Optimization of Wind Turbine Blade of Darrieus VAWT for Low Wind Speeds

D. P. Thorat¹, K. B. Bokankar², S. P. Patil³

¹ME Student, Heat Power, MIT Aurangabad, Maharashtra, India
²Asst. Prof., ³Asso. Prof., Mechanical, MIT Aurangabad, Maharashtra, India

Abstract — In wind turbine, blades are the most crucial component, which are accountable for conversion of wind energy into kinetic energy of shaft. In the early stage, theoretically, blade design was modest and focused on field testing and wind tunnel testing which needs a lot of efforts and resources. Due to the development of computer aided design codes, they provide another way to design and analyzed the wind turbine blades. In this paper, an effort is made to study the important factors considered for the optimization of Vertical Axis Wind Turbine (VAWT) blade such as type of aerofoil, angle of attack (AoA), blade material, CFD, chord length, height of blade, number of blade, starting torque, wind speeds, etc., to identify its suitability for its application in low wind speeds and good agreement is to be made between cost and aerodynamics.

Keywords – Blade, aerofoil, VAWT, CFD etc.

I. INTRODUCTION

As a sustainable energy alternative, wind energy is essentially vital across national and international energy policy in response to climate change. Wind turbine blades are shaped to optimize the power from wind at lowest cost. The design was basically focused on need of aerodynamic shape, but economics mean that the blade shape is a compromise to keep the cost of construction reasonable. The two fundamental categories of wind turbine are the horizontal axis (HAWT) and vertical axis (VAWT). The horizontal axis machines are highly developed and used in all current large scale wind farms. While, the preponderance of research on VAWT design was drifted out since the late 1970s and early 1980s.[¹] Just like an airplane wing, wind turbine blades work by propagating lift due to their shape. The more curved side generates minor thrust while high pressure air pushes on the other side of the aerofoil. The net result is a lift load upright to the direction of flow of the air. The lift force upsurges as the blade is turned to present itself at a greater angle to the wind. This is called the angle of attack. At broad angles of attack the blade “stalls” and the lift declines again. Hence there is an most favorable angle of attack to accomplish the maximum lift.[¹⁶]

II. LITERATURE REVIEW

The objective of the present chapter is to review previous studies carried out on Darrieus Turbine, its basic and computational fluid dynamics analysis in dynamic state, to will help us to design aerofoil for Darrieus Turbine. The method and importance of calculating the above is being given in the present review.

G.J. Darrieus (1931) Although a considerable number of arrangements have been proposed at different times, particularly for utilizing the force of the wind, which comprise wheels having their shafts transverse to the current, especially vertical shafts, none of these arrangements’ have been developed for practical use for the following reasons Their efficiency is as a rule very low, for even when the blades comprising them are not subjected to an adverse effect by the over a part of its course which counteracts the movement, their system of operation in the active part of this course is effective15 inasmuch as it is inseparable from the formation, downstream of eddies and discontinuities from which the kinetic energy given up to the which has passed through the apparatus, represents an appreciable loss.[¹]

Mazharul Islam et al. (2008) studied the main aerodynamic models which are used for performance prediction and design of straight-bladed Darrieus-type Vertical Axis Wind Turbine (VAWT).
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The author have been studied five aerodynamic models single stream tube, double stream tube, multiple stream tube, cascade model, vortex model. It has been found out that at present the widely used models are the double-multiple stream tube model, Vortex model and the Cascade model. Each of these three models has its strengths and weaknesses which are discussed in this paper. [6]

T. Ikoma et.al (2008) Authors were carried out The CFD computation of the drag force and the lift force on a single blade and three blades type turbines. The CFD computation was validated by comparing with model experimental results. After that, the database of the drag coefficient and the lift coefficient of a blade has been made up for theoretical calculations of torque characteristics of the turbine with the blade element and the momentum combined theory. They have been calculated torque around center of turbine with only single blades and they found that torque is negative in angles of -30 to +150 degrees. They also calculated torque around center of turbine with only 3 blades and they found that range of negative torque is wide in single blades as compared to 3 blades. [8]

