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Numerical Simulation of Horizontal Axis wind Turbine with Different Airfoils and Their Performance Comparison

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Abstract

In this study, we choose 5 horizontal-axis wind turbine (HAWT) blade output has been designed by the blade, and the blade aerodynamics are also simulated to

investigate flow structures and aerodynamic characteristics. The design conditions of the turbine blade in order to display the rated wind speed, design tip speed ratio and design angle of attack that have been set to 10-30 m/s, 0,5 and 10°, respectively turbine blade. The last selection is NACA 4412 that has the best performance between 5 selected airfoil. The simulation results are compared with the improved BEM theory at rated wind speed of 10-30 m/s and show that the CFDis a good method on aerodynamic investigation of a HAWT blade.in this study we use two soft wares(fluent &Q-Blade) for our computations.

***Keywords**: airfoil, power, lift & drag coefficient, hawt*

Introduction

The increase in oil prices in the 1970s caused the use of renewable energies such aswind energy to be highly considered. The ever-increasing growth of energy demand, increase in living standards, global warming and finally environmental problems are the reasons for investing in this way. Considering the many environmental and human talents, our country should not lag behind in this field. Wind energy is a good motive force if the energy source is available in a movingair mass.

In the past, simple wind machines were used to grind seeds, and today wind is usedto generate electricity. Wind is an energy source whose power increases as the wind speed increases. This means that high wind speed is very important for us. Now, in order to be able to have the wind at a high speed, we must use tall towers, and the most reliable way to increase the efficiency of a wind generator is to raise the height of the tower. The geographic area of a wind turbine is the most important factor (after wind sources) that determines energy production. Albert Betz, a German physicist, states that only 60% of the wind's energy can be extracted before it slows down. In fact, their performance will decrease. In the real world, well-designed devices can achieve about half of this. Turbines can be divided into two categories according to orientation, direction, production mode and other characteristics: 1- Horizontal axis wind turbines 2-

Vertical axis wind turbines, horizontal axis turbines are the most common and effective type of orientation. The characteristics of horizontal axis turbine rotors are very similar to airplane propellers. The airflow moves on the aerodynamic cross-section of the blades and creates the lift force that causes the rotor to rotate. Vertical axis turbinescan be divided into two types, Savnoius and Darrieus. The Savnoius turbine works like a drag water mill while the Darrieus uses blades similar to horizontal axis turbines. Vertical axis turbines are placed very close to the ground, which has the advantage of placing its heavy equipment such as the gearbox and generator close to the ground, although the wind intensity is lower on the ground and as a result, less electricity will be produced. Did the rotors of the new horizontal axis turbines are very similar to airplane propellers. The airflow moves on the aerodynamic section of the blades and creates the lift force that causes the rotor to rotate. The nacelle of the horizontal axis turbines is the place for the gearbox and generator. The area swept by the blades should be directly facing the wind to have the maximum electricity production. Therefore, horizontal axis turbines must have a system to adjust against the wind, which is called a yaw mechanism. So that whole nacelle can turn towards the wind.

Horizontal axis wind turbines

These types of turbines are the most common wind turbines that are used. All its components (blades, shaft, and generator) are placed on top of a tall tower and the blades are designed to face the wind. The axis of the shaft is horizontal to the ground, the wind causes them to rotate while hitting the blades, at the end of the axis, there is a gear that is connected to the generator and delivers the generated electricity to the power grid.

Figure 1-1 View of horizontal axis turbines

Advantages of horizontal axis wind turbine

1- The blades are towards the center of gravity of the turbine, which helps its stability.

2- The blades can be twisted to be placed at the best angle

3- By screwing the blades to the rotor, damages in the storm are minimized.

4- The height of the tower makes it possible to increase access to strong winds.5- Can be used in rough terrain and far from the coast
6- Most of them have automatic start.

Disadvantages of horizontal axis wind turbine1-
Hard work near the surface of the earth
2-Difficulty in transportation
3- Hardnace in installation
4- It is affected in the vicinity of the radar5-
It is difficult to maintain
Types of horizontal axis wind turbines can be seen in Figure 2-1. Each of these turbines is designed for a specific function and location to have the highest efficiency.

