

AERODYNAMIC ANALYSIS OF HORIZONTAL AXIS WIND TURBINE BLADE FOR LOW WIND CONDITION

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ABSTRACT

Wind turbines operating at low wind speeds constantly experience the problem of poor performance due to reduced aerodynamic behavior on the blades. This is due to the low Reynolds number (Re) resulting from low wind speeds and small rotor size. The use of specially designed low Re airfoils permits start up at lower wind speeds, increasing the startup torque and thus improving the overall performance of the turbine. Aerodynamic performance of a blade profile plays a vital role in improving the efficiency of a wind turbine. To maximize the power output the L/D ratio has to be increased. This work deals with aerodynamic analysis of low Reynolds number airfoils which performs well in low wind speed condition. Few airfoils were identified as low Reynolds number airfoil from the literatures and the analysis was carried out using CFD techniques. Drag and Lift are the two important parameters that are to be considered in aerodynamics apart from momentum and thrust. Once the lift and drag was calculated it is easier to find the L/D ratio of an airfoil at various wind speed condition. Then by maximizing the L/D ratio output power can be increased. On successful completion of the work, problem in increasing power output at low wind sites can be achieved.

KEYWORDS: Low Reynolds Number; Small wind Airfoil; Coefficient of Lift; Coefficient of Drag; Computational Fluid Dynamic

INTRODUCTION

Almost all the high wind condition were already installed with the wind turbines now the research goes toward the low wind condition region where the flow was limited from 3 -10 m/s [1,3]. In such a case the flow has been changed from laminar to turbulent flow which affects the performance of the wind turbine. So in order to optimize the performance of the wind turbine in the low wind condition it was necessary to model the turbine blade which could match the condition [5,6]. The design of low Reynolds number for small wind turbine found out the new low Reynolds airfoil by comparing the low Reynolds number airfoils [11]. It was named as AF300 which was subjected to many experiments in wind tunnel in order to improve its performance at the Reynolds number range of 38,000 to 205,000 [8,9]. AF300 show good aerodynamic performance attaining highest CL and CD ratio. Decrease in adverse pressure gradient ensures that flow does not separate and the decrease in adverse pressure gradient was achieved by increasing the nose radius. Increasing the leading edge nose radius decrease the adverse pressure gradient (APG) which ensure that the flow stay attached to the blade [12]. In this investigation they tested the blade in the Reynolds number range of 0.8×10^5 to 2×10^5 . It performs well in the wind speed of about 4-7m/s and produce C_p of about 0.1,0.21,0.255 at the wind speed of 4,5 and 6 m/s respectively. The best performance is obtained when the starting blade sweeps at 25% of blade radius for different directions of sweep [13]. The simulation results of S-series airfoil developed by the NREL in order to gain the maximum energy from

the low wind speed region. They found that the maximum L/D ratio was desired to obtain the maximum power from the wind. The blade tip should use thin airfoil for high L/D ratio whereas blade root requires thick airfoil for structural support. Also at low AOA lift force increase by decreasing drag force it was achieved by using cambered airfoil. They also suggest some of the cambered airfoil as S818, S825, S826, S830, S831, and S832. The range of Reynolds below 5×10^5 produce good aerodynamic properties and C_p about of 0.25[14]. The efficiency of the wind turbine was based on airfoil which was used to reduce the pressure and increase the lift. Low Reynolds number airfoil suffered from the laminar separation bubbles which can be minimized by addition of trip. At high stall angles low Reynolds number airfoil shows improvement in performances. As the AOA increase the transition point towards trailing edge. The best behaving pitch angle was 20° and the chord integrated pitch angle was high in root and low in tip. Laminar separation bubbles affects the performance of wind turbine and it can be minimized by addition of trip or tabulator and also the adverse pressure gradient should be decreased which ensure that the flow is attached to the blade and increase the lift force. Rotor or blade optimization includes chord and twist distribution, number of blades, airfoil shape, TSR. To maximize the C_p & torque generated C_L L/D ratio should be maximized [16]. For small sized rotor at favorable L/D ratio maximum C_L will available. Starting torque comes from blade root and the power producing torque from blade tip region hence the blade tip should be made of thin airfoil, whereas the blade root was made of thick airfoil for structural support. The parameter that affects the wind turbine performance was leading edge nose radius, mean camber line, maximum thickness, and trailing edge angle[17]. Modification of airfoil trailing edge thickness, camber line has effect on starting character, lift and drag ratio of airfoil [18]. Once optimized the shorter length rotor blades could produce more power compare to larger and less optimized blades. Low Reynolds number airfoils operated below the range of 5×10^5 and have improved performance at high stall angles. As the airfoil drag increase it affects the maximum achievable power, in order to gain the maximum power from the wind maximum L/D ratio was favorable also as the wind speed increases L/D ratio increases. Maximum power can be achieved by lengthening the blade and also by varying the rotor rotational velocity at different wind speeds possible to have power coefficient at maximum values.

