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Performance Evaluation of Small Wind Turbine Using CFD

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Abstract : The main objective of this project is to operate a 3 KW small horizontal axis wind turbine at low wind site and to develop a tool to test the rotor blade and its characteristics without a help of the wind tunnel experiment. This may reduce the wind tunnel experiment analysis, cost as well as transportation cost.Power Coefficient is an important parameter for wind turbines.Coefficient of Power is examined based on Elementary blade element and momentum theory[1].Development of small wind turbine generators which are sufficiently safe and easy to run on individual homes and for self-sufficient and independent power production[1].The coefficient of lift and drag is analyzed in CFD for different wind speed and constant angle of attack 5. Blade profile is based on NACA 4418 airfoil. As per Betz theory, a 3 KW capacity of wind turbine requires 2.3m length of the blade. Blade length is divided into no of division; in each division chord length will be different. Geometry of airfoil is created using Gambit2.3.16 and CFD analysis is carried out in FLUENT 6.3.26, While analyzing the airfoil with different chord length in GAMBIT–FLUENT, will give the performance characteristics of blade for different wind speed. Calculation for Coefficient of Power is done by iterating method[2]. Results are obtained and graphically represented. This approach is very helpful to find Coefficient of Power at different chord position for different blade.
Keywords : CFD, Gambit Fluent, C_p, C_L, C_D, BEM.

Introduction

Improving the Performance of the Wind Turbine is a big Task for a researcher. A lot of work is carried out in a wind turbine. Researchers are showing different output of different condition with different assumptions. When comparing the experimental and theoretical results, where the difference in result will be vast. Researchers are seeking the way to improve the actual performance of the turbine. In this research, Based on Blade Element momentum theory, Blade length is divided into no of elements[9]. CFD analysis is carried out on each element. In the research paper aerodynamic performance characteristics of horizontal-axis wind turbine is determined based on Elementary Blade element Theory[2]. Maximum power efficiency is achieved with the help ofthe lift and Drag coefficient at a constant angle of attack. The Blade cross section is based on NACA 4418.

The most important part in designing a wind turbine blade is the choice of airfoil, Fig 1 shows the nomenclature of theairfoil.

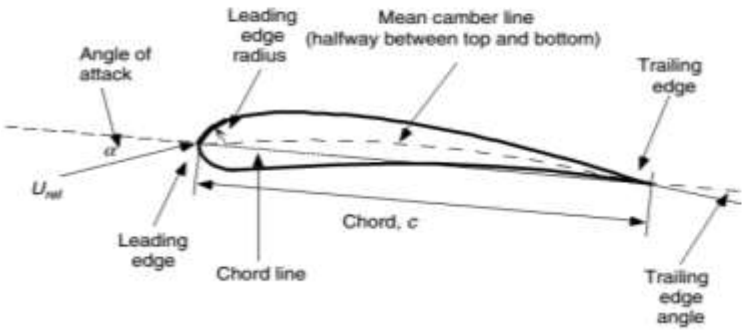


Fig 1: Airfoil Nomenclature

As the entire blade is made up of airfoils sections and the lift generated from this airfoil at every section causes the rotation of the blade, also the performance of the blade is highly dependent on this choice of making the selection and study of the airfoil of prime importance. The chord is a straight line connecting the leading edge to the trailing edge of the airfoil. Airfoils are structures with specific geometric shapes that are used to generate mechanical forces due to the relative motion of the airfoil and a surrounding fluid. Wind turbine blades use airfoils to develop mechanical power.These turbines are used in remote area power systems and it can be combined with diesel/combined generators and a battery system to supply power to a single user or a small grid[3]. The cross-sections of wind turbine blades have the shape of airfoils. The width and length of the blade are functions of the desired aerodynamic performance, the maximum desired rotor power, the assumed airfoil properties, and strength considerations.

Blade element theory relies on two key assumptions[8,9]

- There are no aerodynamic interactions between different blade elements.
- The forces on the blade elements are solely determined by the lift and dragCoefficients.

