Computational Fluid Dynamics Analysis of Wind Turbine Blade at low Reynolds Number and Various Angle Of Attack

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Abstract - *In present work, investigate the lift coefficient and drag coefficient for low Reynolds number and different angle of attack for wind turbine blade. This work NACA 6409 airfoil is considered for analysis of wind turbine blade. And calculate lift coefficient, drag coefficient and lift to drag coefficient at different angle of attack varies 0 degree to 15 degree by Computation Fluid Dynamics (CFD) analysis. The air flow is varying 4 m/second, 5 m/second and 6m/sec. It is observed that result obtain by present CFD analysis drag coefficient increase gradually with increase angle of attack lift coefficient increase gradually with increase angle of attack and lift to drag coefficient increase with angle of attack up to 5 degree and after decrease with angle of attack.*

Key Words: *lift coefficient, drag coefficient, Computation Fluid Dynamics, angle of attack*

1. INTRODUCTION

Wind turbines are rotating prime mover machines which convert wind power in to electrical power with the help of generators. Wind power are solely depends on wind hence, free from pollution, green/clean and renewable source of energy. If the rotational power developed by rotor is directly utilized as mechanical work like water pumping, stone crushing etc. then it is called as wind Mills. and if power is used to generate electricity then it is termed as wind turbines. Wind turbines are classified in two ways, first according to their axis of rotation and second according to power generation. According to power generation wind turbines are classified as micro (<1 KW), mini (1KW-5KW), small (5KW-10KW), intermediate (10KW-1MW), and large (>1MW). The Role of airfoil in Wind Turbine performance and the shape of the aerodynamic profile is decided for blade performance [1]. Even minor changes in the shape of the profile can significantly effected the power curve and noise level [2]. In order to extract the maximum kinetic energy from wind, researchers put more effort in the design of effective blade geometry [3]. A rotor blade may have different airfoil in different sections in order to increases the efficiency, so the modern blades are more complex and efficient comparing to early wind turbine blades. A wind turbine is a complex system which consists of several components, including a rotor, a transmission system, a generator, a nacelle, a tower and other electro-mechanical subsystems.

Terms used in Airfoil Cord are the chord line [4], Cord length [5], Angle of attack [6], Mean camber, Max. Camber, Thickness and Leading edge radius [7]

NACA airfoil series: -The former NACA airfoil series, the 4-digit, 5-digit, and modified 4 and 5-digit, were created using logical equations that describe the camber of the mean-line (geometric mean line) of the airfoil section and section thickness distribution along the length of the airfoil. Later families, together with the 6-Series, are many problematical shapes derived using hypothetical rather than geometrical methods. Before National Advisory Committee for Aeronautics (NACA) developing those series, airfoil design was rather haphazard with nothing to inform the designer except past experience with known shapes and experimentation with alterations to these shapes.

Lift and drag coefficient there are two forces and one moment that act upon an airfoil these being lift, drag and pitching moment [8]. The definitions of these three forces are explained here Lift is the force used to overcome gravity and is defined to be perpendicular to direction of the incoming airflow. It is formed as a consequence of the uneven pressure on the upper and lower airfoil surfaces. The drag force is the force parallel to the direction of incoming airflow. The drag force is due both to viscous friction forces at the surface of the aero foil and to unequal pressure on the aero foil surfaces facing toward and away from the incoming flow. The lift is the force used to overcome gravity and the higher the lift the higher the mass that can be lifted off the ground. For an aero foil, stated that the lift to drag ratio should be extreme. As a result, it can rises efficiency when wind turbine generates electricity. Lift and drag coefficients CL and CD are defined as follows-
Equation of lift coefficient and drag coefficient –

$$\text{Lift cofficiet } (C_l) = \frac{\text{lift force } (F_l)}{\frac{1}{2}\rho U_0^2 C}$$

$$\text{drag cofficient}(C_d) = \frac{\text{drag force}(F_d)}{\frac{1}{2}\rho U_0^2 C}$$

