International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 10 Issue: 12 | Dec 2023 www.irjet.net p-ISSN: 2395-0072

Analysis of Newly Designed Airfoil for Micro-Capacity Wind Turbine Using Qblade Software for Different Parameters

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Abstract - *The effects of climate change and greenhouse gases (GHG) emissions are one of the major concerns today. The energy generation sector has significant role to these emissions. To achieve the Paris agreement goals we must need to increase the renewable energy resources. To attain that wind energy and solar energy are most reliable sources. Worldwide, approximately Two billion people lack access to reliable electricity. However, the electricity generation is usually expensive or required high capital cost. Small wind turbines are most reliable and effective source to achieve this. Wind energy has become one of the fastest growing renewable energy sources, because energy generated by wind power is one of the cleanest energy resources available.*

Small wind turbines are operating at low wind speeds regularly facing poor performance due to separation of bubbles on the blades. This is due to the low Reynolds number (Re) causing by low wind speeds as well as small rotor size. The use of specially designed low Re (5×10^5) airfoils permits to start up at low wind speed regions, if increasing the start-up torque then overall performance of wind turbine is improved. By using QBlade software two different airfoils (NACA 2408 and SD 2030) are analysed and a new airfoil (AG 3307) is design and compare with two airfoils. Newly designed airfoil analyse for 3-bladed rotor having diameter of 2.4 m for low Reynolds number application. We have found that, at wind speed of 7 m/s and Ncrit is 9 we get maximum C_P is 0.556 and at various RPM 200, 300, 400 and 500 we get the 200.39 W, 482.992 W, 512.022 W and 442.523 W maximum power respectively by considering tip speed ratio 6.

Key words: **Wind Turbine, Micro HAWT, QBlade, Airfoil, BEM Theory, low Reynolds number.**

1. NOMENCLATURE

BEM	Blade Element Momentum Method
LLT	Lifting Line Theory
λ	Tip Speed Ratio
λ_r	Local TSR
α	Angle of Attack
A	Rotor Cross-Sectional Area
B	Number of Rotor Blades
CD	Drag Coefficient
CL	Lift Coefficient
c	Chord Length of The Airfoil
D	Drag Force
d	Hub Diameter
L	Lift Force
L/D	Lift-To-Drag Ratio
CP	Power Coefficient
R	Rotor Radius / Blade Ratio

r	Radial Distance from Center Of Rotation
ρ	Air Density
P	Rotor Power
Re	Reynolds Number
θ_T	Twist Angle
θ_p	Pitch Angle
Ψ	Relative Angel
a	Axial Induction Factor
a'	Tangential Induction Factor
ν	Kinematic Viscosity
μ	Dynamic Viscosity
Ω	Angular Viscosity / Rotational Speed

2. INTRODUCTION

As increasing rate of pollution and the decline in fossil fuel, it is now necessary to incline towards renewable energy sources. This can be done through various means such as hydro, biomass, geothermal, solar and wind etc. From all these renewable energy sources we are only focusing on wind energy as it is generally the most effective among all. Wind turbines are the energy harnessing devices that converts kinetic energy of wind into mechanical energy and further it's converted into electrical energy. Wind turbine are mainly classified into two categories first is horizontal axis wind turbine (HAWT) and Vertical axis wind turbine (VAWT). In general, the sectional shape of the Horizontal Axis Wind Turbine (HAWT) blade consists of the two-dimensional (2D) airfoils, which result the lift and drag forces by virtue of pressure differences across the 2D airfoil [1]. For this reason, the BEM theory is mostly used to outline a procedure for the aerodynamic design of a HAWT blade. HAWT is more efficient than VAWT when extracting energy from the wind force due to its design that allows it to exact the energy through the full rotation of the blades [2].

Table -1: Classification of HAWT based of rotor size & Power Rating [3-4]

Size	Rotor diameter (m)		Standard power rating (kW)	
	Minimum	Maximum	Minimum	Maximum
Micro	0.5	3	50 W	2 kW
Small	3	10	2 kW	40 kW
Medium	10	50	40 kW	1000 kW
Large	50	100	1000 kW	6000 kW

The region which receives annual wind speed up to 6 m/s at 10 m height are considered as low wind speed regions in which small wind turbine can produce up to 15 kW of power, having swept area 200 m^2 [5].

Airfoil is the cross-sectional view of the blade which shows the energy capturing performance and the aerodynamic behaviour of the blade. On upper surface of airfoil suction is induced due to this effect the lift can be generated. Hence, this work is mainly focusing on the designing of new airfoil for low wind speed regions with optimum thickness so that the power output can be increase. The designing of new airfoil is generated with the help of Q-BLADE software. It is the software to design and analyse the wind turbine, it's used the BEM for the simulation of wind turbines and it is included with the XFOIL airfoil design and analysis. It is possible to predict wind turbine performance with it. [6]. Low wind speed range considered between 7 to 10 m/s at last results have been compared with existing airfoil designs. Low Re airfoils are designed to be thinner than conventional airfoils which operates at high Re [7]. In their study, they designed two types of blades one is based on the blade element momentum (BEM) theory and other one is constant chord length with non-twist angle. The experimental and numerical simulation results revealed that the maximal power coefficient for the BEMT blade increased by 50% compared with the Baseline blade. BEM based blade has fully attached flow over the airfoil without separation whereas the baseline covers only a partial region amounting about 76%. It is because, the flow over the blade uses BEM with the twist angles is still attached to the blade root near the leading edge. The partition of flow is controlled by the twist angle used in the BEM blade. This proves that the BEM blade has a maximum power coefficient than that of the baseline at low tip speed ratios [8].

As per Betz limit, theoretically wind turbine extracts the maximum 59.2% of kinetic energy from the wind. This value is further reduced as per airfoil and blade design, therefore airfoils and blades design plays important role to get sufficient output from the wind turbine [9].

3. SELECTION OF DIFFERENT AIRFOIL

In this paper we studying airfoils for the low wind speed region, on that basis we are selecting the Airfoils of their low Reynolds number below 5×10^5. Low Reynolds number airfoils are designed to be thinner than traditional airfoils that operate at high Re [54]. We have considered the thickness is nearly 8% of the airfoil as percent of the chord. In this present work we have selected the two different airfoils namely NACA 2408 and SD 2030 on their low Reynold number and low wind speed applications. These Airfoils are selected from UIUC Airfoil coordinates database [10]. These airfoils are found the better performance in comparison. The results obtained by using QBlade and all selecting airfoil thickness is near to 8 mm. For that Airfoils the tip speed ratio is 6, angle of attack 7 and Reynold Number is 5×10^5 are consider.