Components of a Horizontal Axis Wind Turbine

The primary components of a horizontal axis wind turbine include the rotor, blades, tower, nacelle, power transmission system, generator, gearbox, brake, control system, and hydraulic system. The components of a horizontal axis wind turbine are illustrated in Figure 1-3

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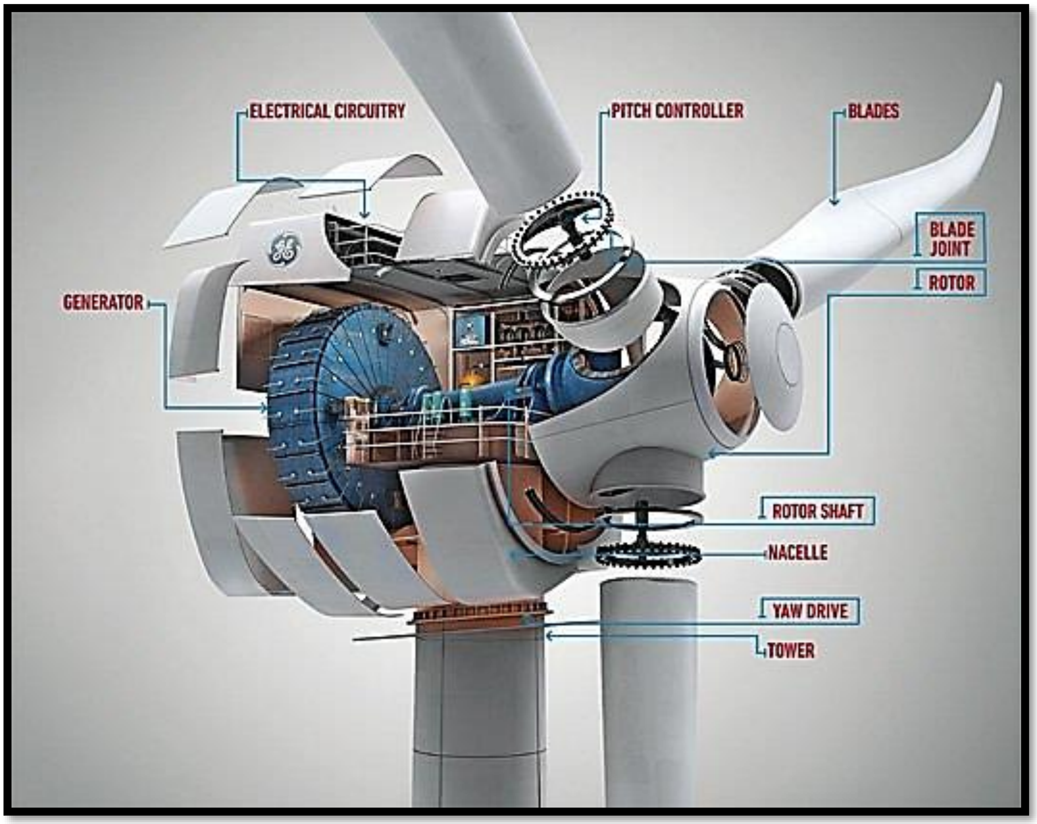


Figure 1-3 Components of a Horizontal Axis Wind Turbine

- **Review of airfoils**

  Aerodynamic force is generated by a specific shape known as an airfoil, which, as air flows around it, creates a pressure difference between its upper and lower surfaces. The airfoil has a thin, elongated shape, similar to that of a fish or spindle. The front is rounded, while the rear tapers to a point. Essentially, a cross-section of a wing produces an airfoil shape. Tail surfaces and propellers also closely resemble airfoils.

  an airfoil is characterized by a leading edge and a trailing edge. Additionally, an airfoil has a chord and curvature. The chord is an imaginary straight line connecting the leading edge to the trailing edge and helps define the wing's area. It also provides a reference for measuring the geometric angle of attack. Figure 1-5 & 1-6.