Tip speed ratio:-
The tip speed ratio is defined as the ratio of the blade tip speed to wind speed. It is an important parameter for wind turbine design and its definition is shown in Equation –

$$\text{Tip speed ratio}(\gamma) = \frac{\omega \times R}{U_o}$$

The number of blades mostly influences the Horizontal Axis Wind Turbine performance. The most common formats are two-blade and three-blade machines. Some small Horizontal Axis Wind Turbines may have more than 3 blades, and generally they are low speed wind turbines. Low speed turbine *operates with large torque and other side, high speed wind turbines have 3 blades can hence to achieve same wind energy utilization with low driving torque.*

Untwisted and twisted blades for some modern wind turbines, the blade tips are designed using a thin airfoil for high lift to drag ratio, and the root region is designed using a thick version of the same airfoil for structural support [9]. The crucial factors for choosing airfoil are: maximum lift to drag ratio and low pitch moment as one untwisted blade, the stall condition occurs from the span wise station (r/R) is 16%. In order to increase the effective flow velocity at the rotor blade from the blade root to the tip, it is better to twist blades. This thesis work primarily on designing the blade for installed power in the regions of low wind power density region. The aerodynamic flow profiles of wind turbine blade have critical effect on aerodynamic blade efficiency of wind turbines. This includes the selection of an appropriate airfoil section for the proposed wind turbine blade [10]. The NACA 64 series is selected as the basic group for investigation because that show the good low speed performance and the power curve is superior in the low and medium wind speed ranges [11]. The air over the wind blade has been turbine blade analyzed to find the pressure and velocity variation using ANSYS FLUENT 14.5 effected of angle of attack on the lift and drag over the blade has also been analyzed

2. DESIGN CRITERIA OF BLADE PROFILE

Airflow over a stationary air foil produces two forces, a lift force perpendicular to the air foil and a drag force in the direction of air foil, the existence of the lift force depends on laminar flow over air foil. When the air foil is move in the direction of the lift this translation will combine with the motion of the air to produce a relative wind direction (W), the air foil has been reoriented and maintain a good lift to drag ratio. The lift and drag forces can be split into components parallel and perpendicular to the direction of the undisturbed wind. The lift is perpendicular to the relative wind but is not in the direction of aerofoil translation, and these components combined to from the tangential force and axial force. The tangential force acting on the turbine rotor in the direction of translation which is available to do useful work, and allow for the blades to rotate around to horizontal axis and causes a torque that drive some load connected to the turbine rotor . The other force is axial force on the direction of the undistributed wind which must to be used in the design of air foil supports to assure structural integrity, and the tower must be strong enough to withstand this force.

2.1. Aerofoil drag characteristics:-

The definition of the drag coefficient for wind turbine blade is based not on the frontal area but on the plan area, for reasons that will become clear later. The flow past a body which has a large span normal to the flow direction is basically two-dimensional and in such cases the drag coefficient can be based upon the drag force per unit span using the stream-wise chord length for the definition For-

$$C_d = \frac{F_d\,(\text{Drag force per unit lenth})\,.}{0.5 \times \rho \times U^2 \times C}$$

Basic Principal of Lift:

The cross-sectional shape of the blade is called an airfoil. The blade provides lift by creating a condition where the pressure above the turbine blade is lower than the pressure below the turbine blade. Since the pressure below the wing is higher than the pressure above the wing, there is a net force upwards. Viscosity is essential in generating lift. The following two ways to show that the lower pressure on the blade is- (a) One method is the Bernoulli Equation, (b) A second method is Euler's Equations (which is the Bernoulli equation is derived from) across the streamlines.

Aerofoil lift force coefficient:-

Lift force is upward force acting on the blade profile due to low pressure generated at top of air foil and this force affected by velocity the angle of attack. At any velocity, lift force will be increases at beginning but after the some angle of attack these force will be decreases. Lift force will be increases, increases the velocity of wind. Thus lift coefficient also increases.