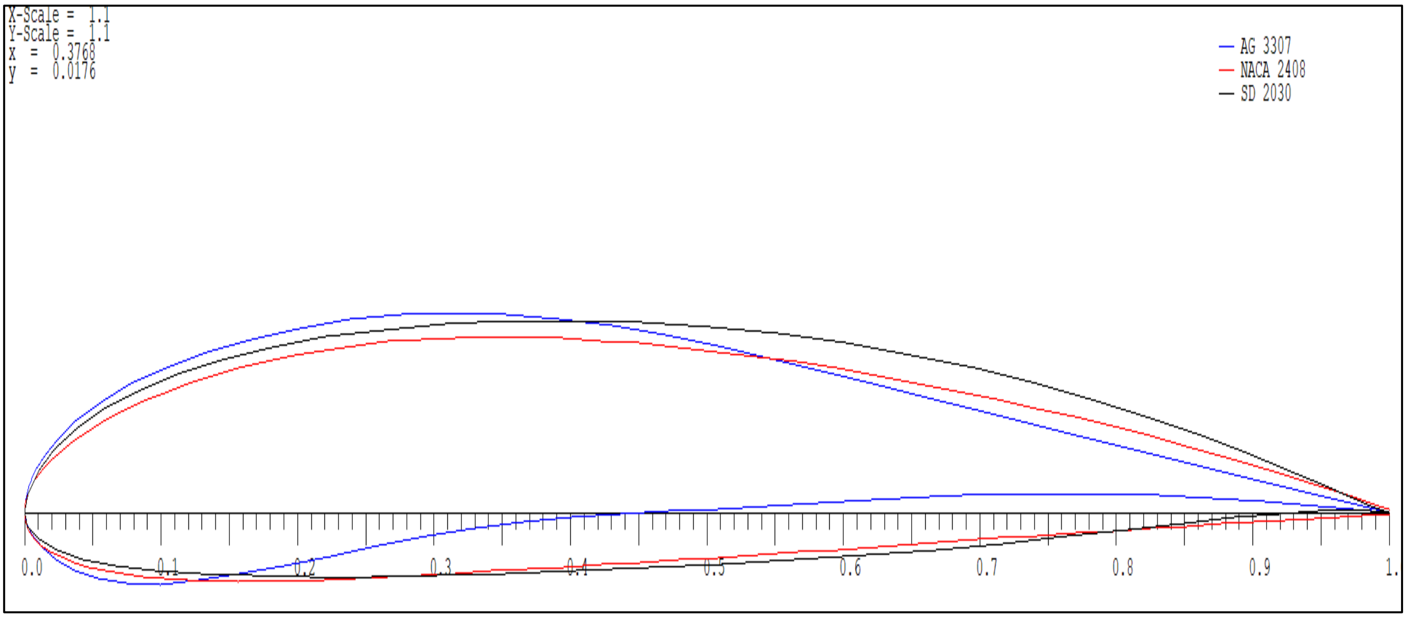


Figure -1: Different shapes of airfoils in QBlade software.

4. DESIGN A NEW AIRFOIL

This study deals with the designing of the special airfoil for the wind turbines working in low wind speed regions, for horizontal axis wind turbine. Various factors have been taken under consideration for the designing of airfoil [11]. Our aim is improving the aerodynamic performance and efficiency of the airfoil. For obtaining higher efficiency in low-speed regions, torque produced at the rotor of the wind turbine should be high enough to rotate efficiently. This can only achieve when the aerodynamic performance of the blade is higher. Therefore, to get high efficiency C_L/C_D ratio should be higher [12]. To achieve higher C_L/C_D is always our main objective so that the rotor C_p can be increased. They can do experiment on NACA 2415 and NACA 4412 airfoil, and they get the results are if changing both thickness and camber ratio of airfoils played a big role of their aerodynamic performance [13]. Blade element momentum theory (BEM) [14] says that the C_p has a positive relation with C_L/C_D, larger the higher the C_p.

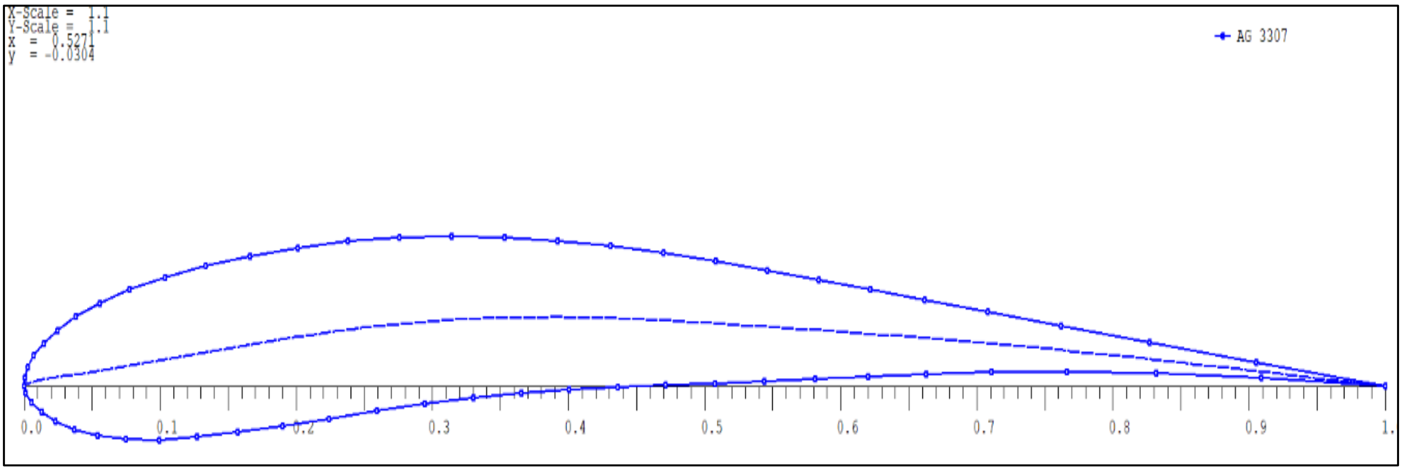


Figure -2: AG 3307 Airfoil Design in QBlade Software.

A thin airfoil is designed to perform over large range of operating conditions. small wind turbines are operating at low Reynolds Number. The low Reynolds number and

advantageous centrifugal stiffening effects, provide optimal performance for small wind turbines [15]. During normal operation, at variable speed HAWT operates between below stall and over the limited lift range as compared with constant speed wind turbines. For these operating conditions, minimizing leading edge roughness effects like no loss in the maximum lift coefficient is not particularly critical [16]. To counter the possible variations in the tip speed ratio caused by atmospheric turbulence, the best lift to drag conditions were designed to occur over range of lift coefficients centred about the designed lift coefficient [7].

