in the boundary layer thickness above it, causing excessive increase in pressure drag, a loss in aerodynamic lift and noise [7, 11, 12] .Separation bubble degrades the overall aerodynamic performance of an airfoil resulting in the reduction of a turbine's startup and power coefficient [4].

## 2. Nomenclature

| | |
|---|---|
| CL | Lift coefficient |
| R | Blade Ratio |
| CD | Drag Coefficient |
| r | Radial distance from center of rotation |
| TSR | Tip speed ratio |
| $V_\infty$ | Free stream wind velocity |
| a | Axial induction factor |
| c | Chord length |
| Ω | Rotational speed |
| v | Kinematic viscosity |
| AOA | Angle of attack |

## 3. Small wind turbine rotor blades

Smaller blades with smaller chord lengths combined with low wind conditions leads to the blades operating at low Reynolds numbers from the root to tip [15]. It is vital that small wind turbine rotors have a good start-up response to low wind speeds in order to generate maximum possible power [4, 10, 17]. Most of the starting torque comes from near the blade root whereas the tip generates most of the power producing torque [18]. The starting torque of small wind turbines is small due to their small rotor size deeming it insufficient to start at low wind speeds [7]. Small wind turbines suffer from a lot of resistive torque generated by friction linked to gearbox train, bearings and generator, all of which the rotor has to overcome before it can start rotating. As wind turbines get smaller, cogging friction associated with the generator increases [18]. To overcome this problem, small wind turbines have multiple rotor blades to compensate for the low starting torque [7]. The increased number of blades aid in the quick start of the rotors and allows the turbine to operate at much lower cut-in wind speeds. Although not a good strategy, considering the added cost associated with the extra blades, the cost difference becomes insignificant due to the small size of the turbine [12]. Nevertheless, high performance gains from the wind must be accomplished through aerodynamic optimization of the rotor blades. Aerodynamic optimization of the rotor blades is associated with optimization of the chord and twist distribution, number of blades, choice of airfoil shape, and the tip speed ratio, TSR [19]. With blade optimization, power coefficients close to the Betz limit of 59.2% can be realized for wind turbines. There is always a trade-off between aerodynamic optimization of the blades and the associated costs, limiting the full potential of aerodynamic optimization as a result of the high cost of production.

Parameters associated with blade geometry optimization are important, because once optimized, shorter rotor blades would produce power comparable to larger and less optimized blades. The efficiency of the rotor largely depends on the blade's profile [6, 14] in increasing the lift to generate sufficient torque. As discussed earlier, the airfoil is one of the fundamental parts of a rotor blade design. Its purpose is to induce suction on the upper surface of the blade to generate lift. Drag is also generated perpendicular to the lift and its presence is highly undesirable. In order to maximize the power coefficient and the torque generated, the lift coefficient, CL and the lift to drag ratio, L/D ratio for the airfoil must be maximized [6, 20, 22]. Higher L/D ratios contribute to higher values of torque and it is desirable that at favorable L/D ratios, there is maximum CL in order to have a small sized rotor [14]. Airfoils resistant to laminar flow separation and separation bubbles will greatly improve the performance of small wind turbines without the need for higher rotor solidity. Together with aerodynamic optimization, lighter blades with low rotational inertia would yield better performance at lower wind speeds.

## 4. Selection of Low Re Small Scale Airfoil

Selection of suitable airfoil for small scale HAWT is very important because HAWT generally operate at low Reynolds number for whole span. If selected airfoil is not suitable for low Re application then power & torque both degrade drastically. Traditional airfoils, like NACA were designed for the operation of large wind turbines and full scale aircrafts, which are not suitable for low Re HAWT's. Today number of airfoils are designed by NREL and NACA (like 63 series), which are suitable for low Re applications and generate power up to 5kw. The first step in the selection of airfoil is to estimate the suitable Re at which blade will operate Philippe Giguere et. Al[9].

Expression to find Reynolds number is given by Equation (1) [21].

$$Re = \frac{c\sqrt{[v_{\infty}(1-a)]^2 + [\Omega r]^2}}{v} \qquad \text{.......... (1)}$$

In case of variable speed wind turbines, the rotational component Ωr is normally much higher than the free stream velocity, thus the Re can be estimated by Equation (2) [21].

$$RE = \frac{v_{\infty}(TSR)(r/R)c}{v} \qquad \text{........... (2).}$$

Generally for velocity ranging 5 m/s to 8 m/s the Reynolds number is taken as 80000 to 250000. After the selection of Re second step is to analyze the airfoils which are suitable for estimated Reynolds number. And check maximum L/D ratio and corresponding to that ratio we will get AOA for design then coefficient of lift is estimated for AOA design. One more thing is found during study that root part of blade does not contribute much to the power generation but essential for stating the rotor. And maximum of the power is contributed through tip end of rotor blade so it is good to use thick airfoil for root end to provide strength and thin airfoil section for tip end. Some of the thick and thin airfoils are given in table 2, which provide information about (L/D)max , AOA design at Re 100000 and Re 200000. From s. no. 1 to 10 thick (maximum thickness >=14 % of chord) airfoils are there and 11 onwards thin (maximum thickness <=12 % of chord) airfoil profile.