METHODOLOGY

In order to install the wind turbine in the low wind speed region it was necessary to optimize the wind turbine blade suitable for such low wind condition [19]. The airfoil was the fundamental part of the blade which determines the efficiency of the blade. So the first step in the research was the selection of the airfoil with low Reynolds number range of 1×10^5 to 2×10^5 and to optimize the airfoil to get the maximized C_L & C_D . After the selection, optimization of the airfoil it was necessary to evaluate the performance of the airfoil using CFD techniques to get the desired results of maximized C_L & C_D . Once the process of evaluation of the optimized airfoil gets over, development of the blade using the optimized airfoil is carried out. Further optimization of wind turbine blade has to be done to maximize the C_p . Finally blade has to be evaluated to get the desired output of maximized Power coefficient C_p . Iterative approach for optimizing coefficient of power, coefficient of lift and drag of wind turbine rotor' has studied for a given wind speed and blade angular velocity, it is shown that the maximum power efficiency is achieved when the blade is twisted according to a program that depends upon the variation of the sectional lift and drag coefficients with angle of attack. It also explains the mathematical model in which when the wind speed varies there exists rotational velocity which maximizes the output. They carried out the investigation by considering the C_D and tip loss correction factor and without considering the C_D and tip loss correction factor.

Airfoil Design and XFOIL Testing

Analysis the airfoil we need to model the airfoil profile. It can done in DESIGN MODULER or it can be modeled in other software like AUTOCAD, SOLIDWORKS etc. In this work the modeling was done in DM in WORKBENCH. The final modeled airfoil containing the C MESH around it was shown in figure 1. In order to carry out the flow analysis the geometry was finely meshed so that flow was get even fine. In meshing the area which are getting inward (toward) the airfoil was biased from larger to smaller and vice versa. The meshed part of the airfoil was shown in figure 2. As the name indicates the complete problem setup was provided here. General setup made in this section was pressure based type using absolute velocity formulation and steady time periods and viscous laminar 2D space model air materials [20]. The next important step in the process was providing the boundary condition to the geometry for our desired condition. The boundary condition given in this analysis was inlet zone magnitude and direction using absolute reference and velocities are 4 to 10 m/s. Take Reference cross sectional area, depth, temperature and viscosity values are 1m^2 , 1m, 288K and 1.7894E^{-5} respectively. The complete problem setup after providing the various parameters and boundary conditions it looks like the shown in figure 3.

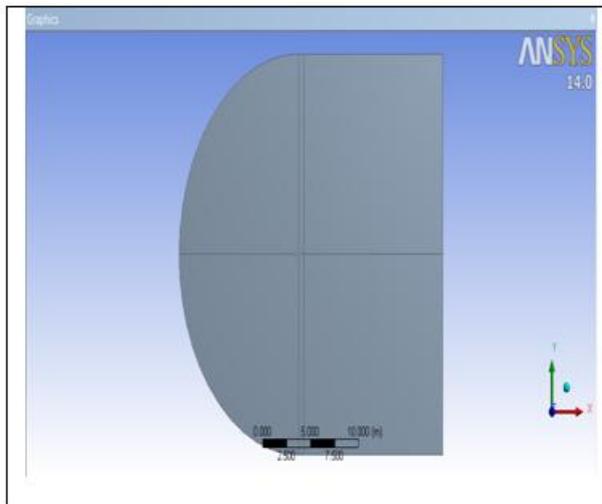


Figure 1: Modeling of Geometry of Airfoil

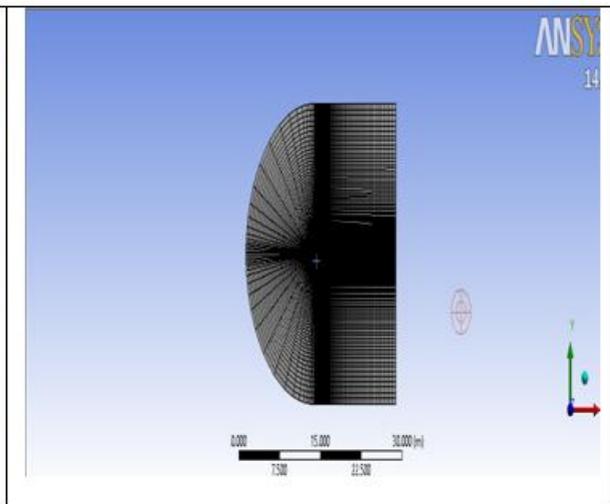


Figure 2: Meshing of Airfoil in CFD (FLUENT)

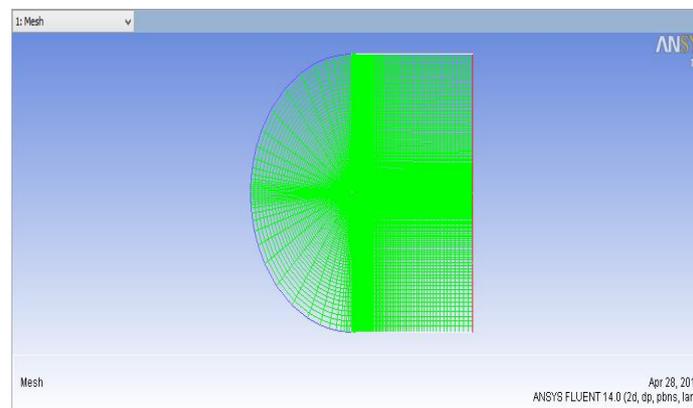


Figure 3: Problem Setup in CFD FLUENT

AIRFOIL SELECTION

Based on the calculation of the Reynolds number from the local wind speed the following airfoils were selected

for analyzing in the desired wind conditions and the profiles of the selected profiles as shown in the following figure 4.