The airfoil is named as AG 3307 having maximum thickness 7.96% and maximum camber 3.15%. The new airfoil design should be able to produce higher C_L/C_D at Reynolds number of $5{\times}10^5$.

Direct designing method is used for designing the new airfoil after understanding and analysing the parameters of the selected airfoils. Angle of attack is taken between 0° to 20°. Total 60 2D coordinates were taken for the designing airfoil. Mach number was taken as 0 for every analysis. For all the analysis value of Ncrit was selected as 9 that represents the normal wind tunnel conditions.

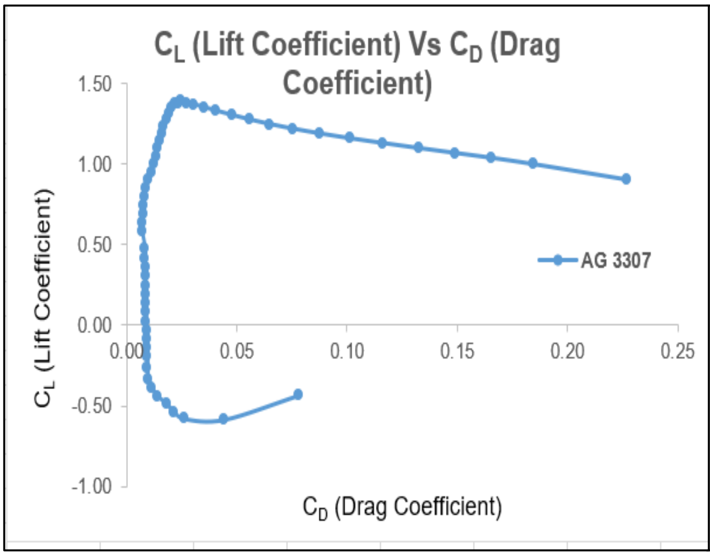


Figure -3: Lift Coefficient Vs Drag Coefficient

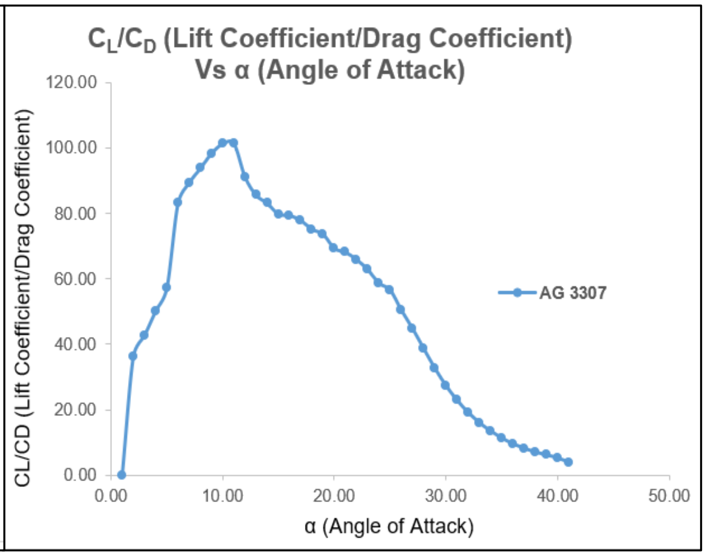
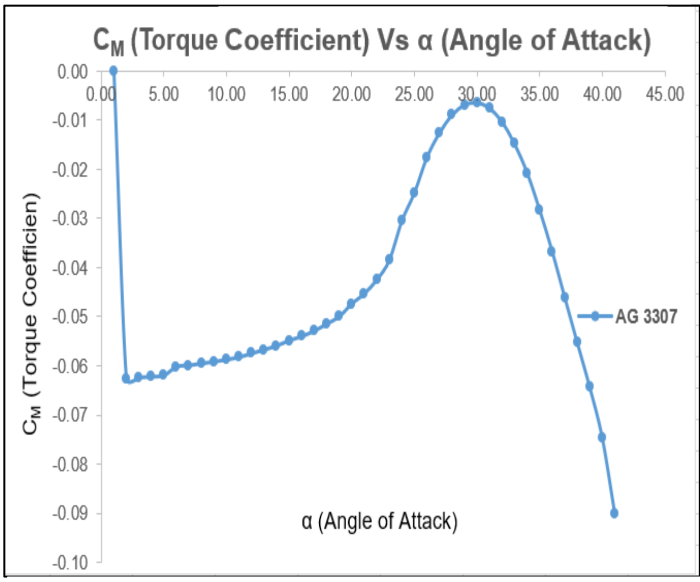


Figure -4: Lift Coefficient/Drag Coefficient Vs Angle of Attack



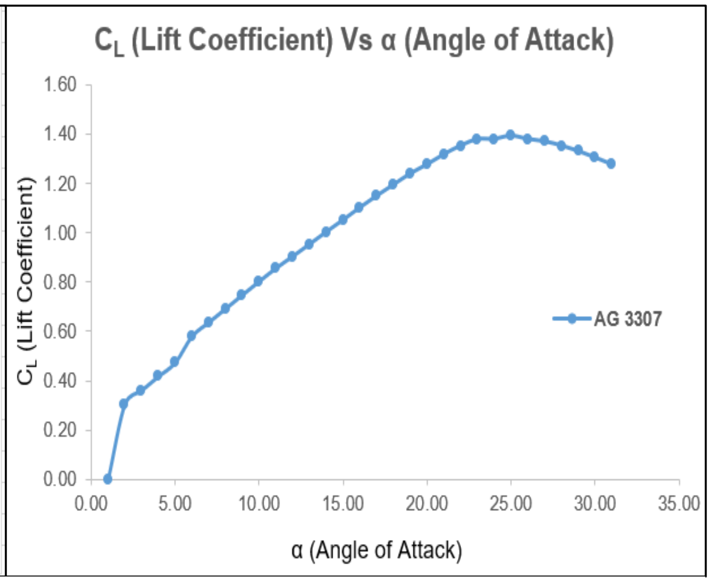


Figure -5: Torque Coefficient Vs Angle of Attack

Figure -6: Lift Coefficient Vs Angle of Attack

In the XFOIL analysis we get the four important graph and alpha value. In that Qblade software the airfoils is simulated to create a polar, in that you will get the C_L Vs C_D, C_L Vs Alpha, C_L/C_D Vs Alpha Viz. graphs. We can even visualize the boundary layer & pressure produce.