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$$C_l = \frac{F_l\,(\text{lift force per unit length})}{\frac{1}{2}\rho U_0^2 C}$$

Betz Limit:-

The coefficient of power of a wind turbine is a measurement of how efficiently the wind turbine can be converts the wind energy into electrical energy.

$$C_{power} = \frac{\text{Electricity produce by turbine}}{\text{Total wind energy available}}$$

Material selection:- For development of small wind turbine blades Developed from NACA 6409 profiles using a specified design methodology for small size horizontal axis wind turbine systems.. The investigations are carried out by varying the material compositions used for blade development. The following are the materials used for fabrication of wind turbine blades. (a) Metal like aluminium (b) Glass fibre reinforced with polyester resin blade (c) Glass fibre reinforced with polyester resin sandwiched with UV hard foam (d) Glass fibre reinforced with Epoxy resin sandwiched with UV hard foam. UV hard foam is used as a central beam, which increases the stiffness properties of the blade. NACA 6409 airfoil shape used for the development of blade profiles.

3. Computational Fluid Dynamics

Computer is used to perform the calculation requires to simulate the interaction of liquids and gases with body. With supercomputer, better solutions can be achieved. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios such as transonic or turbulent flows. For designing and analyzing the engineering systems which involve fluid flow, there are basically two approaches: experimental and numerical. The experimental approach involves a complete testing rig setup for performing experiments on a scaled model of the prototype machine, while the latter is based on either analytical or computational solution of differential equations governing the flow through the system. Any numerical simulation of fluid flow problems consists of various distinguished processes. These are 1. Model the geometry of problem domain. 2. Choose appropriate mathematical model of the physical problem. 3. Choose a suitable discretization method. 4. Generate a grid based on problem geometry and the discretization method. 5. Use a suitable solution technique to solve the system of discrete equations. 6. Set suitable convergence criteria for iterative solution methods. 7. Prepare the numerical solution for further analysis.

3.1 DISCRETIZATION METHODS:- Choice of a method for a particular problem depends on many factors like geometry of the problem domain, predominant trend in a particular application and preference of analyst. Each method has its own advantages and limitations. **Finite Volume Method: -** Finite volume method (FVM) is a discretization method in which the fluid domain is divide into very small cells having finite volume by generating grid. **Finite Element Method: -** The finite element method (FEM) is a very popular discretization approach especially in structural mechanics. Initially its use was limited to stress analysis problems. After the evolution of weighted residual approach FEM is more generalized. **Finite Difference Method:-** The finite difference method is the easiest method in terms of programming and formulation and is commonly used for simple geometries. It is the oldest method for solving partial differential equations numerically.

4. METHODOLOGY

Blade profile selection: we choose the NACA 6409 blade air foil for analysis. These profile given the better performance at low speed having high lift to drag ratio and good stall properties. **NACA Four-Digit Series: -** 1. Pick values of x from 0 to the maximum chord c.

2. Compute the mean camber line coordinates by plugging the values of m and p into the Following equations for each of the x coordinates.

$$Y_c = \frac{m\,[2px - x^2]}{p^2}$$

From x=0 to x = p

$$Y_c = \frac{m}{(1-p)^2}[(1-2p) + 2px - x^2]$$

From x = p to x = c

S. No.	X- axis	Y-axis
1	1	0
2	0.951	0.005
3	0.9	0.009
4	0.85	0.014
5	0.8	0.018
6	0.75	0.022
7	0.7	0.026
8	0.6	0.03
9	0.6	0.033
10	0.55	0.036
11	0.5	0.038
12	0.45	0.04
13	0.4	0.04
14	0.35	0.04
15	0.3	0.039
16	0.25	0.037
17	0.199	0.035
18	0.149	0.031
19	0.099	0.025
20	0.074	0.022
21	0.049	0.018
22	0.024	0.012
23	0.012	0.009
24	0.007	0.007
25	0.005	0.006