R. Gupta And Agnimitra Biswas (2010) studied steady-state two-dimensional CFD analysis to simulate the flow over a twisted three-bladed H-Darrieus rotor. Authors evaluated aerodynamic coefficients, such as lift, drag, and lift-to-drag coefficients with respect to angles of attack up to 45 degrees for wind velocities 7m/s and 9m/s. Authors has been developed new approach for the evaluation of aerodynamic coefficients experimentally. For this purpose they derived correlation equations for lift and drag coefficients. Both the computational and experimental results were compared by them and they found that the results showed good matching between the two approaches. [11]

S. Rajakumar and D. Ravindran (2012) studied the approach for the determination of aerodynamic performance characteristics of Horizontal Axis Wind Turbine (HAWT). The author examined optimum twist of a windmill blade on the basis of elementary blade-element theory. Results for a typical airfoil cross-section show that the optimum angle of attack and optimum twist angle of the blade improves the performance of the wind turbine. The author has been present a new formulation of performance prediction equations of horizontal-axis wind turbines. These equations were successfully applied to an existing machine producing 1.5 MW electrical powers. For this work two different airfoil sections NACA 4410 and NACA 2415 are taken into consideration by author. [7]

A. Rossetti and G Pavesi (2013) the author presented and compared different approaches to describe the self-start of an H-blade Darrieus rotor in the present paper. The Blade Element Momentum approach was compared with 2D and 3D CFD simulations.

The author have been studied five aerodynamic models single stream tube, double stream tube, multiple stream tube, cascade model, vortex model. It has been found out that at present the widely used models are the double-multiple stream tube model, Vortex model and the Cascade model. Each of these three models has its strengths and weaknesses which are discussed in this paper. [6]

Robert Howell et.al (2013) an author has been manufactured and tested small model VAWT turbine over a range of operating conditions. They found that straight turbine rotor blade, operates at relatively low tip speeds with an aspect ratio of 4:1 and its performance shows vast dependencies on the rotor blade surface finish. Below a critical Reynolds number, the performance is improved by roughing the surface of the turbine, but above this Reynolds number the power coefficient is less good. [9]

2.3 Experimental Analysis of Airfoil of Darrieus Turbine

Robert E. Sheldahl et al. (1981): This report describes a wind tunnel test series conducted at moderate values of Re in which 0<α < 180 force and moment data were recorded for four symmetrical blade airfoil sections (NACA-0009, -0012, -0012H, and -0015), and how an airfoil property synthesizer code can be used to extend the measured properties to arbitrary values of Re (10^4 < Re < 10^7) and to certain other section profiles (NACA-0018, 0021, 0025). [12]

Michael S. Selig et al. (2011): The wind tunnel test techniques described in this paper have been validated and used to test over 200 airfoils at low Reynolds numbers at UIUC. The study concentrates on calculations for lift and moment, and airfoil drag. This article highlighted new approach on the AG455ct airfoil with a large 30%-chord flap deflected over a wide range that might be used for glide path control or extreme maneuvering. In a next set of tests, a flat-plate airfoil was evaluated with leading edge serration geometries to analyze the effects on stall characteristics. The results back the outcomes of other researchers that leading edge serrations lead to higher lift and softer stall. The results propose that these characteristics are handled by lower drag in the stall and post-stall range, but drag data was not obtained in these conditions. [15]

Marco Raciti Castelli et al. (2012): In this paper, authors modeled for the evaluation of energy performance and aerodynamic forces acting on a tiny straight edged Darrieus type vertical axis wind turbine depending on blade analytical section has been developed, based on an analytical code coupled to a solid modeling software which was linked to a finite volume CFD code for the calculation of rotor performance. Author has been obtained results, based on two candidate blade profile architectures, which are characterized by a conventional NACA 0021 blade profile and a newly developed DU 06-W-200 non-symmetric profile; demonstrate the better performance of the latter.
The increased DU 06-W-200 overall aerodynamic performance (up to nearly 2% with respect to NACA 0021) is due to an increased blade performance during downwind operation: even though the maximum torque values are generated during the upwind revolution of the turbine, downwind blade operation has proved to be determining in improving DU 06-W-200 rotor aerodynamic behavior. Finally, it has been proved that the maximum torque values generated during the operation of a vertical axis wind turbine blade correspond to mutual position where rotor blades are experiencing very high relative angles of attack, even beyond the stall limit.\[14\]