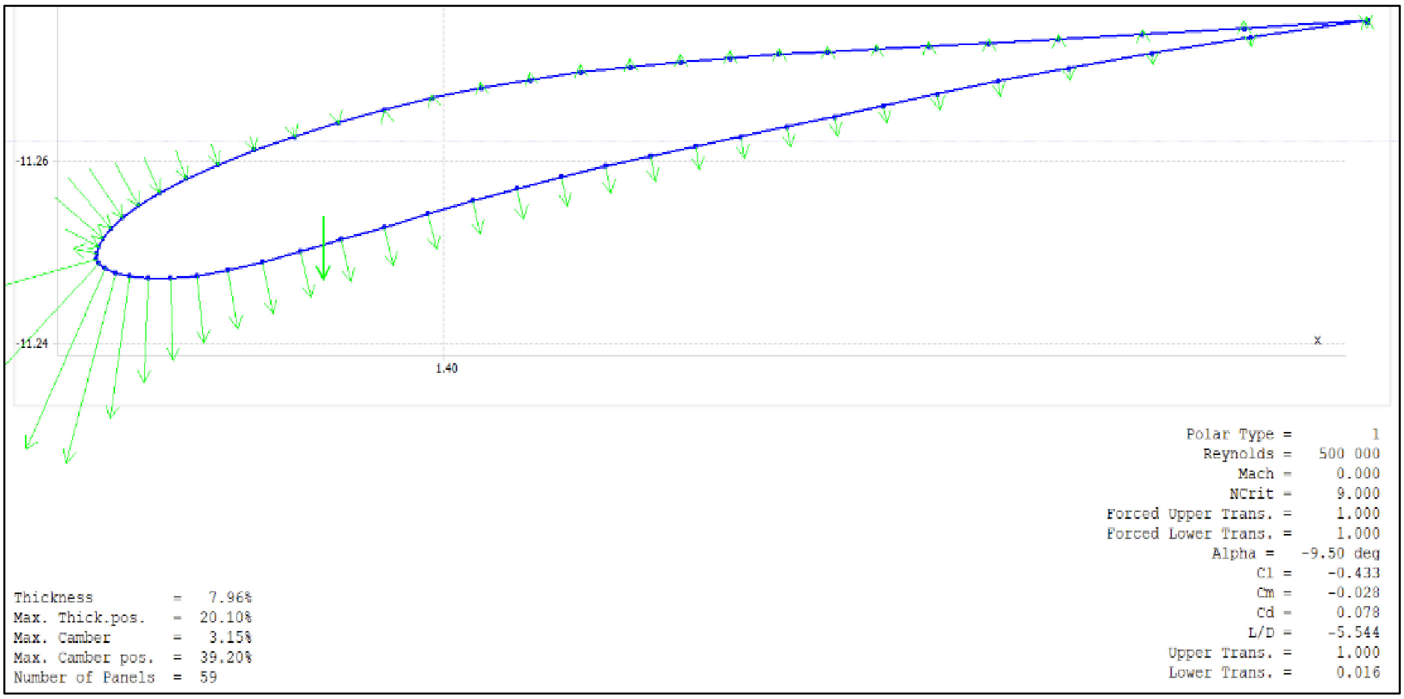


Figure -7: Shows boundary layer and pressure exerted on different points

In Figure 7 shows boundary layer and pressure graph we can get image of our airfoil shape on that pressure exerted on its boundary. From that we can easily visualize that how much pressure is exerted on it. From here we can also get our maximum thickness, maximum camber all etc.

Table -2: Characteristics of the new airfoil

Profile type	AG 3307
Optimal Angle of attack	5
Lift coefficient	0.85
Blade Length	1 m
Hub radius	0.2 m
Number of blades	3
Design wind speed	7 m/s
Optimal Design tip speed ratio λ	6
Axis of rotation	Horizontal

5. MATERIAL AND METHOD

For manufacturing HAWT there are many materials like wood, steel, plastic and composites. But for HAWT blades are lighter and more flexible, advanced fabrication methods and composite materials have been introduced, this also resulting reduction in structural damping. [1]. In whole blade we can use the AG 3307 airfoils, we have take 11 sections for designing the blade, they carry the chord length of 1.2 m and the hub diameter is 0.2 m, total rotor diameter is 2.4 m are created. The entire blade is twisted at different twist angle on each section.

Various design parameters and geometry of airfoil involves the angle of attack (α), relative thickness, Camber, Reynolds number and 2D coordinate geometry as shown in **Figure 8**.

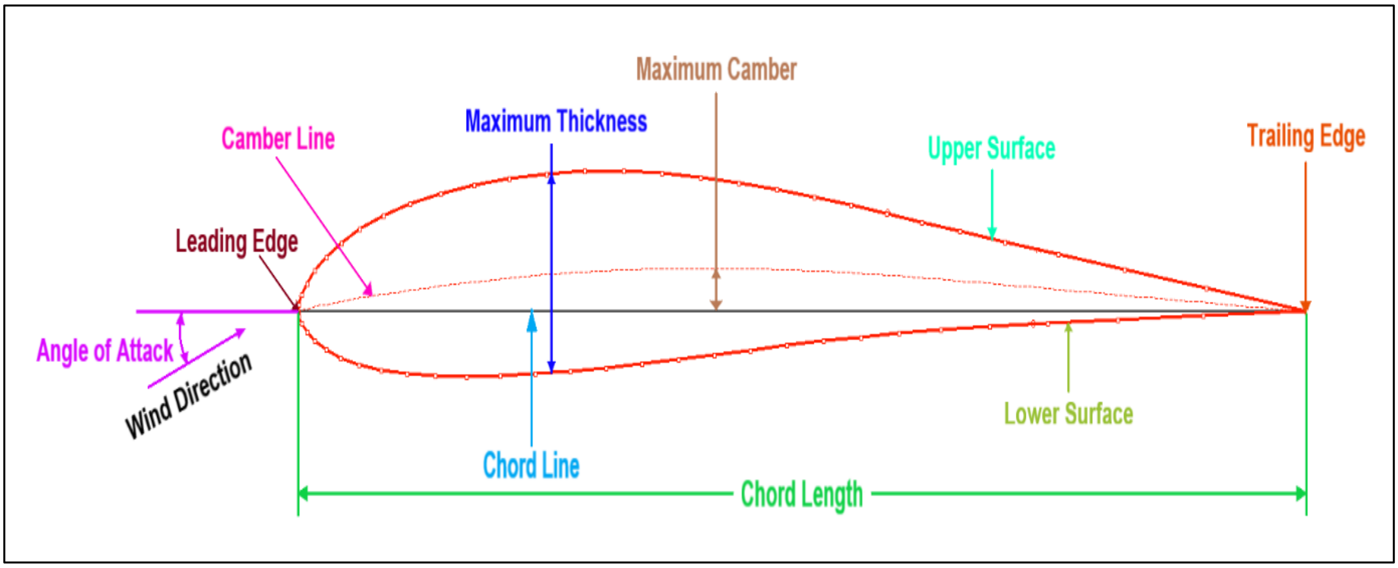


Figure -8: Geometry of airfoil section

6. GOVERNING EQUATIONS AND PARAMETERS

Wind turbine converts the kinetic energy of wind into electrical energy. The extractable power from the wind is given by [17].