S. No.	X-axis	Y-axis
26	0.005	-0.005
27	0.008	-0.005
28	0.013	-0.007
29	0.026	-0.009
30	0.051	-0.011
31	0.076	-0.013
32	0.101	-0.015
33	0.151	-0.017
34	0.201	-0.019
35	0.251	-0.019
36	0.3	-0.02
37	0.35	-0.02
38	0.4	-0.019
39	0.45	-0.018
40	0.502	-0.016
41	0.55	-0.014
42	0.6	-0.012
43	0.65	-0.01
44	0.7	-0.007
45	0.749	-0.004
46	0.8	-0.002
47	0.85	-0.001
48	0.9	0.0013
49	0.95	0.0017
50	1	0

Where x = coordinates along the length of the airfoil, from 0 to c (which stands for chord, or length) y = coordinates above and below the line extending along the length of the airfoil, these are either y_t for thickness coordinates or y_c for camber coordinates. t = maximum airfoil thickness in tenths of chord (i.e. a 15% thick airfoil would be 0.15). m = maximum camber in tenths of the chord. p =position of the maximum camber along the chord in tenths of chord

Calculate the thickness distribution above (+) and below (-) the mean line by plugging the value of t into the following equation for each of the x coordinates-

$$Yt = \frac{t}{0.2}\left[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right]$$

Determine the final coordinates for the airfoil upper surface (X_U, Y_U) and lower surface (X_L, Y_L) using the following relationships.

$$X_u = x - y_t \sin\theta$$

$$Y_u = y + y_t \cos\theta$$

$$X_l = x + y_t \sin\theta$$

$$Y_l = y_c - y_t \cos\theta$$

Where $\theta = \frac{dy}{dx}$

Coordinate point of NACA 6409 air foil:-

Specification of NACA 6409 low speed wind blade profile- Max thickness 9% at 29.3% chord. And Max camber 6% at 39.6% chord Source

Velocity consideration:- We are selected the velocity for investigation is 4 m/sec, 5m/sec, 6m/sec. At low speed wind turbine blade NACA6409 to generated the power approximately one
kilowatt at maximum efficiency for approximate 5 m/sec wind velocity.

ANSYS (CFD) Work Process

Preparation of geometry- Geometry Modeling: -Creation of Model by using ansys cfx modeling tools for generating the geometry of the part of which we want to perform the analysis. We selected the coordinate point of NACA 6409 airfoil in NACA website and imported coordinate point in ansys cfx software and it join two different curve in upper and lower part and get the geometry of NACA 6409 air foil.

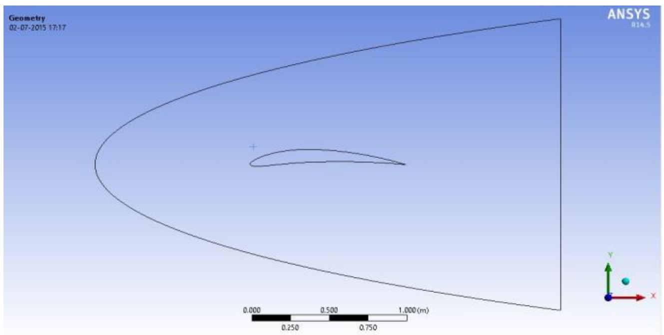


Fig 4.2 geometry of wind turbine blade

Meshing:-Meshing is a critical operation in CFD. In this process, the geometry is discretized into large numbers of small Element and nodes. The arrangement of nodes and element in space in an appropriate manner is called mesh. The CFD analysis accuracy and duration depends on the mesh size and orientations. With the increase in mesh size (increasing no. of element), the CFD analysis speed decrease but the accuracy increase. In this analysis performance node size is 0.05 used for tetragonal element. Number of node are 24244 and element is 11981

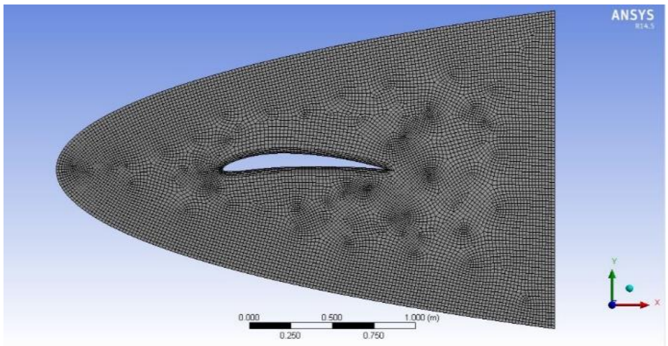


Fig.4.3Meshing of NACA 6409 air foil.