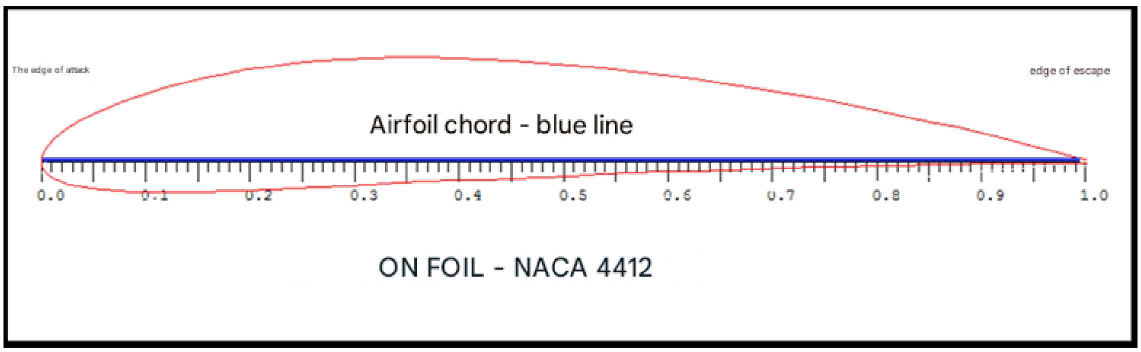


Figure 1-5 View of a Standard Airfoil

Figure 1-6 Different Parts of an Airfoil

Types of airfoils used in horizontal axis wind turbines

Airfoils used in horizontal axis wind turbines include:
General aviation airfoils:
NACA 63-4XX
NACA 63-6XX
NACA 64-4XX
NACA 44XX
Dedicated airfoils:
S8XX series (NREL, USA)
FFA W-XXX (FOI- Sweden)
Risφ-A1-XXX (also B, P-series, Risφ, Denmark)
DUXX-W-XXX (Delft, Netherlands)
DU and Series airfoils used in horizontal axis turbines.