$P_{avail} = 1/2\ \rho A V^3 C_p$

Where,

ρ is the density of air.

A is the swept area of rotor.

V is the velocity of wind.

C_p is the theoretical maximum power coefficient for any wind turbine. It's called Betz limit.

In that modelling of Airfoil, the BEMT method is use. It Consist of two theories, First is the axial momentum theory and the second one is the blade element theory. In axial momentum theory, the propeller is regarded as an actuator disc in which the forces are distributed continuously in the azimuth direction. Meanwhile, the BEM theory which was developed by Drzewiecki in 1892, consists in dividing the blade in N elements along the radius so that each element was considered as small airfoil. [18]

Blade Element Theory is use in QBlade software. In this method simulation of wind turbine and it's integrated with the XFOIL airfoil design and analysis. In that method we predict the performance of wind turbine. In that we make the cross-section profile of blade which shows the energy capturing performance and aerodynamic behavior of blade. On the upper surface suction is induced because of that lift can be generated. So, this method is use for designing of airfoil at low wind speed region.

7. COMPARISON OF AIRFOILS

After analysing and designing new airfoil we have compare all airfoils to check the results. In this we are comparing new airfoil AG 3307 and other two Airfoils namely NACA 2408 and SD 2030. New AG 3307 is developed with the aim of improvement of performance of small wind turbine. Table 3 shows the comparison of these blade based on various factors such as maximum thickness, maximum camber, angle of attack in degree of maximum C_L/C_D, maximum C_L/C_D and maximum C_L. We are comparing that airfoils at Reynolds Number of 5×10⁵, Ncrit is 9 and Mach number is taken as 0.

Table -3: Characteristics of airfoils

Airfoils	Max. thickness (% chord length)	Max. chamber (% chord length)	Angle of attack (degree) at max. C_L/C_D	Max. C_L/C_D	Angle of attack (degree) at max. C_L	Max. C_L
AG 3307	7.96	3.15	5	101.37	12	1.39
NACA 2408	8.00	2	4.5	87.78	10.5	1.15
SD 2030	8.56	2.25	2.5	103.64	10	1.15

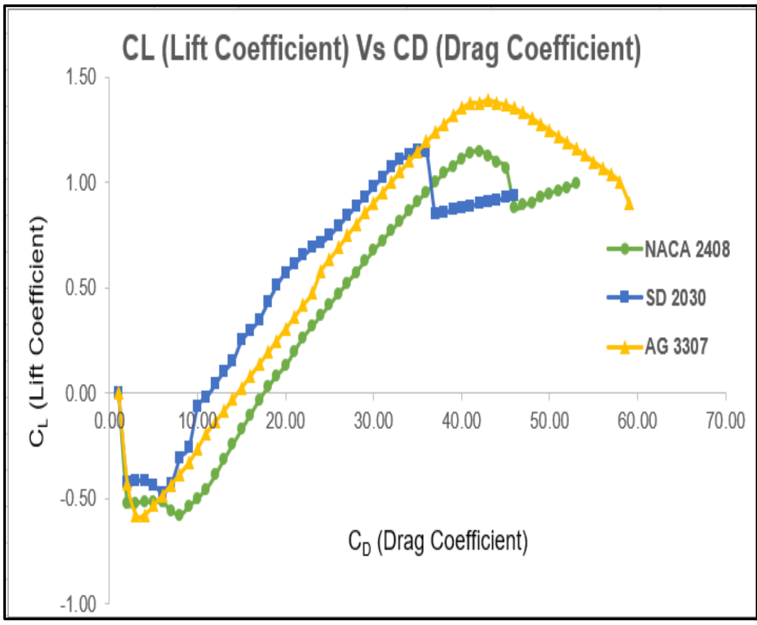


Figure -10: Lift Coefficient Vs Drag Coefficient

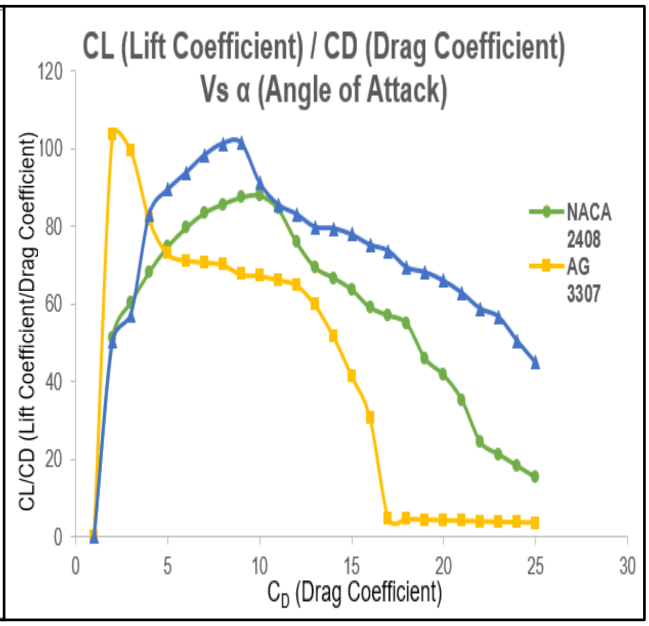
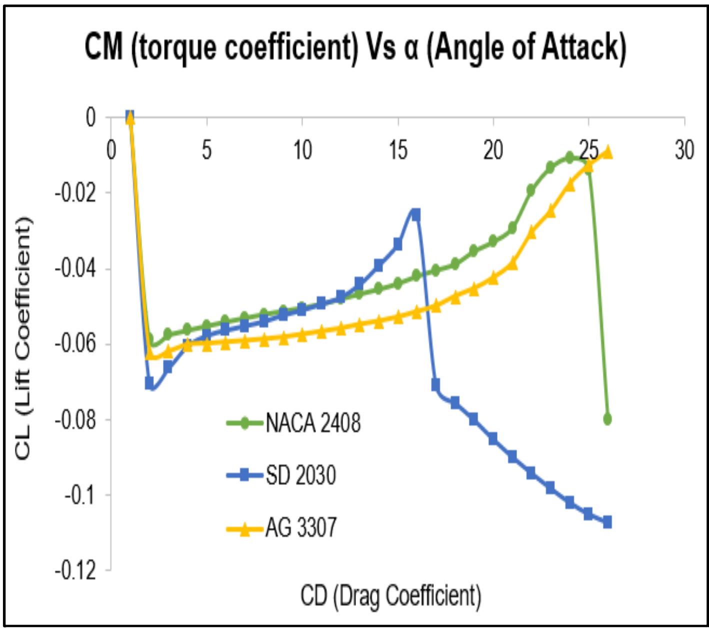