Boundary Condition: -Define the desired boundary condition for the problem i.e. velocity, mass flow rate, temperature, heat flux etc. the boundary condition are- (a) Inlet - Velocity: 4 m/s, 5m/s, 6m/s **(b)** Outlet - Pressure: Atmospheric **(c)** Rotor (Body) - Smooth: Rotating **(d)** Wall - No Slip and Stationary **(e)** Fluid – Air

Solution Method: -Choose the Solution method to solve the problem should be First order, second order. **Solution Initialization**:-Initialized the solution to get the initial solution for the problem. **Run Solution: -**Run the solution by giving no of iteration for solution to converge.

Post processing For observing the interpretation of result. The result can be observed .In various graph, value and variation plot in over blade etc.

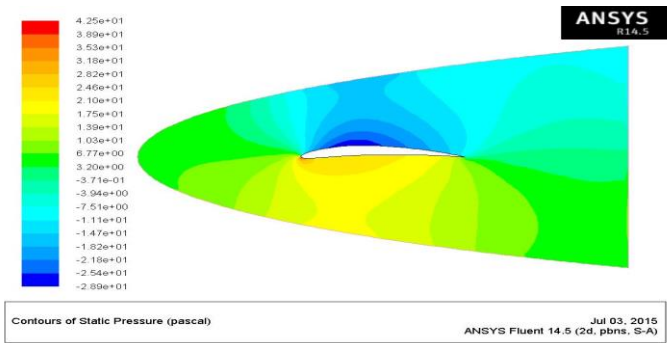


Fig.4.4 Pressure plot of NACA 6409 air foil.

these fig 4.4 show the pressure variation in air foil by different colours. Red colour show high pressure and blue coloure show low pressure thus at the upper porsion of air foil low and compare to high pressure at lower surface and at the leading edge high presure because it is stagnation point in flow field that show by red colour.

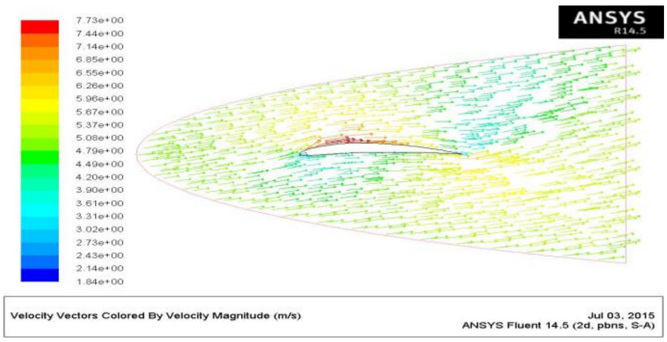


Fig.4.5 Velocity vector plot in NACA 6409 air foil.

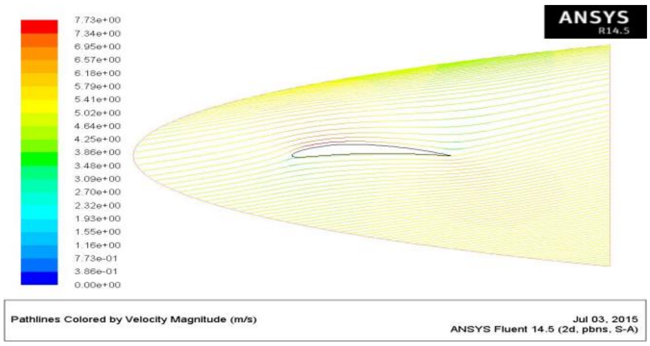


Fig.4.6 velocity path line over the NACA 6409 air foil.

Fig. 4.5 and fig 4.6 sho that the directon of velocity vector and path line of flow over air foil and different coloure show different magnitude of velocity of flow.