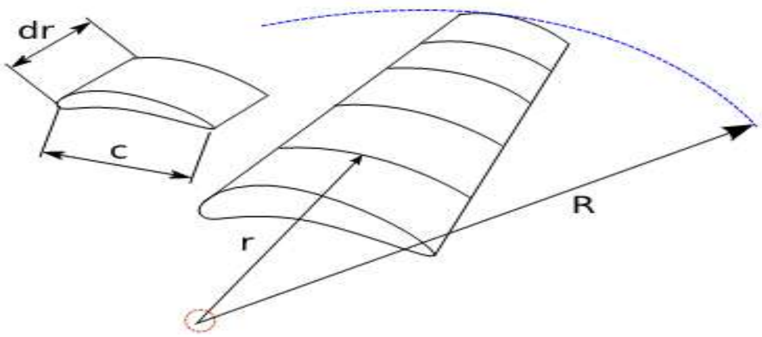


Fig 2:Blade element model

Consider a blade divided up into N elements as shown in Figure 2. Each of the blade elements will experience a slightly different flow as they have a different rotational speed (Ωr), a different chord length (c) and a different twist angle (γ). Blade element theory involves dividing up the blade into a sufficient number (usually between ten and twenty) of elements and calculating the flow at each one. Overall performance characteristics are determined by numerical integration along the blade span.

Designof Wind Turbine

Selection of power output can be predicted by speed of wind and kind of wind turbine use. In this project the power output range is 3KW for low wind speed.Length of the blade depends on thepower output and velocity of site. Here power is 3 KW and Velocity is 8m/s, then corresponding blade length is obtained b

$$P = 1/2 \times Cp \times \rho \times A \times V^3 \quad (1)$$

Where, (P) power of wind in KW, (C_P) power co-efficient, (ρ) Density of air in kg/m³, (A) swept area in m², (V) wind velocity in m/s. Selection of Airfoil depends on thickness, lift co-efficient, drag co-efficient and length of the chord. Performance mainly depends on lift and drag co-efficient. The co-efficient carried out wind tunnel data. Among these factors NACA 4418 airfoil has chosen for this project.Power co-efficient ofthe blade was calculated by following steps. It takes iteration method to obtain the most probable solution.

Table 1. Specification of theBlade

Number of Blades	3
Wind Velocity	3-8 m/s
Tip Speed Ratio	3-8

Blade length has been segmented as 10 elements. Each element has various chord lengths, solidity, radius ratio and relative velocity.

Radius ratio(μ) of the blade can be calculated by the following relation.[9]

$$\mu = \frac{r}{R} \qquad (2)$$

Where μ-radius ratio, (r)-elemental radius in m, (R)-blade length in m. Generally Power Output, Starting Torque and Reynolds Number are mainly dependent on Blade Radius(R)[5]

Local tip speed ratio(λ_r) can be calculated by product of local radius and rotational speed to wind speed.

$$\lambda_r = \frac{r \times \Omega}{V} \qquad (3)$$

Where (λ_r) -Local Tip speed ratio, (r)-Local Radius in m, (Ω)-Blade rotational speed in rad/sec,

(V) - wind velocity in m/sec

Chord(C) is used to find the solidity of the blade. The following expression is usedto find chord length,[9]

$$C = \frac{r \times \Omega (16 \times \pi \times R^2)}{r^2 \times 9 \times 80} \qquad (4)$$

Where C-chord length in m, r-local radius, Ω-blade rotational speed, R-blade length

Solidity(σ′) is calculated by the total blade area divided by the rotor disc area and is a primary parameter in determining rotor performance[9]

$$\sigma' = \frac{B \times C}{2 \times \Pi \times r} \qquad (5)$$

where σ′- rotor solidity, B- no of blades, C-chord length, r- local radius. Horizontal axis wind turbine efficiency depends on the tip speed ratio and solidity[1]

Relative flow angle(β) can be calculated by the following relation.

$$\beta = 90 - 0.666 tan^{-1} \frac{1}{\lambda r} \qquad (6)$$

Where β-flow angle, λ_r-Local Tip speed ratio

Tip loss correction factor (Q) can be calculatedby following relation[2]

$$Q = \frac{2}{\Pi} COS^{-1}(exp(-\left(\frac{B}{2 \times \mu \times \cos\beta}\left(1 - \frac{r}{R}\right)\right) \qquad (7)$$

Where Q-Tip loss correction factor, B-number of blades, β-flow angle, μ-radius ratio, r- local radius,R-blade length