Figure -11: Lift Coefficient / Drag Coefficient Vs Angle of Attack



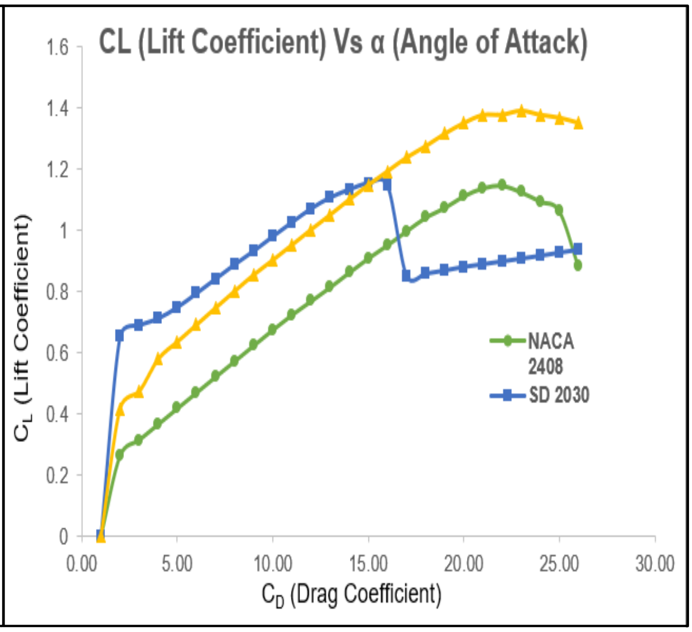


Figure -12: Torque Coefficient Vs Angle of Attack

Figure -9: Lift Coefficient Vs Angle of Attack

Lift-to-drag ratio increases with increase in angle of attack, after attaining the higher value of AOA at 5 then this ratio is decreases. From analysation of all the airfoil we can find that, our Airfoil is getting the maximum angle of attack value is 12 at maximum C_L are 1.39 at 5×10^5 Re.

8. OPTIMUM DESIGN OF BLADE

In the blade design, the designing of AG 3307 airfoil is 7.96 thick, and its camber are 3.15 percent. This airfoil is made for the low wind speed region, at low Reynolds number of 5×10^5 using QBlade software. From the QBlade software analysis we get the C_L Vs C_D, C_L Vs Alpha, C_L/C_D Vs Alpha Viz. graphs. From that we get that is our airfoil is better than another airfoil. After that the next step is to design the airfoil, for that at below the formulae are given for design the blade.

Aerodynamic efficiency is based on the blade design, optimization of shape for ideal rotor which considered the effect of wake rotation can be done by considering coefficient of drag.

(Cd=0) and tip losses (F=1)

Local tip speed ratio

$\lambda_r = \lambda$

From this we can calculate the relative angle (4) corresponding to each element of blade it is given as:

$$\varphi = \frac{2}{3} tan^{-1}(\frac{1}{\lambda_r})$$

Chord length from this value of relative angle:

$$C = \frac{8\pi r}{B}(1 - cos\varphi)$$

In above equation the "Ci designed lift coefficient and 'r' is local radius of blade induction factor calculated from equation

Where is solidity which is defined by the ratio of blade area to swept area and can be calculated

Also pitch angle is calculated using relative angle ψ and angle of attack α as:

$$\theta_p = \varphi - \alpha$$

From above equations we easily designed the blade. Blade is designed for tip speed ratio of 6 tip speed is selected from range 5-8. From the above formulas we calculate the various parameters require to design the blade.

Table 5 Design parameter of rotor blade

Sr. No	Local Radius r (mm)	Local TSR λ_r	Chord Length c (mm)	Relative angel ψ (°)	Solidity σ'	Axial induction factor a	Tangential induction factor a'	Pitch angle θ_p (°)	Twist angle θ_T (°)
1	200	1	174.01	30	0.415	0.317	0.183	23	23.69
2	300	1.5	147.78	22.46	0.235	0.324	0.095	15.46	16.15
3	400	2	123.11	17.71	0.147	0.328	0.051	10.71	11.4
4	500	2.5	103.85	14.53	0.099	0.329	0.041	7.53	8.22
5	600	3	89.3	12.29	0.071	0.331	0.022	5.29	5.98
6	700	3.5	78.01	10.63	0.053	0.331	0.022	3.63	4.32
7	800	4	69.17	9.36	0.041	0.33	0.031	2.36	3.05
8	900	4.5	61.96	8.35	0.033	0.333	0.003	1.35	2.04
9	1000	5	56.15	7.54	0.027	0.334	-0.006	0.54	1.23
10	1100	5.5	51.29	6.87	0.022	0.33	0.031	-0.13	0.56
11	1200	6	47.21	6.31	0.019	0.335	-0.015	-0.69	0