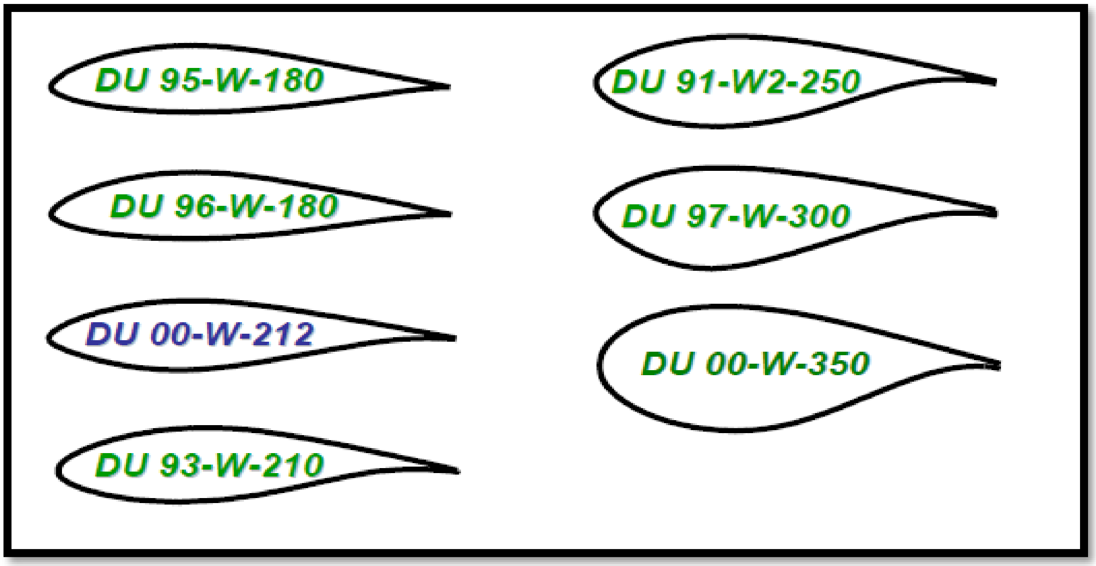


Figure 1-7 Airfoils used in horizontal axis turbines of the DU family

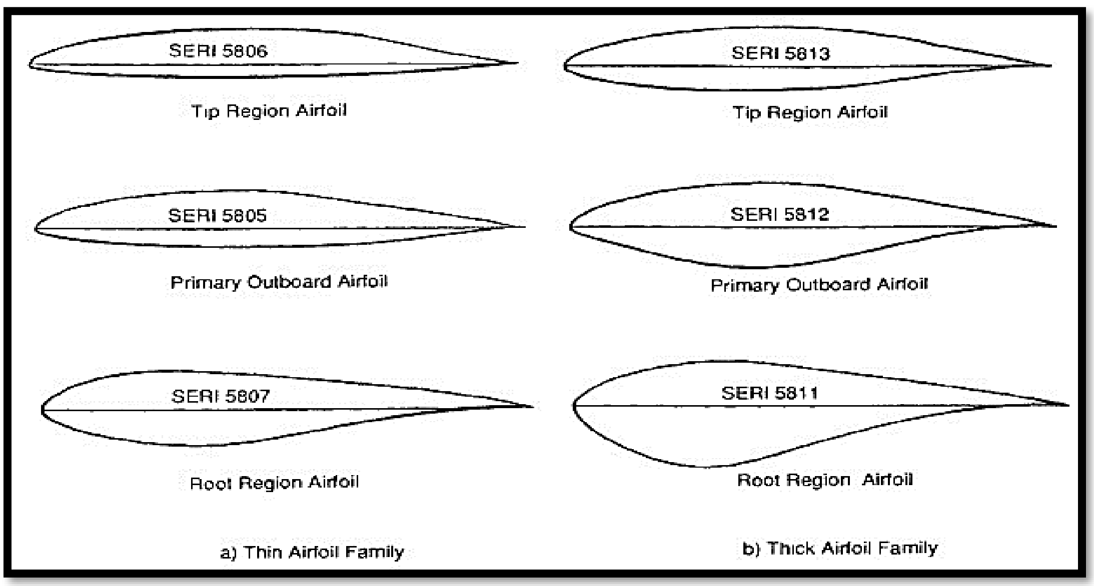


Figure 1-9 Airfoils used in horizontal axis turbines of the Series family

Lift-to-Drag Ratio Curve (L/D vs. Angle of Attack or L/D-Alpha)

The lift-to-drag ratio (L/D) is one of the most critical characteristics of an airfoil and aircraft. Known as the aerodynamic efficiency ratio, this parameter signifies the effectiveness of the airfoil in producing lift relative to the drag it incurs.

A higher L/D ratio indicates a more aerodynamically efficient airfoil, meaning it can generate more lift with less drag. This efficiency is crucial for achieving optimal performance in both aviation and wind energy applications, as it affects fuel consumption, endurance, and the overall effectiveness of the airfoil.