The axial induction factorprovides the maximum possible efficiency can be determined by following relation[2].

$$a = \frac{\{(Cl\times(\sin\beta))+(Cd\times(\cos\beta))\}\times\sigma'}{4\times Q\times\{(\cos\beta)^2\}+\{(Cl\times(\sin\beta))+(Cd\times(\cos\beta))\}\times\sigma'} \qquad (8)$$

Where C_l- Co-Efficient of lift, C_d-Co-Efficient of drag, σ′-rotor solidity

The Angular induction factor can be determined by following relation.[2,9]

$$a' = \frac{(1-a)\times\sigma'\times\{(Cl\times(\cos\beta))-(Cd\times(\sin\beta))\}}{4\times Q\times\lambda_r\times(\cos\beta)^2} \qquad (9)$$

Power is expressed by power extracted from the wind to power available in the wind, It indicated the performance of wind turbine. The Efficiency of the wind turbine is depends on power co-efficient wind turbine.

Power Coefficient can be calculated by[8,9]

$$Cp = \frac{8}{\lambda^2}\int_{\lambda_h}^{\lambda} Q\lambda_r{}^3 \times a' \times (1-a) \times \left(1-\frac{Cd}{Cl}\tan\beta\right) d\lambda_r \qquad (10)$$

CFD Analysis

Computer simulation software is used to study the flow characteristics of the wind turbine blade and this was done by using FLUENT software. The objective of the simulation is to focus on the study of flow over the blade at different wind speed, tip speed ratio and at a constant angle of attack**.**

In order to perform a flow simulation by using FLUENT software, Airfoil is surrounded by a domain is created where the flow characteristics are analyzed. The meshing of the domain is done by using the GAMBIT software. All the geometries of the airfoil are created based on its coordinates before any mashing is done .

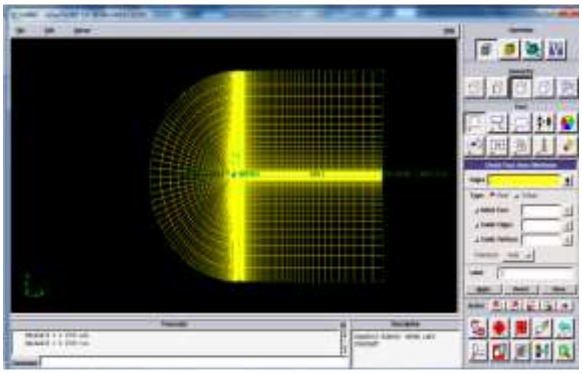


Fig 3: Mesh Generation

In this project, use of FLUENT to analyze the performance characteristics of airfoils while subject to the free stream velocity of air.The type of flow ismodeled in FLUENT to analyze the flow around the airfoil is the one-dimensional flow along the axis of symmetry.For flow over an airfoil, use the pressure-based implicit solver and Velocity formulation will be absolute, and flow will not vary with respect to time.i.e. steady.For viscous model, Inviscid model is selected.For material, ideal-gas is chosen for the air (fluid) and density of air is 1.225kg/m^3 constant. For incompressible flow over an airfoil, it is recommended to set the operating pressure to the ambient value of 101,325Pa.For Boundary condition, farfield1 (velocity inlet) and Farfield2 (wall) is set to the velocity-inlet boundary type. Then, a component has to be selected under velocity Specification Method and the x and y-components are set to that for the free stream. Here, wind velocity (v=8 m/s) is selected based low wind site condition.And theangle of attack is $\alpha = 5°$. For instance, the x-component is 8*cos5°=7.9695, the y-component is 8*sin5°=0.6972.The Result is achieved by iteration until it converges and flattens, the output can be displayed in contours or in vectors, such as Pressure Coefficient, Static pressure, Coefficient of Lift and Coefficient of drag, and Velocity distribution.