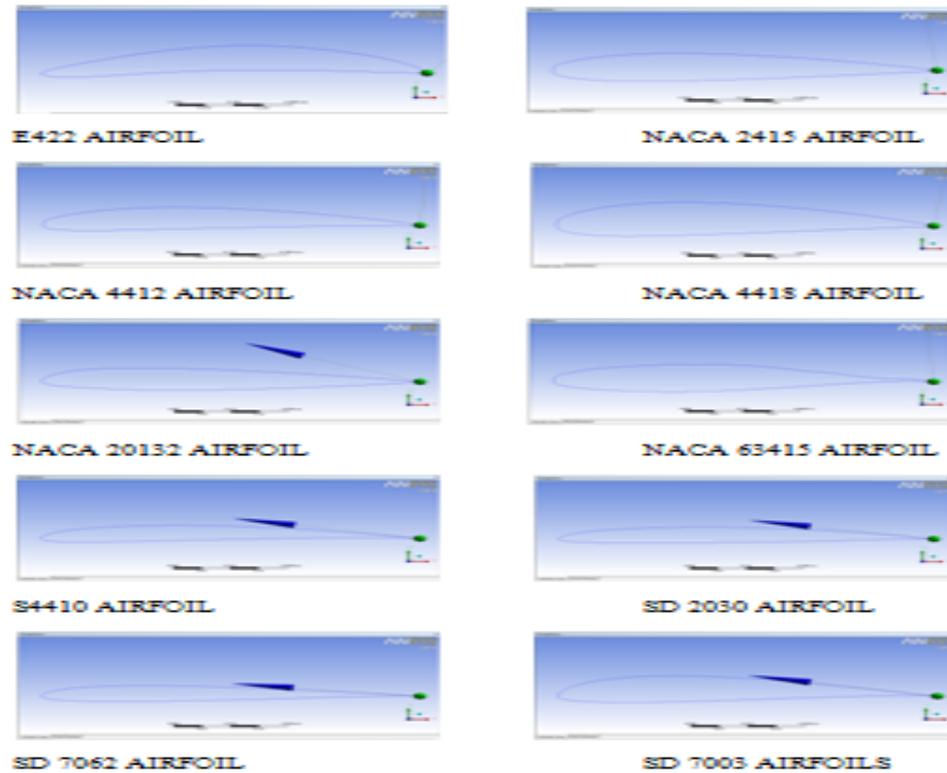


Figure 4: Airfoil Profiles

Calculations of Reynolds number

The formula for calculating the Reynolds number was given below

$$Re = \frac{UL}{\nu} = \frac{\rho UL}{\mu} \tag{1}$$

Where

μ fluid viscosity, $= 1.7894e^{-5}$

ρ is the fluid density, $= 1.3$

U is the velocity of fluid passing the air foil surface $= 4-10m/s$

L is the length of the flow (chord length) $= 1m$

And the Reynolds number $Re = (1.3 * 4 * 1) / 1.7894e^{-5}$

$= 2.90500 * 10^5$

Calculations of Lift & Drag Coefficient

The lift and drag are the two important parameters that play a vital role in aerodynamics and the calculations of these parameters can be done by the following equations

$$C_l = \frac{L}{\frac{1}{2}\rho U^2 c} = \frac{\text{Lift force per unit length}}{\text{Dynamic force per unit length}} \quad \text{----- (2)}$$

$$C_d = \frac{D/l}{\frac{1}{2}\rho U^2 c} = \frac{\text{Drag force per unit length}}{\text{Dynamic force per unit length}} \quad \text{----- (3)}$$

For the profile E422 (V = 4m/s, AOA = 3⁰)

$$C_L = 0.05894.$$

$$C_D = 0.004589$$

$$L/D = C_L/C_D = 12.55$$

RESULTS AND DISCUSSIONS

Analytical Method

The main part of the analysis was carried out in this step. The various parameters like lift, drag, momentum were monitored through this option. Also the residual were controlled in order to converge the solution and also to increase the degree of exactness. Normally the residuals were in the range of 10⁻³ but in order to increase the convergence criteria it was necessary to change the residual values to 10⁻⁵. Solution controls under relaxation factors are considered pressure, density, body force momentum values are 0.2, 1, 1 and 0.5 respectively in order 1000 number of iteration to simplify the results as shown in figure 5, 6, 7 and 8.