**Table 1:** Various airfoils of low Reynolds number for HAWT's with their (L/D)max ratio and AOA design at Re 100000 and Re 200000.

| S. NO | Airfoil | Re 100000 | | Re200000 | |
|---|---|---|---|---|---|
| | | (L/D)max | AOA design | (L/D)max | AOA design |
| 1 | EPPLER e403 | 47.4 | 7.5 | 66.92 | 6 |
| 2 | EPPLER e407 | 50.6 | 7.75 | 72 | 6 |
| 3 | EPPLER e417 | 46.8 | 7.25 | 65.6 | 5.5 |
| 4 | EPPLER e555 | 51.2 | 8.5 | 69.1 | 7.5 |
| 6 | FX 60-157 | 46.5 | 7.5 | 56.5 | 5.75 |
| 7 | FX 60-160 | 51 | 8.25 | 72.3 | 7 |
| 8 | SG6040 | 50.5 | 9 | 72.9 | 7.75 |
| 9 | SG6050 | 50 | 9.5 | 74.7 | 7.75 |
| 10 | SOMERS S102 BLUNT | 42.6 | 6 | 60.5 | 5 |
| 11 | SOMERS S102 SHARP | 40.5 | 6.25 | 59.6 | 5 |
| 12 | E216 | 68.5 | 6 | 99.2 | 4 |
| 13 | EPPLER 66 | 64.6 | 6.5 | 91.7 | 5 |
| 14 | EPPLER 67 | 60.9 | 7 | 86.8 | 5.75 |
| 15 | EPPLER 393 | 60.6 | 8.5 | 87.5 | 7.25 |
| 16 | FX 63-100 | 67 | 6 | 92.9 | 4.75 |
| 17 | FX 60-100 | 62.8 | 5.5 | 85.2 | 4.25 |
| 18 | SG6043 | 66.5 | 7 | 98 | 5.5 |
| 19 | SG6051 | 58.1 | 7.5 | 82.2 | 6.5 |
| 20 | GOE 547 | 60.4 | 7.25 | 86.9 | 6 |
| 21 | GOE 602 | 59.5 | 6.25 | 80 | 4.75 |

## 5. CONCLUSIONS

The turbine with Higher L/D ratio produces maximum power, reduces standstill load and also develop maximum torque. So small scale HAWT's having low Reynolds number need air foil with maximum lift to drag ratio. For Re 100000 and 200000, the suitable airfoils are SG6040, SG6041, SG6050, SG6043, E216, E555 and E407. In NACA 63 series NACA63-415 is most suitable for low Re application as it shows higher L/D ratio and stall also occurs at higher AOA. By increasing trailing edge thickness the L/D ratio increases up to optimum AOA and decreases after that angle. Thick airfoil at root provides sufficient strength to the system. Thin airfoil with shorter chord length reduces weight & size and also increases performance by increasing power coefficient. So a 3-bladed rotor is designed from airfoils SG6041, SG6050, SG6043 [13] by mixing them at required percentage of chord. In order to match an airfoil profile to any given thickness, the profile thickness is simply multiplied by a certain percentage that makes it match that thickness [16]. In this design, the point of mixing the three profiles was chosen at the beginning of the last third of the blade which should result in a thick blade, chord length distribution for new designed mixed airfoil blade rotor have a greater than the simple airfoil blade throughout the blade length which means higher strength and with increase in TSR the smoothness of power coefficient curve increases which clears that designed mixed airfoil blade rotor perform better than the simple airfoil blade.

Selected airfoils shown below.

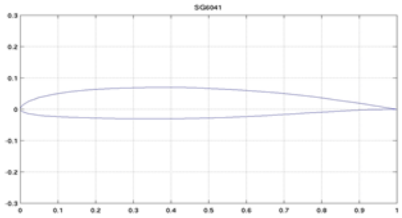

Fig (a) Airfoil SG6041

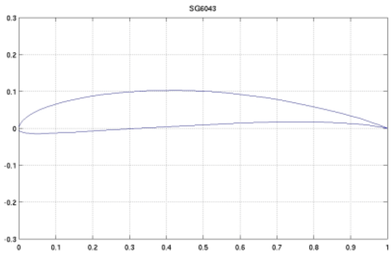

Fig (b) Airfoil SG6043

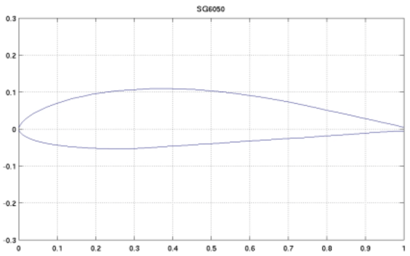

Fig (c) Airfoil SG6050

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