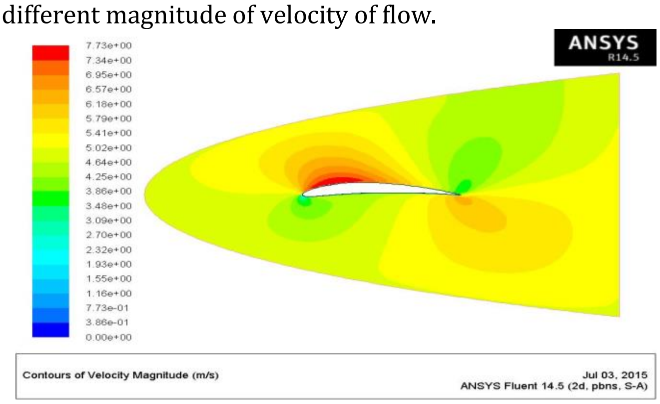


Fig.4.7 velocity magnitude over NACA 6409 air foil.

these fig. 4.7 show that velocity variation in air foil by different colour. Red colour show high velocity and blue colour show low velocity thus at the upper porsion of air foil velocity is high and lower porsion compare to velocity low and at the leading edge of airfoil aproximate zero velocity because it is stagnation point in flow field that show by blue colour.

5. RESULT AND DISCUSSION

In this work Horizontal axis wind turbine blade with .NACA 6409 performance has been investigated for different angle of attack and various low velocities. The airfoil NACA 6409 is chosen for investigation as shown in various figure. The airfoil profile and boundary circumstances are formed. NACA 4-series profiles are obtained from Java foil. A Mesh Domain for the fluid around the airfoil is formed using Design Modeler in ANSYS software. A fine mesh is formed for the fluid flow area of the domain in ANSYS CFX software:-

TABLE 5.1 Show the different value of drag coefficient and lift coefficient with respected to angle of attack

ANGLE OF ATTECK	DRAG COEFFICIENT		
	4m/sec	5m/sec	6m/sec
1	0.18249	0.23273	0.22139
2	0.2074	0.25265	0.23874
3	0.2383	0.27913	0.25957
4	0.27119	0.30258	0.29213
5	0.30052	0.32844	0.33045
6	0.33739	0.361022	0.36831
7	0.36988	0.39644	0.41433
8	0.41825	0.43803	0.46614
9	0.45713	0.48506	0.51948
10	0.50774	0.53557	0.58559
11	0.55871	0.58955	0.65618
12	0.61104	0.65583	0.7389
13	0.71357	0.744223	0.828882
14	0.79963	0.83558	0.92405
15	0.86123	0.936489	1.05132

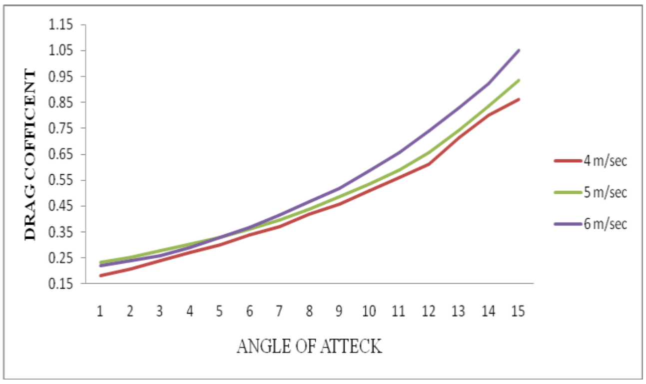
TABLE 5.2 Show the different value of lift coefficient and lift coefficient with respected to angle of atteck