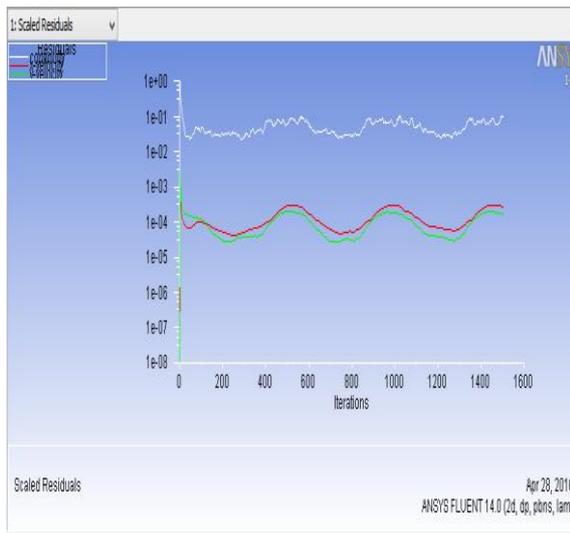


Figure 5: Convergence History of Residual

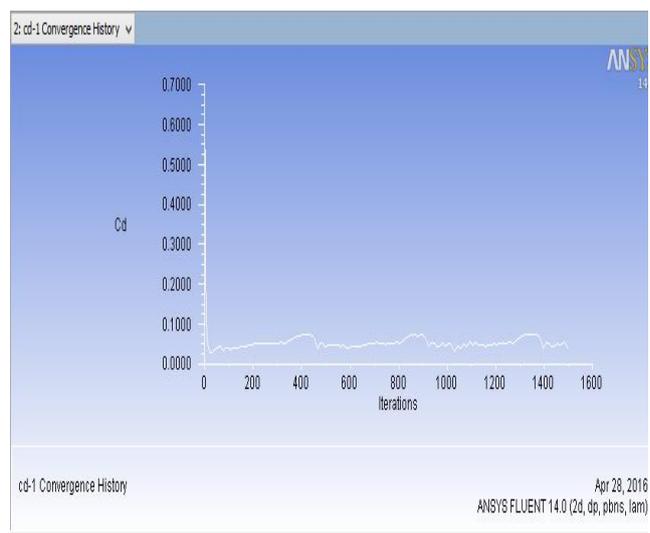


Figure 6: Convergence History of Drag Force



Figure 7: Convergence history of Lift Force.

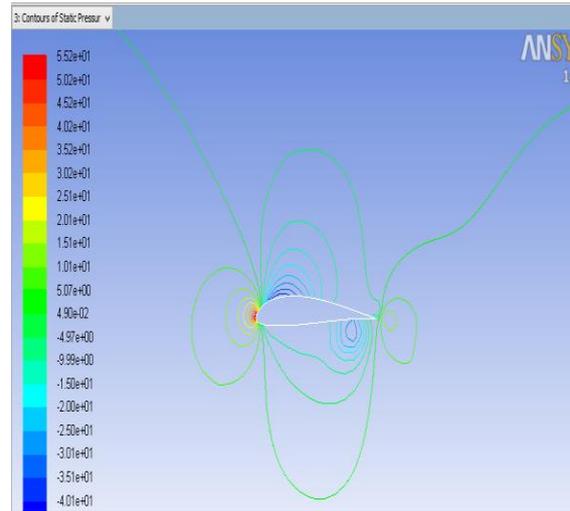


Figure 8: Pressure Contour around the Airfoil.

The profile E422 initially the number of divisions and the elements was the number of nodes and the elements were 27169 and 26900 respectively. The lift and the drag force obtained was 0.710 and 0.08876 respectively and after grid independence the number of nodes and elements were 96480 and 96000 respectively and the lift and drag force was 0.61298 and 0.048776 respectively.

Experimental Results

The low Reynolds number airfoils had been identified from the literatures and the model had been created using ANSYS. The airfoils used for the analysis are E422, SD2030, SD7003, NACA63416, NACA23012, SD7062, S4110 were considered because of their performance in low Reynolds number and low wind velocities. In order to carry out the analysis some of the parameters need to be obtained, they are the local wind speed conditions, temperatures of the location, geographical location, angle of attack, free stream velocity. The objective of the project was to carry out the analysis in the low wind speed condition hence the local wind speed condition was chosen which was in the range of 4-10m/s. The angle of attack was at the optimum values from -30 to +30 so that the lift value will be obtained at the optimum values.

AOA VS L/D Ratio for Various Profiles at Constant Velocity

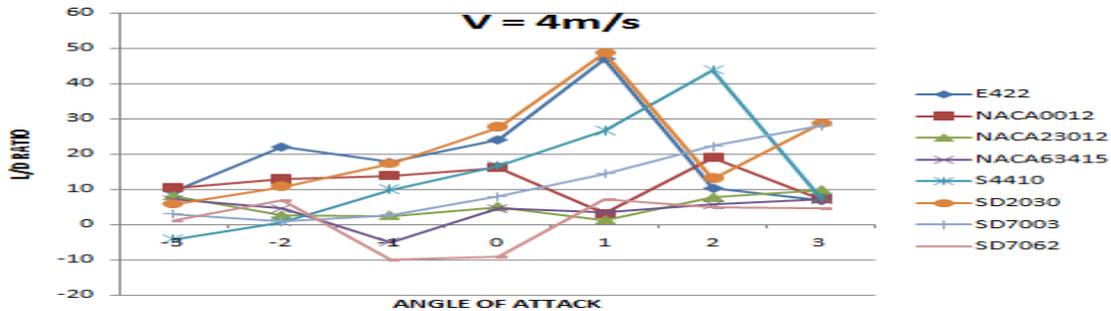


Figure 9(a): AOA VS L/D Ratio for Various Profiles at V = 4m/s.

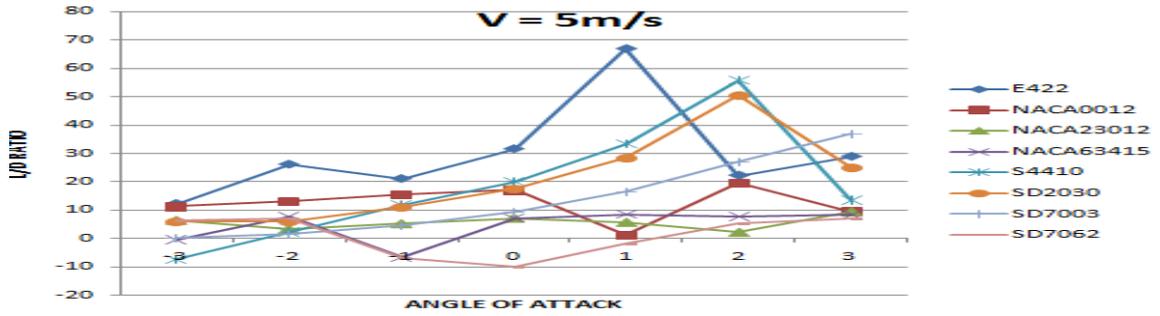


Figure 9(b): AOA VS L/D Ratio for Various Profiles at V = 5m/s.