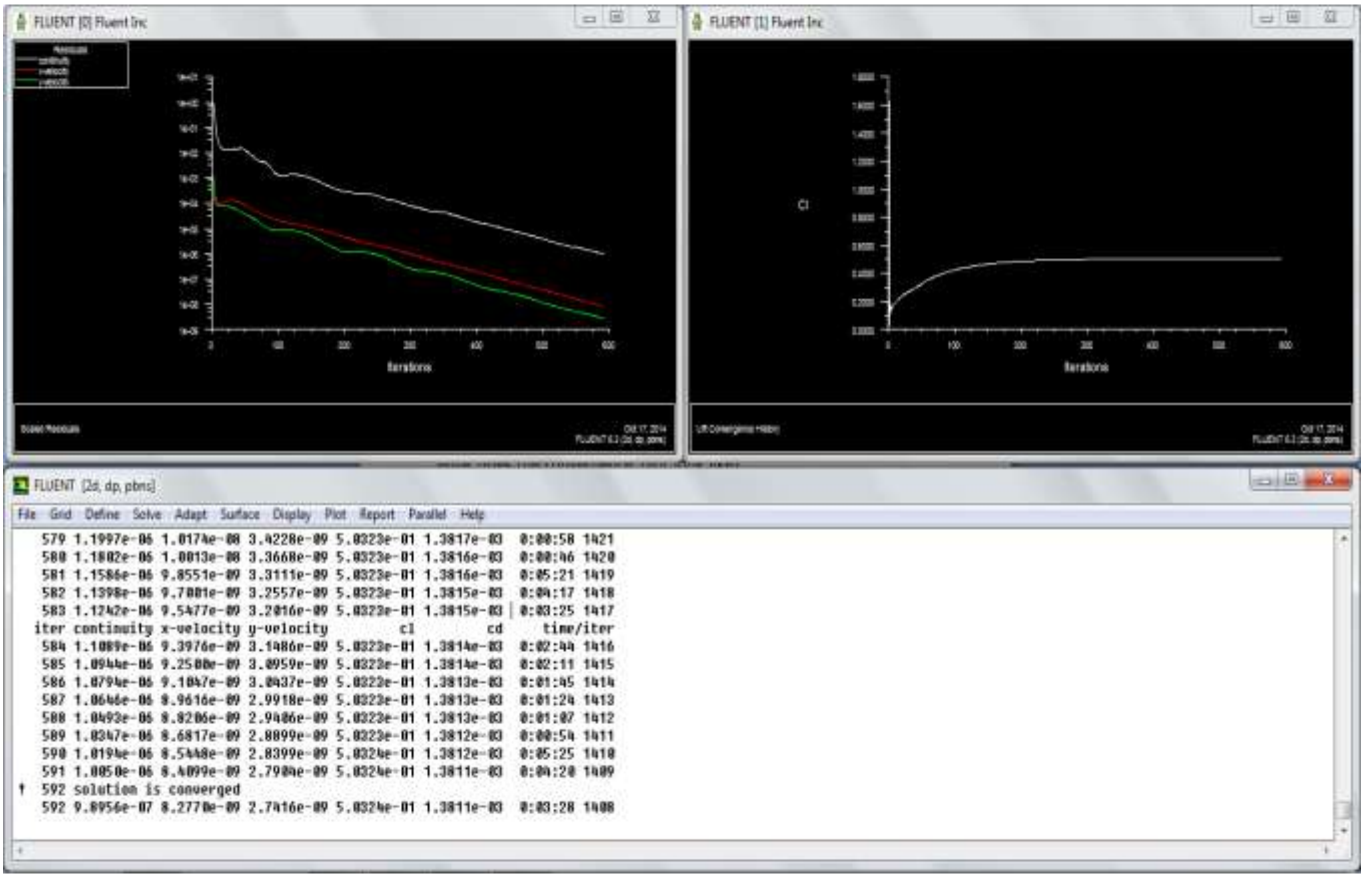


Fig 4:Gambit Fluent Result screen for C_L and C_D C_L and $C_D$vs Velocity from CFD Analysis

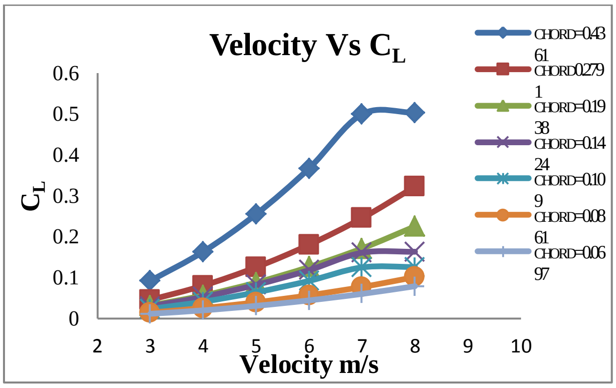
Table 2: Coefficient of lift vs Velocity