ANGLE OF ATTECK	LIFT COEFFICIENT		
	4m/sec	5m/sec	6m/sec
1	0.96915	1.3325	1.10414
2	1.20978	1.60522	1.40553
3	1.48158	1.861	1.67809
4	1.75295	2.0992	1.93277
5	1.99842	2.3089	2.15827
6	2.22871	2.48276	2.365
7	2.42012	2.6124	2.56662
8	2.62097	2.7407	2.72656
9	2.79376	2.82851	2.87291
10	2.97159	2.91266	3.02638
11	3.12703	2.86183	3.1228
12	3.20789	2.8644	3.21952
13	3.20603	2.8514	3.28514
14	3.17531	2.8424	3.35981
15	3.0872	2.81008	3.39919

TABLE 5.3 Show the different value of lift to drag coefficient and lift coefficient with respected to angle of atteck

ANGLE OF ATTECK	Lift to Drag Coefficient		
	4m/sec	5m/sec	6m/sec
1	5.310701956	5.725518842	4.987307466
2	5.833076181	6.353532555	5.887283237
3	6.217289131	6.667144341	6.464884232
4	6.463918286	6.937669377	6.616129805
5	6.649873553	7.029898916	6.531305795
6	6.605738167	6.877032425	6.421221254
7	6.542986915	6.589647866	6.194627471
8	6.266515242	6.256877383	5.849229845
9	6.111521887	5.831257989	5.53035728
10	5.85258203	5.438430084	5.168086887
11	5.596874944	4.854261725	4.759060014
12	5.249885441	4.367595261	4.357179591
13	4.49294393	3.831378498	3.963338569
14	3.970974076	3.401708993	3.635961258
15	3.584640572	3.000654573	3.233259141

The Lift coefficient and drag coefficient is calculated for this NACA 6409 series for the angle of attack 1° to 15° in the velocity of 4 m/sec, 5 m/sec and 6 m/sec show in table above mention. The lift force at varies lengths from hub to tip is analyzed and it is clear that lift force increases from hub to tip for all range of angle of attack.



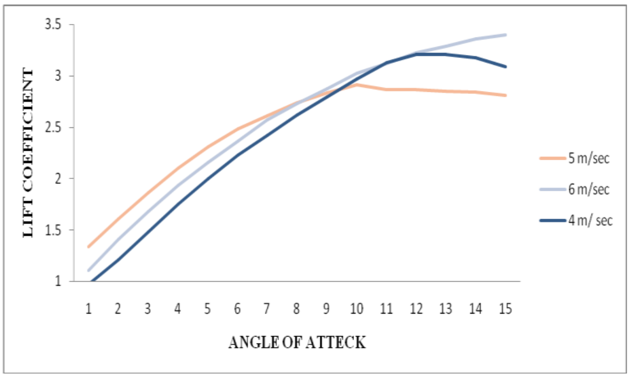
Chat-5.1 show the relation between drag coefficients with respected to angle of attack

Fig. 5.1 show the relation between drag coefficient with respected to angle of attack, will be drag coefficient increases with increase in angle of attack up to 12°at 4 m/sec

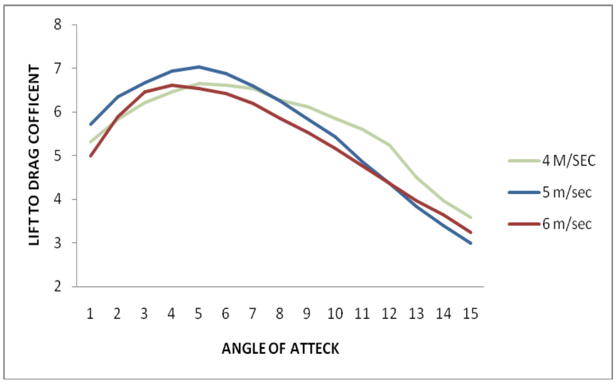
The drag forces begin gradually increasing up to 10⁰ of attack angel and then it growth of is rapidly. The rate of increase in lift is more for angle of attack from 1°to 10°and between 10° to 15° the rise in lift force is less.

Lift coefficient to drag coefficient ratio increases linearly 1⁰ to 6⁰ but after 6⁰ to 15⁰ will be decreases. Because of after the 6⁰ lift force is increases less compare to increases to drag force. Lift to drag ratio maximum at 6⁰ of angle of attack. Thus blade angles of attack are design at 6°at 4 m/sec velocity because maximum lift to drag ratio at these angle of attack.