Karunakaran C.S et al. (2013): Authors has made an attempt to investigate and compare the flow over a typical scaled down models of NACA 23015 airfoil and Kline-Fogleman (KFm2) airfoils at different angles of attack in subsonic wind tunnel. Both were tested in wind tunnel for pressure tapping and the lift and drag forces were calculated. The analysis were done at a free stream velocity of about 25m/s in subsonic wind tunnel. Magnitudes of static pressure admitted the quality of flow field experienced. It was then found out through comparison that the Kline-Fogleman variant with a step at 50% chord length acquired better lift characteristics. The KFm2 did not stall till angles of α=45° after that it leveled off with a good L/D ratio. This can be of very useful as leveling off prohibits the risk of accidents happened by free fall at critical angles.\[18\]

P. Ghosh et al. (2014): Authors has been studied flow characteristics over a symmetrical airfoil experimentally in a low speed wind tunnel. The pressure distribution on the airfoil surface was obtained, lift and drag forces were measured and mean velocity profiles were obtained over the surface. They were carried out Experiments by varying the angle of attack, from 0° to 120° and ground clearance of the trailing edge from the minimum possible value to free stream velocity region. This region of high pressure extended almost over the entire lower surface for higher angles of attack. Hence, higher values of lift coefficient are obtained when the airfoil is close to the ground.\[16\]

### III. Wind Turbine Blade

Two major configurations of wind turbines exist based on their blade constuction and Operation. The first type is the horizontal axis wind turbine (HAWT). The second major type of wind turbine is the vertical axis wind turbine (VAWT). All the wind turbine types mentioned can be seen in Fig. 2

3.2 Vertical Axis Wind Turbines

Recently, VAWTs have been gaining popularity due to interest in personal green energy solutions. Small companies all over the world have been marketing the new machines e.g. Helix Wind, Urban Green Energy, and Wind spire etc. VAWTs target individual homes, farms, or small urban areas as a solution of providing distributed energy sources. This widens the gates of new era of energy resources available to individuals and opens up a whole new market in alternative energy technology. Because VAWTs are small, quiet, easy to build in, can operate without yawing or can take wind from any direction, with operating efficiently in turbulent wind conditions. A new area in wind turbine research has opened up to satisfy the demands of personals willing to take control and spend on small wind energy technology. The VAWT rotor, comprised of a number of constant cross-section blades, is designed to achieve good aerodynamic qualities at different angles of attack. Dissimilar to the HAWT where the blades apply a constant torque about the shaft as they rotate, a VAWT rotates perpendicular to the flow, causing the blades to produce an variation in the torque about the axis of rotation.
This is due to the fact that the regional angle of attack for each blade is a function of its mutual location. Because each blade has a different angle of attack at any instant, the average torque is typically referred as the objective function. Even though the HAWT blades must be constructed with varying cross-sections and twist, they only have to survive at a single angle of attack allover an complete rotation. However, VAWT blades are designed such that they exhibit good aerodynamic performance throughout an complete rotation at the different angles of attack they experience leading to high time averaged torque.

3.3 Modern VAWT Types

There have been multifold designs of vertical axis wind machines over the centuries and currently the vertical axis wind turbines or water can be broadly divided into three basic types, namely (1) Savonius type (2) Darrieus type, and (3) H-Rotor type.

3.3.1 Savonius Turbine

The Savonius -type VAWT, was invented by a Finnish engineer S.J. Savonius in 1929. It is basically a drag force driven wind turbine with two cups or half drums fixed to a cardinal shaft in opposing directions. Each cup/drum captures the wind and so turns the shaft, bringing the opposing cup/drum into the flow of the wind. This cup/drum then reruns the process, causing the shaft to turn further, thus completing a full rotation.\[12\]

3.3.2 Darrieus Turbines

The modern Darrieus VAWT was invented by a French engineer George Jeans Mary Darrieus. He submitted his patent in 1931 in the USA which included both the “Eggbeater (or Curved Bladed)” and “Straight-bladed” VAWTs. Darrieus concept is shown in Fig. 4.