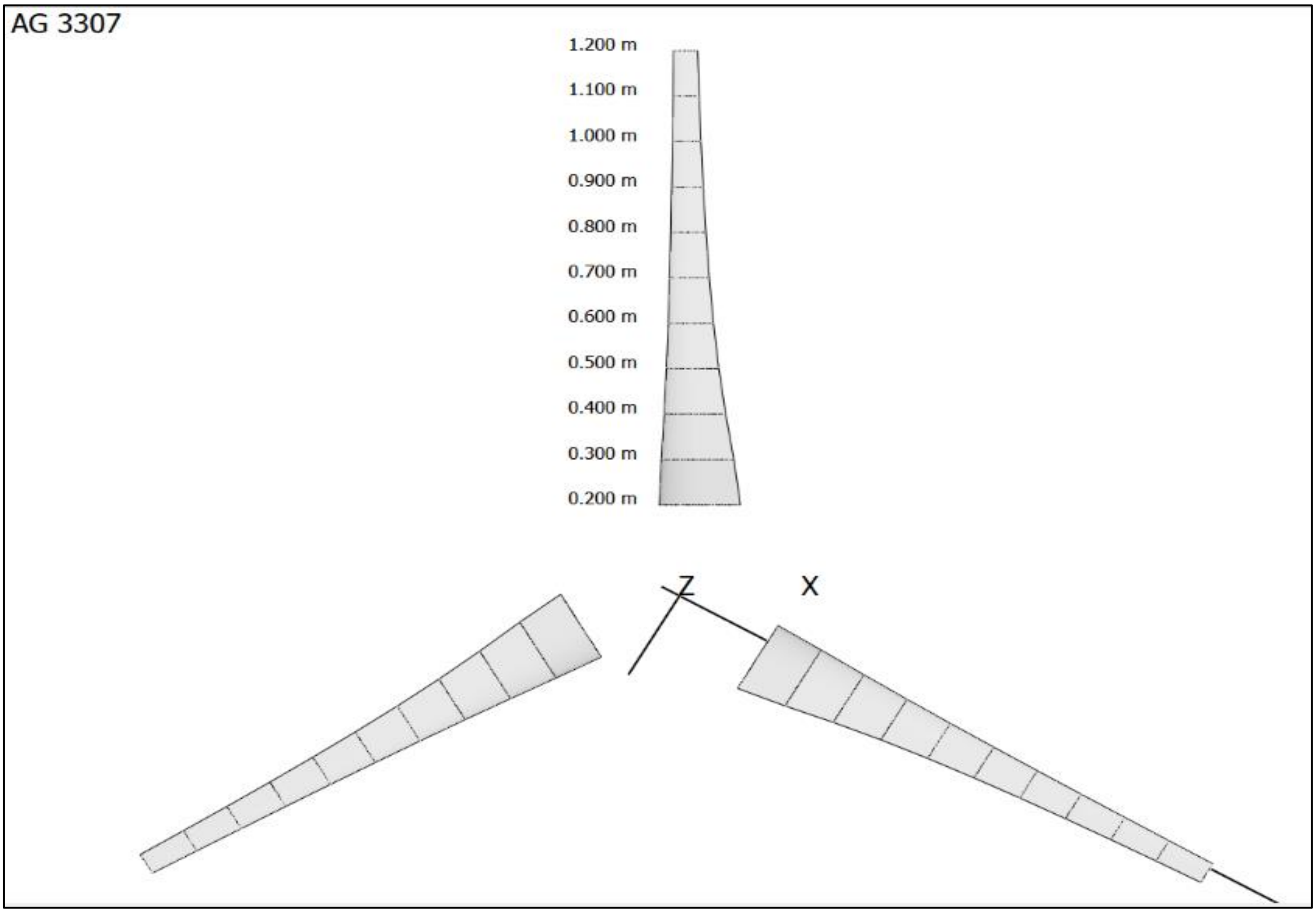


Figure -13: Rotor blade in Qblade

9. RESULT AND DISCUSSION

The analysis of micro-capacity turbine is done by using QBlade software for different airfoils are NACA 2408 and SD 2030 and newly design airfoil is AG 3307. In the XFOIL direct Analysis we compare all the airfoils.

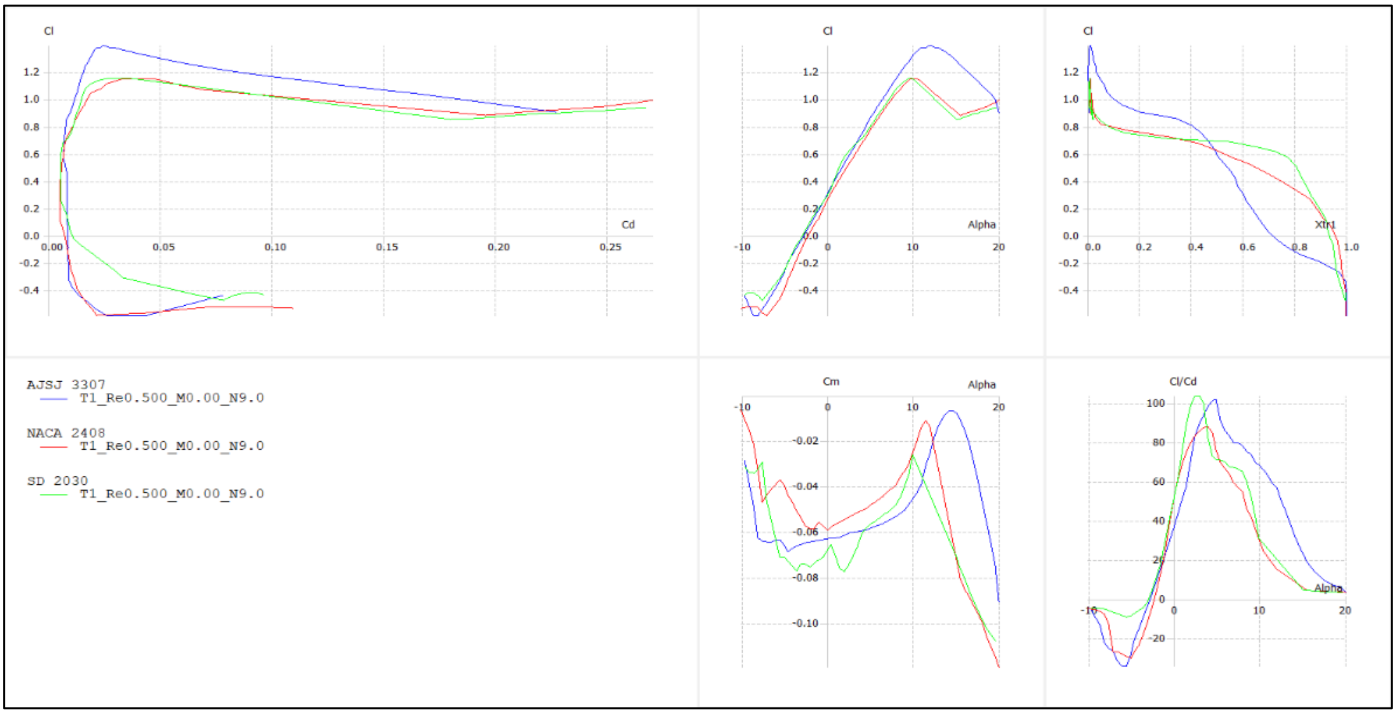


Figure -14: Analysis of all airfoils in Qblade software

From above Figure we can get the C_L Vs C_D, C_L Vs Alpha, C_L/C_D Vs Alpha Viz. graphs. At the tip speed ratio of 6. From above analysis AG 3307 airfoil we can get that is at the low Reynolds number our airfoil gets higher results compare to other airfoils. Then after blade design we go to Rotor BEM Simulation in that we get the C_P Vs TSR and C_T Vs TSR Graphs. In that we can define the rotor simulation at the Tip Speed Ratio range from 1 to 17 and increment of 0.5. After start BEM we get the graphs are shown below.