The CFD analysis also carried out using ANSYS cfx software. The velocity and pressure distribution at various angles of attack of the blade is shown in above Figure



Chat-5.2 show the relation between lift coefficient with respected to angle of attack



Chat-5.3 show the relation between lift to drag coefficient with respected to angle of attack

The coefficient of Lift and drag is calculated for this NACA 6409 series for the angle of attack 1° to 15° in the velocity of 5 m / second. The lift force at varies lengths from hub to tip is analyzed and it is cleared that lift force increases from hub to tip for all range of angle of attack.

The drag forces begin gradually increasing up to 10⁰ of attack angel and then it growth of is drastically. The rate of increase in lift is more for angle of attack from 1°to 10° and between 11° to 15° the rise in lift force is less.

Lift coefficient to drag coefficient ratio will be increases at 1⁰ to 6⁰ but after 6⁰ to 15⁰ will be decreases. Because of after the 8⁰ lift force is increases less compare to increases to drag force. Lift to drag ratio maximum at 6⁰ of angle of attack. Thus blade angle of attack is design at 6°at 5 m/ sec velocity because maximu0m lift to drag ratio at these angle of attack.

The CFD analysis also carried out using ANSYS cfx software. The velocity and pressure distribution at various angles of attack of the blade is shown in above Figure. These results are concurring with wind tunnel experimental values. Hence the results are validated with the experimental work.

The coefficient of Lift and drag is calculated for this NACA 6409 series for the angle of attack 1° to 15° in the velocity of 6 m/second. The lift force at varies lengths from hub to tip is analyzed and it is cleared that lift force increases from hub to tip for all range of angle of attack.

In the lift force increases with increase in angle of attack up to 10°at 6 m/sec and it starts to increases gradually after 10° angle of attack.

The drag forces begin gradually increasing up to 10^0 of attack angel and then it growth of is rapidly. The rate of increase in lift is more for angle of attack from 1°to 10° and between 10° to 15° the rise in lift force is less.

Lift coefficient to drag coefficient ratio will be increases at 1^0 to 6^0 but after 6^0 to 15^0 will be decreases. Because of after the 6^0 lift force is increases less compare to increases to drag force. Lift to drag ratio maximum at 6^0 of angle of attack. Thus blade angles of attack are design at 6° at 6 m/sec velocity because maximum lift to drag ratio at these angle of attack.

The CFD analysis also carried out using ANSYS cfx software. The velocity and pressure distribution at various angles of attack of the blade is shown in above Figure. These results are concurring with wind tunnel experimental values. Hence the results are validated with the experimental work.

CONCLUSIONS

Low speed wind turbine blade are investigated at various angle of attack –

(a) The comparison and examine of the overall aerodynamic performance of airfoil NACA 6409 with various angle of attack, it can see that aerodynamic parameters (especially lift-to-drag ratio) are greatly affected by Reynolds number and angle of attack.
(b) At constant shaft speed, the angle of attack increases with increasing wind speed. The blade Stalls when the angle of attack exceeds 15 degrees. In a stall condition the air can no longer,flow smoothly or laminar over the rear side of the blade, lift therefore falls and drag increases.
(c) Lift coefficient to drag coefficient ratio will be increases at 1^0 to 5^0 but after 5^0 to 15^0 will be decreases. Because of after the 5^0 lift force is increases less compare to increases to drag force. Lift to drag ratio maximum at 5^0 of angle of attack. Thus blade angle of attack are design at 5° at 4 m/ sec velocity because maximum lift to drag ratio at these angle of attack.
(d) Low speed wind turbine blade performance are also affected by type of air foil use , size of blade and weight of blade and wind speed thus blade are built by less weight strong material such as glass fiber etc. and optimum blade length.
(e) NACA 4 digit series and 5 digit series are showing that better performance in low and medium wind speed range. Thus these NACA series of turbine blade are used for low wind speed region such as urban area tapping at medium height.

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