The Darrieus-type VAWTs are basically lift force driven wind turbines.\[12\]

Fig. 3 Savonius Turbine\[6\]

Fig. 4 Types of Wind Turbine\[3\]

Figure 3.3: Darrieus Turbine\[6\]
3.4 Darrieus Turbine Advantages
1. Simple in design and easy to manufacture. Also, it is very easy to install in roof of home. Due to which it is best suited for developing countries like India.
2. High co-efficient of performance. Owing to this property, it is best suited for power generation application in remote areas.
3. Eliminates use of yaw control and reduces complexity. This improves reliability
4. Ideal for use in small scale applications like charge the battery and small bulb.

3.5 Darrieus Turbine Disadvantages
1. Low power output.
2. Poor mechanical efficiency compared to HAWT
3. Low power to unit weight ratio

3.6 Darrieus Turbine Applications
1. Small scale standalone Wind turbine that can be used to generate electrical power for household applications.
2. To charge batteries, powering telecommunications and several other low power applications.

3.7 Basic Aerodynamics

As the VAWT have a rotational axis at right angle to the onrushing airflow, the aerodynamics involved are more complicated than of the more conventional HAWT. The main part of turbine is blade which is airfoil shape, so we will define terms regarding that airfoil.

The NACA airfoils are airfoil shapes for wind turbine which are created by the National Advisory Committee for Aeronautics (NACA). The form of the NACA aerofoils is illustrated regarding arrangement of digits taking after "NACA". The numerical cryptograph can be depicted into mathematical statements of airfoil to produce the cross-area of the airfoil and compute its properties. The NACA airfoil provision provides the 4-digit, 5-digit, and adjusted 4/-5-digit configuration. They were constructed utilizing scientific comparisons that portray the camber of the mean-line (geometric centerline) of the airfoil area and also the segment's thickness transfer along the length. Subsequently, including the 6-Series, confused shapes were contained using hypothetical techniques. Prior to the National Advisory Committee for Aeronautics (NACA) added to these arrangements, airfoil configuration was somewhat discretionary outlines aside from past involvement with known shapes and experimentation with adjustments to those shapes.

The NACA four-digit blade sections define the profile by
1. First digit provides maximum camber which is in percentage of the total chord length.
2. Second number gives the distance of maximum camber from leading edge in tens of percentage of the chord.
3. Last two digits describe maximum thickness of the airfoil as percentage of the chord.

3.7.1 Airfoil and Its Working

Airfoil is a streamline body, or a lifting surface, of simple shape that provides sufficient lift and considerably less drag at small angles of attack. An Airfoil is considered to be a two dimensional body because its geometric sections normal to span do not change. As the air flows over the airfoil, the velocity on the upper surface is more than the free stream velocity and the velocity on the lower surface is less than the free stream velocity. Hence by Bernoulli’s theorem Pressure on the lower surface is more than the upper surface and a perpendicular force is created in upward direction which is known as Lift. Modern airfoils have evolved after years of theoretical and experimental research. The design philosophy of an airfoil is useful in many other disciplines that use Newtonian fluids.

3.7.2 Geometry of an Airfoil

1. Lift Coefficient ($C_L$)

Is a dimensionless coefficient that relates the lift generated by airfoil, the dynamic pressure of the fluid flow around airfoil, and a reference area associated with the body This is given as follows
$C_L = \frac{L}{\frac{1}{2} \rho v^2 A}$, \hspace{1cm} (3.1)

Where $A$ is area of airfoil, which is given by product of chord length to width,

$A = C \times b$ \hspace{1cm} (3.2)

2. **Drag Coefficient ($C_D$)**

Is a dimensionless coefficient that is used to signify the drag or resistance of an object in a fluid condition such as air for aerofoil. This is given as follows

$C_D = \frac{D}{\frac{1}{2} \rho v^2 A}$ \hspace{1cm} (3.3)

3. **Angle of Attack ($\alpha$)**

The angle of attack is the angle between an airfoil and the forthcoming air. A symmetrical airfoil will create zero lift at zero angle of attack. But as the angle of attack increases, the air is deflected through a larger angle and the vertical component of the airstream velocity increases, developing more lift. For narrow angles a symmetrical airfoil will cause a lift force roughly proportional to the angle of attack.