Velocity vs Coefficient of Lift							
CHORD→	0.4361	0.2791	0.1938	0.1424	0.1090	0.0861	0.0698
VELOCITY↓	C_L	C_L	C_L	C_L	C_L	C_L	C_L
3	0.091697	0.04497	0.031393	0.02946	0.02287	0.014065	0.010962
4	0.16304	0.07995	0.055816	0.05238	0.040673	0.025007	0.019493
5	0.25473	0.1249	0.087208	0.08184	0.06354	0.03907	0.030452
6	0.36683	0.1799	0.12559	0.1178	0.091516	0.056266	0.043858
7	0.49928	0.24486	0.17093	0.1604	0.12456	0.07658	0.05968
8	0.50324	0.3221	0.2248	0.1628	0.1254	0.10075	0.07848

Table 3: Coefficient of Drag vs Velocity

Velocity Vs Coefficient of Drag							
CHORD→	**0.436332**	**0.279253**	**0.193925**	**0.142476**	**0.109083**	**0.086189**	**0.069813**
VELOCITY↓	C_D	C_D	C_D	C_D	C_D	C_D	C_D
3	0.000323	0.000154	0.000105	0.000101	0.000078	4.94E-05	3.92E-05
4	0.000573	0.000273	0.000186	0.000178	0.000137	8.74E-05	6.91E-05
5	0.000898	0.000428	0.000292	0.000279	0.000215	0.000137	0.000109
6	0.00129	0.000614	0.000419	0.000401	0.00031	0.000197	0.000156
7	0.00176	0.000839	0.000572	0.00054	0.000422	0.000268	0.000213
8	0.001381	0.000864	0.000592	0.000546	0.000318	0.000278	0.000226

From the above table, Graphs are plotted between Velocity vs CL and Velocity vs C_D



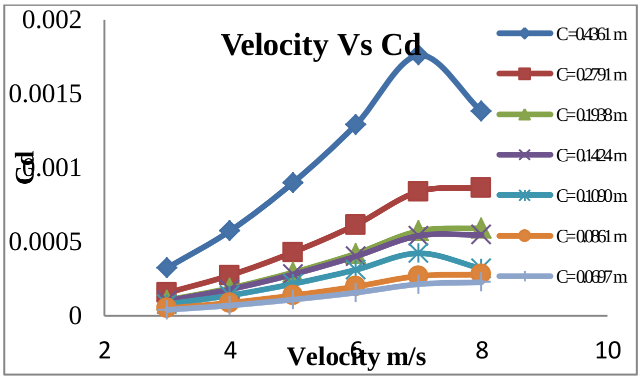


Fig 5: Velocity vs C_L& C_D

Results and Discusion

The theoretical calculation of the wind blade was performed with various wind velocities. The results are listed below.The below table shows the power coefficient of the wind turbine as the wind velocity increases for various tip speed ratios.

Table 4: Velocity Vs Power co-efficient

	TSR = 3	**TSR = 4**	**TSR = 5**	**TSR = 6**	**TSR = 7**	**TSR = 8**
Velocity	**Cp**	**Cp**	**Cp**	**Cp**	**Cp**	**Cp**
3	0.0481	0.0593	0.0708	0.0824	0.0939	0.1051
4	0.0852	0.1047	0.1246	0.1443	0.1634	0.1814
5	0.1323	0.162	0.1917	0.2204	0.247	0.2704
6	0.1891	0.2303	0.2706	0.3076	0.3386	0.3571
7	0.2549	0.3083	0.3583	0.3997	0.4185	0.3262
8	0.2867	0.3474	0.4041	0.4512	**0.4731**	0.3821

For Wind velocity 3 m/s, achieved power coefficient is 0.0481 at tip speed ratio 3.Similarly, For Wind velocity 8 m/s, achieved power coefficient is 0.3821 at tip speed ratio8. Maximum Power Coefficient Cp=0.4731 is achieved at tip speed ratio 7 and wind velocity 8 m/s.