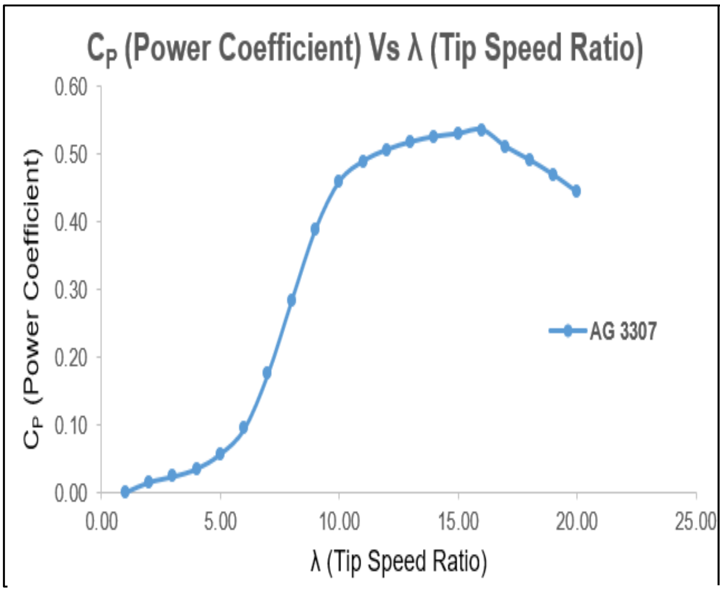


Figure -15: Power Coefficient Vs Tip Speed Ratio

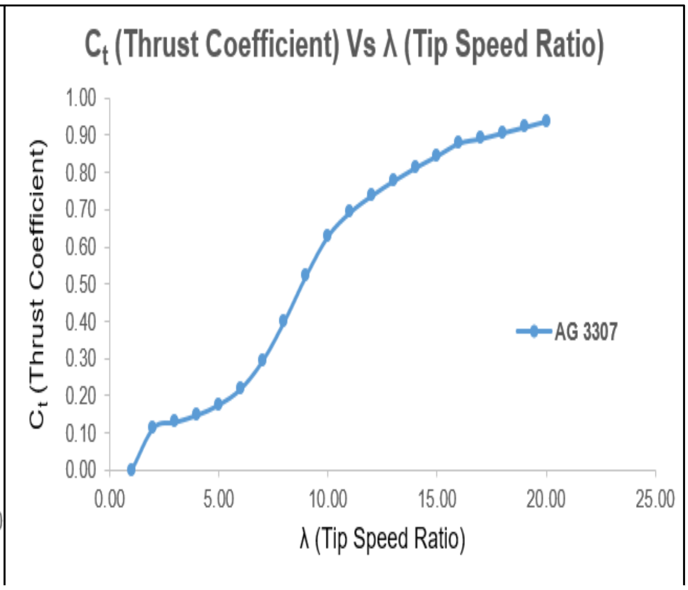


Figure -16: Thrust Coefficient Vs Tip Speed Ratio

From obtain simulation the Maximum coefficient C_P for AG 3307 airfoil which is 0.54 at tip speed ratio of 6. AG 3307 airfoil have a larger value of C_P and C_T, which will increase the power output. This value is higher than that of the other airfoils at the same tip speed ratio.

In Figure 17 we can get in Multiparameter BEM Simulation. In that we can get how much power output we get at how much speed. In this simulation we can take the 7 m/s wind speed and from that we can get the 176.768 W power output. Also, one parameter affects the power output that is Rotational speed, for this analysis we can take 200 m/s speed. We can also compare for different rotational speeds are 200, 300, 400 and 500 RPM are shown in Figure 19.

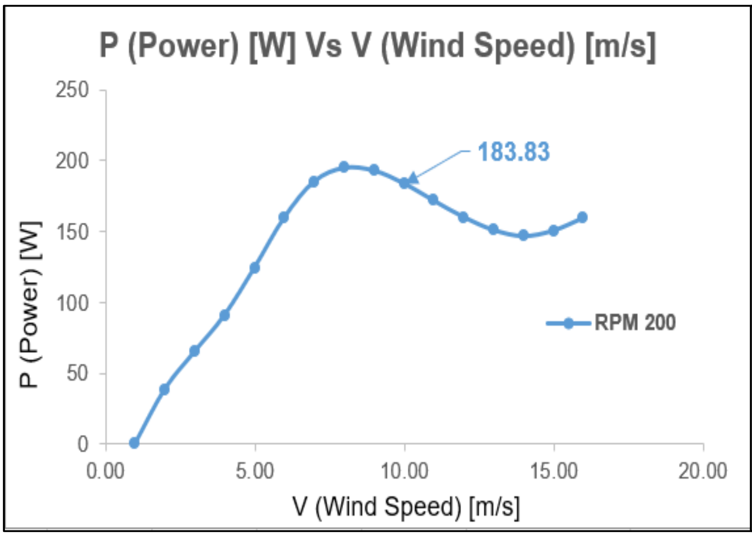


Figure -18: Power Vs Wind Speed at 200 RPM

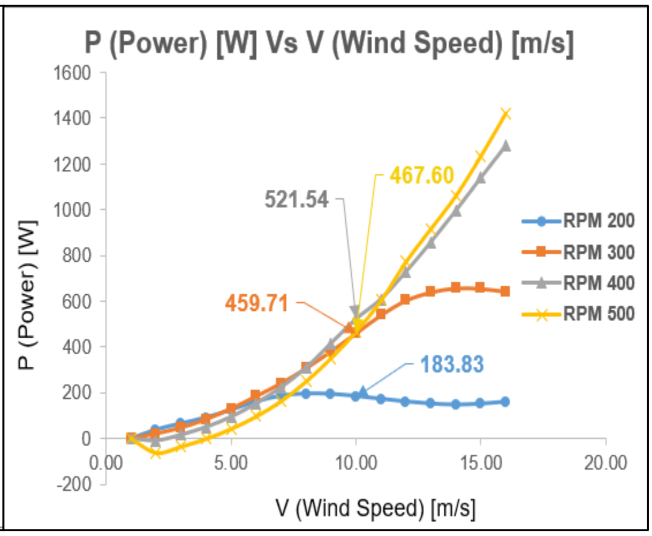


Figure -19: Power Vs Wind Speed at 200-500 RPM

We have found that, at wind speed of 7 m/s and at various RPM 200, 300, 400 and 500 we get the 183.83 W, 459.71 W, 521.54 W and 467.60 W maximum power respectively by considering tip speed ratio 6. As we see that, more increase in rotational speed affects the power.

10. CONCLUSION

In this study after analyzing NACA 2408 and SD 2030 we designed a new Airfoil AG 3307 for horizontal axis wind turbine at low Reynolds Number is 5×10^5 and compare all the airfoils. We have compare all airfoils in QBlade software by BEM theory. All the comparison like C_L/C_D, C_L/Alpha, C_L/C_D Vs Alpha and from that we conclude that airfoil AG 3307 is good among all the airfoils.

We get the maximum power coefficient for the AG 3307 airfoil is 0.54 at tip-speed ratio of 6 and the maximum lift/drag coefficient is 101.37 at Angle of Attack of 5° and at various RPM 200, 300, 400 and 500 we get the 183.83 W, 459.71 W, 521.54 W and 467.60 W maximum power respectively by considering tip speed ratio 6.

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12. BIOGRAPHIES

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