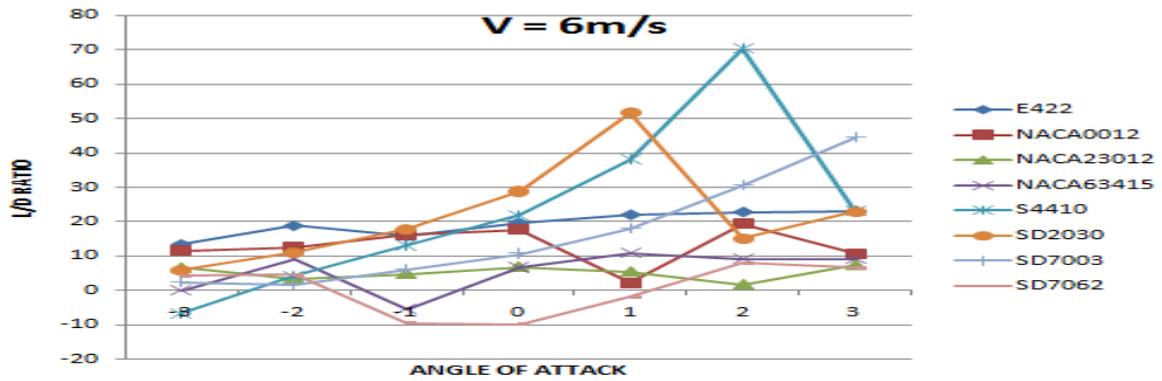


Figure 9(c): AOA VS L/D Ratio for Various Profiles at V = 6m/s.

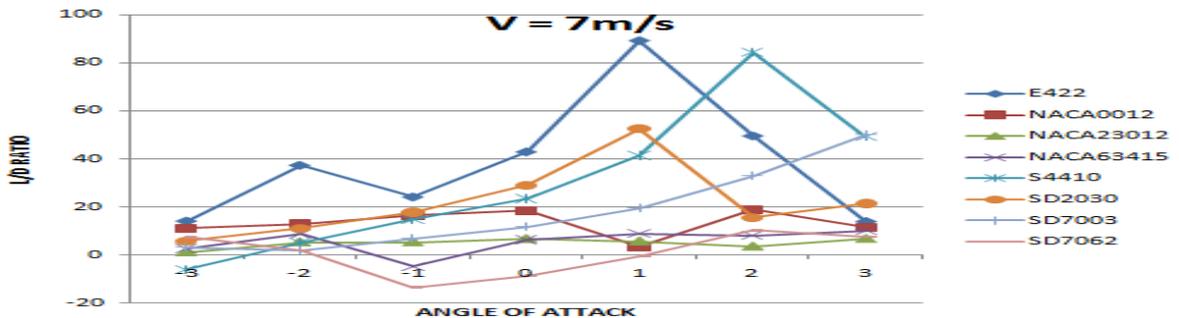


Figure 9(d): AOA VS L/D Ratio for Various Profiles at V = 7m/s.

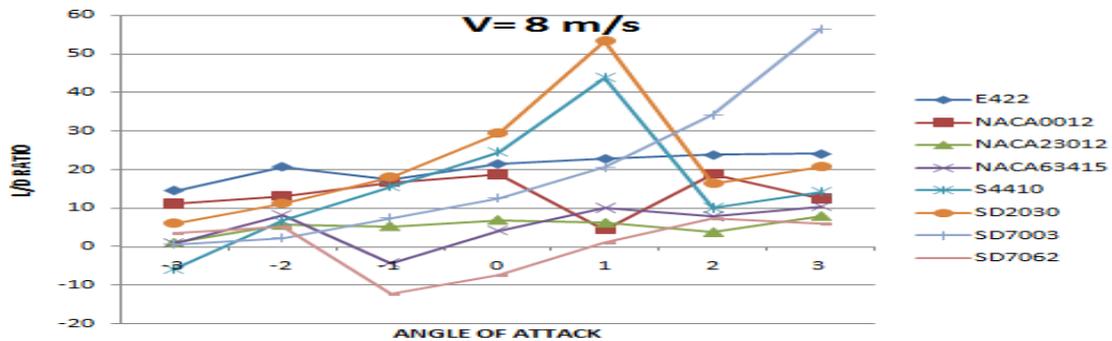


Figure 9(e): AOA VS L/D Ratio for Various Profiles at V = 8m/s.