If the turbine is represented in a two dimensional ways following two characteristics are more obvious.

1. The independence of wind direction.
2. The main disadvantages are the high local angles of attack involved and the wake coming from the blades in the upwind part and from the axis. The rotational speed can be differed by the turbines controller for a certain wind speed. The rotational speed $\omega$ is therefore represented by the tip speed ratio $\lambda$.

$\lambda = \frac{Re \omega}{V_{\infty}}$ \hspace{1cm} (3.4)

The Reynolds number is a measure of the viscous behavior of air

$Re = \frac{\rho V_c}{v}$ \hspace{1cm} (3.5)

5. **Solidity ($\sigma$)**

Is the ratio of product of number of blades (N) and (C) chord length of aero foil of each blade divided by twice the product of radius of turbine $R$ and it is given by

$\sigma = \frac{NC}{2R}$ \hspace{1cm} (3.6)

6. **Power Coefficient ($C_P$)**

The performance of the turbine is given by the power coefficient $C_P$. This coefficient represents the produced energy of the turbine as part of the total wind energy captured by the swept area of the turbine. This area gives the frontal area of the turbine given by the height times the diameter.

7. **Deep Stall**

If the angle of attack over a wing is increased, at some moment the airflow will separate. The separation starts at the trailing edge of the airfoil and shifts forward with raising angle. If the angle is gone further the separation moves forward to the leading edge. This phenomenon is called deep stall.

8. **Dynamic Stall**

Dynamic stall is a phenomenon that results at airfoils with fast changes in angle of incidence. The conclusive effect of this changing angle is a difference in the lift, drag and moment characteristics between increasing and decreasing angle of incidence.

9. **Closure**

Consistent Wind flow is observed in even village and city and most of the parts of India almost throughout the year. So Darrieus turbine is very much useful in remote villages for production of cheap electricity where still electricity is not still reached. Darrieus turbine is operated on a lift generated by the aero foil so efficiency of the Darrieus turbine is more compare to the drag driven turbine.
They have some advantages over axial flow turbines: they are having High co-efficient of performance, they can easily drive a generator above install it, they do not need to yaw and blades are untwisted and of uniform cross section, so they can be extruded at low cost. So, it’s a best way to generate power by Darrieus turbine from low wind flow. Darrieus turbine can also be used to generate electrical power for household applications. To operate water pumps, charging batteries, powering telecommunications and several other power applications.

IV. NEED FOR ANALYSIS

1. The main aim of literature serve is to study the design process of various aero foils (Symmetrical And Camber profile) NACA 4 Series, NACA 5 Series, NACA 6 Series and their flow simulation to understand how they work. Due to time limitation, I studied only NACA 4 Series three Symmetrical blade profile and one camber profile.

2. As airfoil is important part of the wind turbine all lift and drag value are depend upon airfoil so after literature review it has been found that very few work is done on NACA 0021, NACA0015, NACA0009, NACA4421.

3. So it is decided to study the effect of all four NACA blade profile with different angle of attack in 2 D CFD analysis and different chord length all four blade profile for different higher Reynolds number

4. Future scope of employing the inverse method to get the desired air foil shape according to given parameters.

V. CONCLUSION

The coefficient of Lift and drag is calculated for wind turbine blade for the different angle of attack 0° to 6°. The coefficient of Lift increases with increase in Angle of attack up to 14°.

The aerofoil blade has an aerodynamic profile in cross section to create lift and rotate the turbine. The results demonstrate the pressure distribution over the airfoil. It could be observed that the upper surface on the aerofoil experiences a higher velocity compared to the lower surface.

By increasing the velocity at higher Mach numbers there would be a shock wave on the upper surface that could cause discontinuity. The pressure on the lower surface of the airfoil is greater than that of the incoming flow stream and as a result of that it effectively pushes the airfoil upward, normal to the incoming flow stream.

The drag force begin of dominate beyond this angle of attack. The rate of increase in lift is more for angle of attack from 0° to 6° and between 0° to 6° the rise in lift force is less.

The maximum L/D ratio is achieved at 5° of angle of attack, for the average velocity. It is found that blade with 5° angle of attack has the maximum L/D ratio.

REFERENCES