Table 5: Velocity Vs Power

	TSR = 3	**TSR = 4**	**TSR = 5**	**TSR = 6**	**TSR = 7**	**TSR = 8**
Velocity	**P**	**P**	**P**	**P**	**P**	**P**
3	13.219	16.2978	19.458	22.646	25.807	28.885
4	55.504	68.2084	81.172	94.006	106.449	118.175
5	168.337	206.127	243.918	280.435	314.281	344.055
6	415.773	506.359	594.967	676.319	744.478	785.154
7	889.9705	1076.414	1250.986	1395.532	1461.172	1138.911
8	1494.202	1810.554	2106.059	2351.531	**2465.67**	1991.401

For Wind Velocity 3 m/s, generated power is13.21 Watt at tip speed ratio 3. Similarly,For Wind Velocity 8 m/s, generated power is 1991.40 watt at tip speed ratio 8. Maximum Power P=2465.67 watts is achieved when the tip speed ratio=7 and wind Velocity 8.From the **Table 4** and **Table 5** values, Graphs are plotted between wind velocity Vs power co-efficient and wind velocity Vs power.

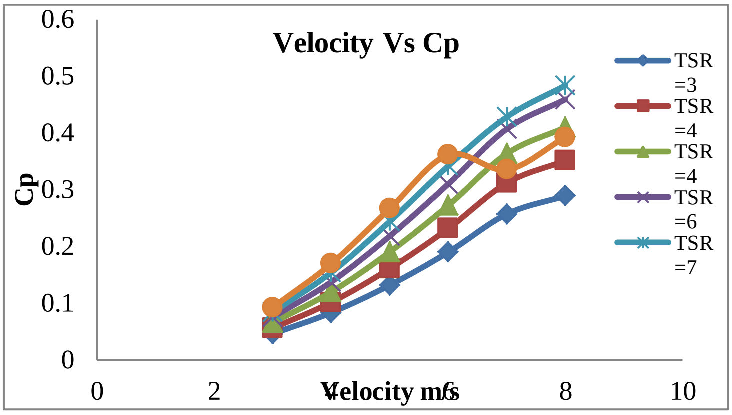


Fig6: Velocity vsC_p

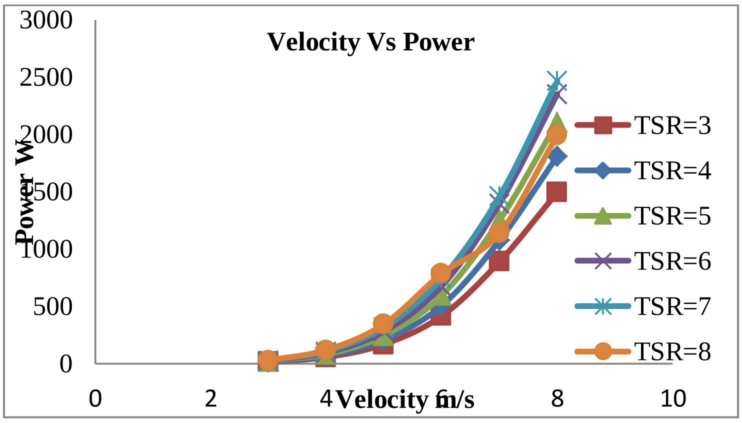


Fig 7: Velocity vs Power

The Wind Velocity range is between 3 to 8 m/s. These curves are drawn at various constant tip speed ratios. **Figure 6** shows that power coefficient is increasing with respect to wind velocity from 3 m/s to 8 m/s at different constant tip speed ratio. Even **Figure 7**.Shows that Power is increasing with respect to wind velocity from 3m/s to 8 m/s at different tip speed ratio.

Conclusion

The Mathematical model of 3KW wind turbine blade performance has been evaluated theoretically. The Power co-efficient of the wind turbine was calculated for various wind velocities and tip speed ratios .The selected airfoil was mashed by using GAMBIT. The 2D flow analysis of the selected airfoil has been conducted byANSYS Fluent. The result showed that the power co-efficiency increases with an increase in velocity and tip speed ratio at different chord positionsof NACA 4418 airfoil(for the selected range). This tool is very helpful to find theCp for small wind turbine blade of any airfoil, if C_l and C_d values of that airfoilare known at different chord positions.

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