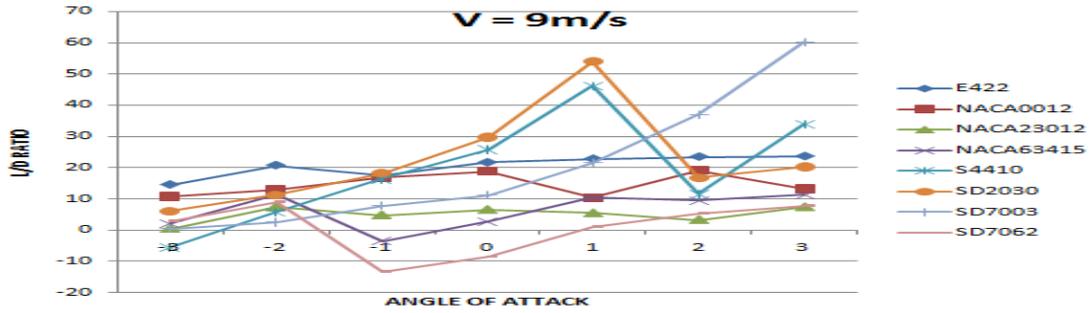


Figure 9(f).AOA VS L/D Ratio for Various Profiles at V = 9m/s.

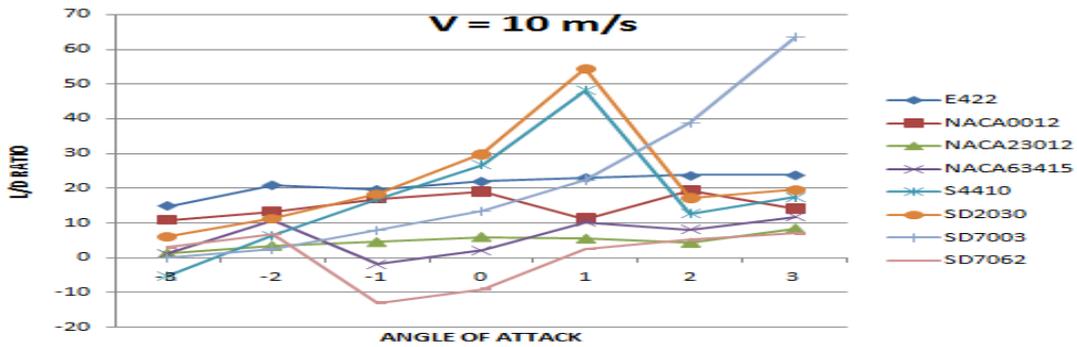


Figure 9(g): AOA VS L/D ratio for Various Profiles at V = 10m/s.

The selected airfoils were modeled and then the desired velocities were given and analyzed. The graph for the various velocities as shown in figure 9(a, b, c, d, e, f, g).While considering the velocities it was obvious that with increasing in velocity the L/D ratio also increase (up to 7m/s) and then the L/D ratio decrease because the optimum value of drag force was greater than the lift force which reduce the L/D ratio which was undesirable in improving the power coefficient. And also the profile SD7003 shows the improves performance in all the velocity at the optimum AOA which means it was one of the profile that can give the better performance in the low wind speed sites. E-422 airfoil gives the maximum value of 86 in terms of L/D ratio a velocity V=7m/s after that the L/D ratio gets decreased because of increasing in the drag force.

Velocity VS L/D Ratio for Various Profiles at Optimum Angle of Attack

The small wind turbines was installed in the region which was not best of their wind speed so the starting wind speed of the rotor blade was important. The wind turbine performs well in the angle of attack from -4⁰ to 3⁰, once the angle of attack reaches beyond the value the L/D ratio gets decreased due to increase in drag force on the upper side of the blade.

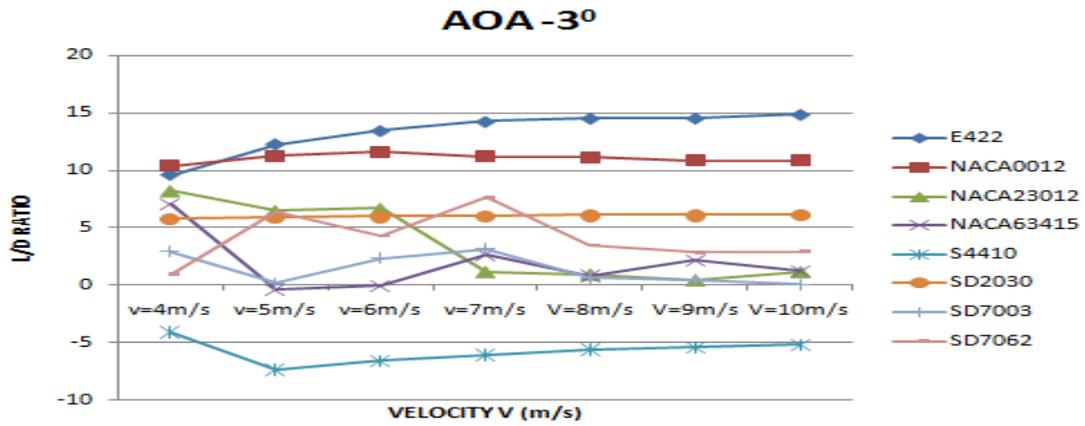


Figure 11(a): Velocity VS L/D Ratio for -3°

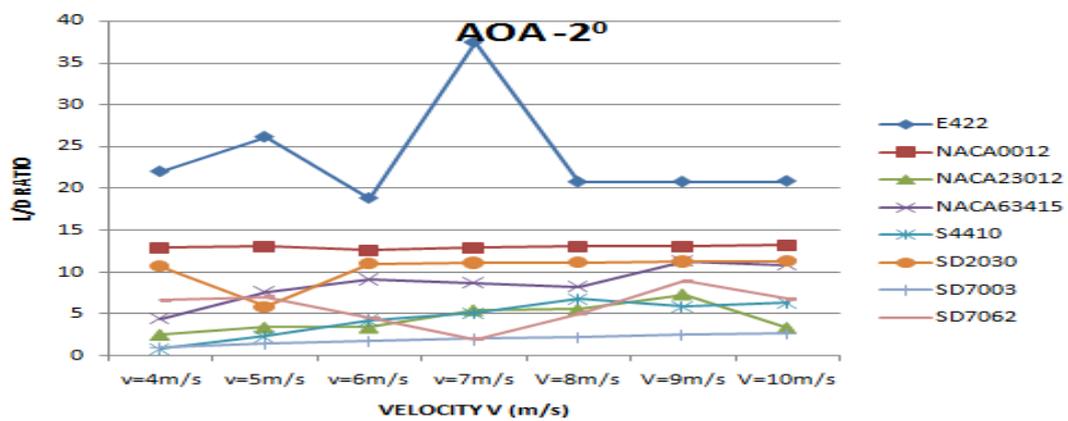


Figure 11(b): Velocity VS L/D Ratio for -2°

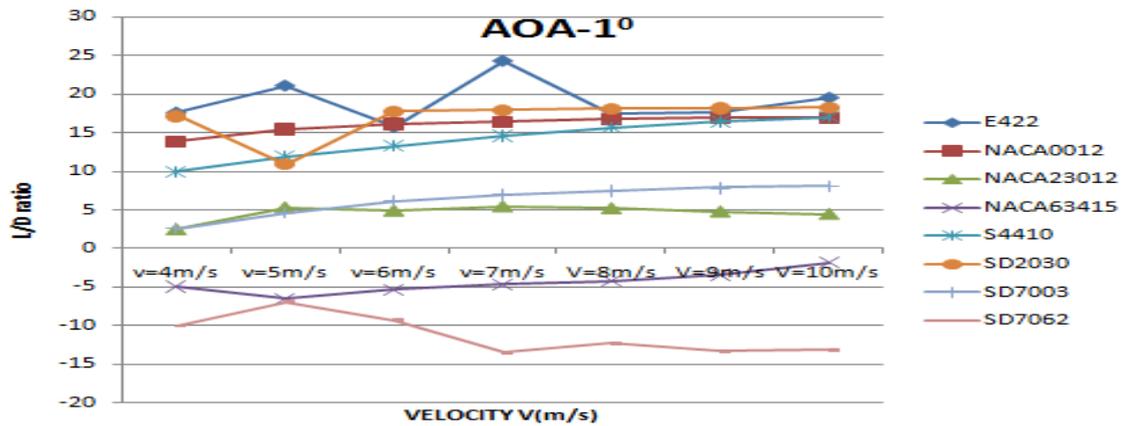


Figure 11(c): Velocity VS L/D ratio for -1°

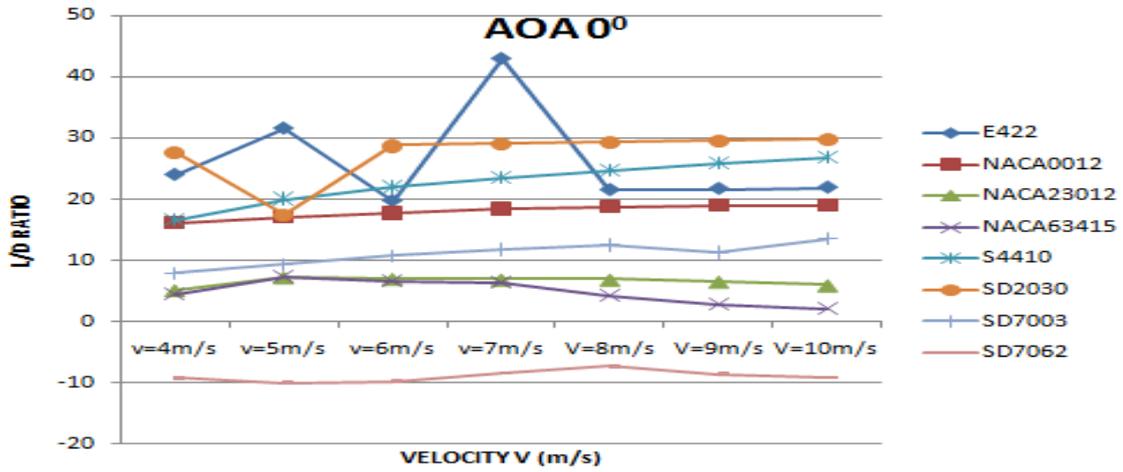


Figure 11(d): Velocity VS L/D Ratio for 0°

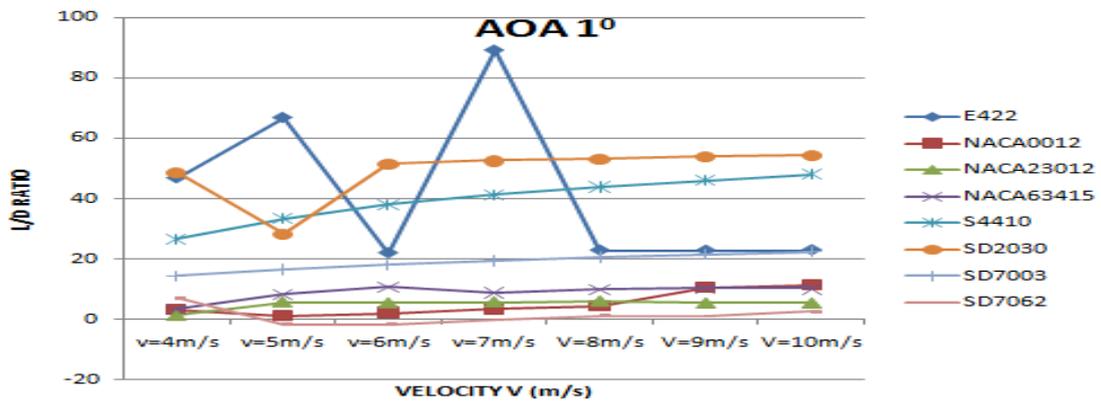


Figure 11(e): Velocity VS L/D Ratio for 1°

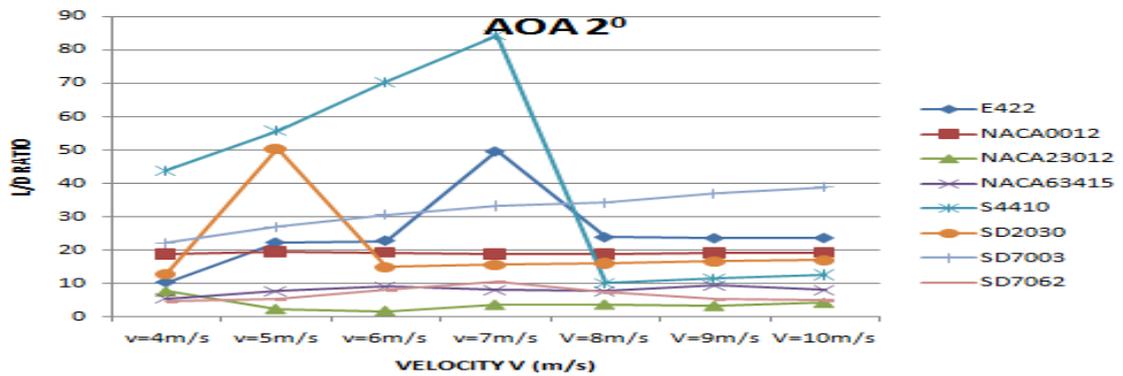


Figure 11(f): Velocity VS L/D Ratio for 2°

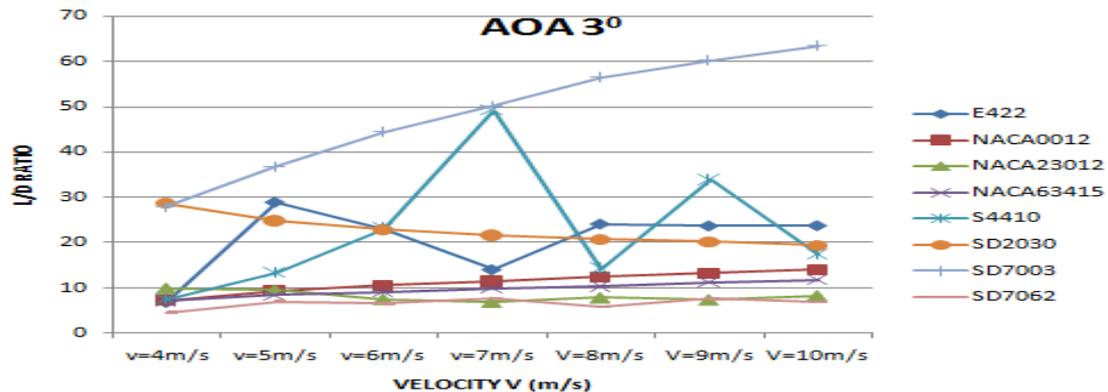


Figure 11(g): Velocity VS L/D Ratio for 3°

The angle of attack was chosen between -3° to $+3^{\circ}$ because it was the optimum angle of attack in which the maximum value of L/D ratio was achieved for obtaining the maximum power from the wind. Different profile behaves differently in this range which was given in the figures 11(a, b, c, d, e, f, g). In all the above cases the profiles E422 behaves well in the given velocity followed by NACA0012, SD2030 and the other members show ordinary performance. When the profiles was considered separately S4410 and SD2030 performs well achieve the peak C_p of about 80 and 60 respectively.

CONCLUSIONS

It was concluded that the laminar separation bubble was the main problem in the low wind speed airfoils which can be eliminated by adding GF to the trailing edges and also by adding the tabulators. In order to perform well in the low wind speeds the blades should made of low weight and also to withstand the turbulence intensity in the region because of tall buildings and trees. The low wind speed airfoils analyzed in this work performs well in that region and also the simulated results were compared with the experimental work done in the wind tunnel and found that the results agree well in the cases.

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NOMENCLATURE

A	: Rotor swept area (m^2)
L	: Lift force (N)
D	: Drag force (N)
U	: Wind velocity
c	: Chord length (m)

- C_L : Coefficient of lift (dimensionless)
- C_D : Coefficient of drag (dimensionless)
- C_P : Coefficient of power (dimensionless)
- L/D : Lift to drag ratio (dimensionless)
- Re : $\rho V_\infty c / \mu$, Reynolds number (dimensionless)
- ρ : Density of air (kg/m³)
- α : Angle of attack(rad)
- μ : Viscosity (kg/ (m s))