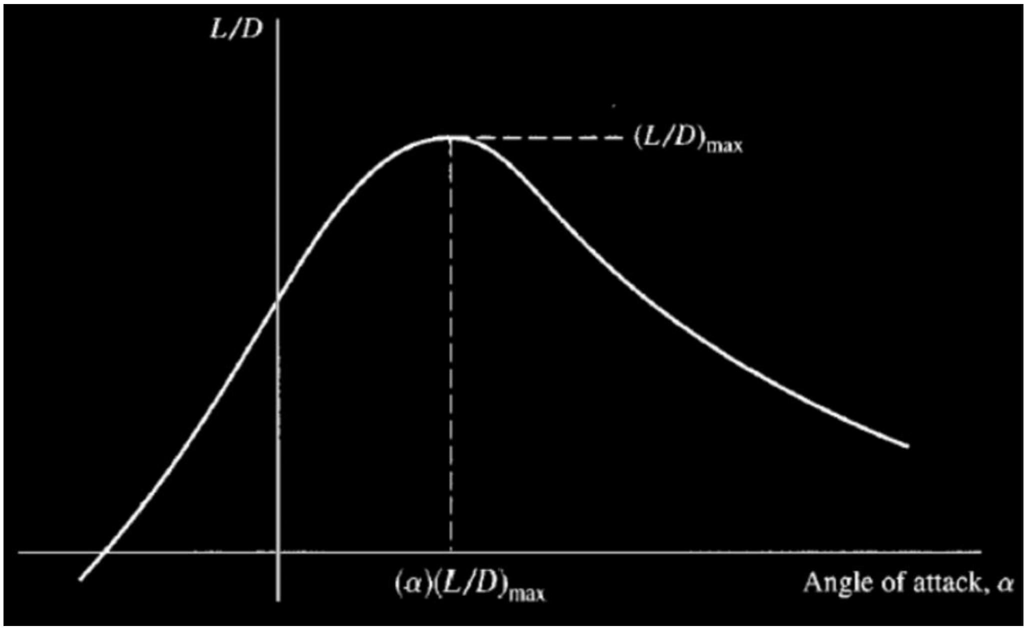


Figure 1-9 L/D Ratio vs. Angle of Attack Curve

- **Equations governing airfoils**

Unlike "vertical axis" turbines, the main factor in creating the necessary torque for the rotation of the blade in horizontal axis turbines is the lift force. To better understand the reason for the rotation of the turbine blade, consider the wing of an airplane as an example. Wind with a relative speed of 7 and an angle A 5-degree attack hits the plane's wing. The aerodynamic section of the wing causes the wind to pass faster in its upper part than in its lower part. According to Bernoulli's law, this phenomenon causes the lift force and as a result, the plane takes off. ".

The air currents will meet at the same time because the distance that the air travels in the upper part of the wing is greater, so the speed of the air flow should behigher so that the upper and lower currents of the wing meet at the same time. According to Bernoulli's law, when As V1 increases, P1 must decrease so that the solution to Bernoulli's equation is correct. As a result, the air pressure in the upper part of the wing decreases and the plane climbs up.

Due to the rotation of the blade, the direction of the relative wind that hits the turbine is similar to that of an airplane wing.

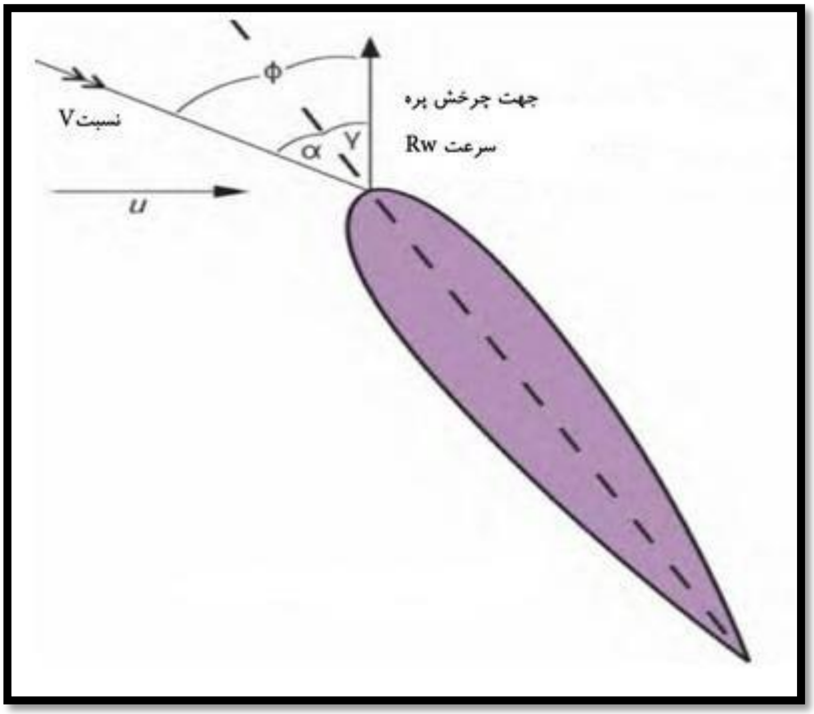


Figure 2-3 Wind effect on wind turbine blade

The position of the vane (angle ϒ) is such that the lift force "causes the movement of the vane in the circular path and the power is transferred from the vane to the turbine shaft. It should be noted that the relative wind path is different from the direct wind path due to the movement of the vane. be". In figure 3-4, this path is shown with an angle φ. which is equal to the sum of the angles of attack. Due to the increase in the relative wind speed from the root to the tip of the blade, the design of the blade section has been upgraded from standard airplane shapes to special wind turbine designs.

In this study, five standard airfoils have been selected for analysis, as shown in Figures 3-3 and 3-4.

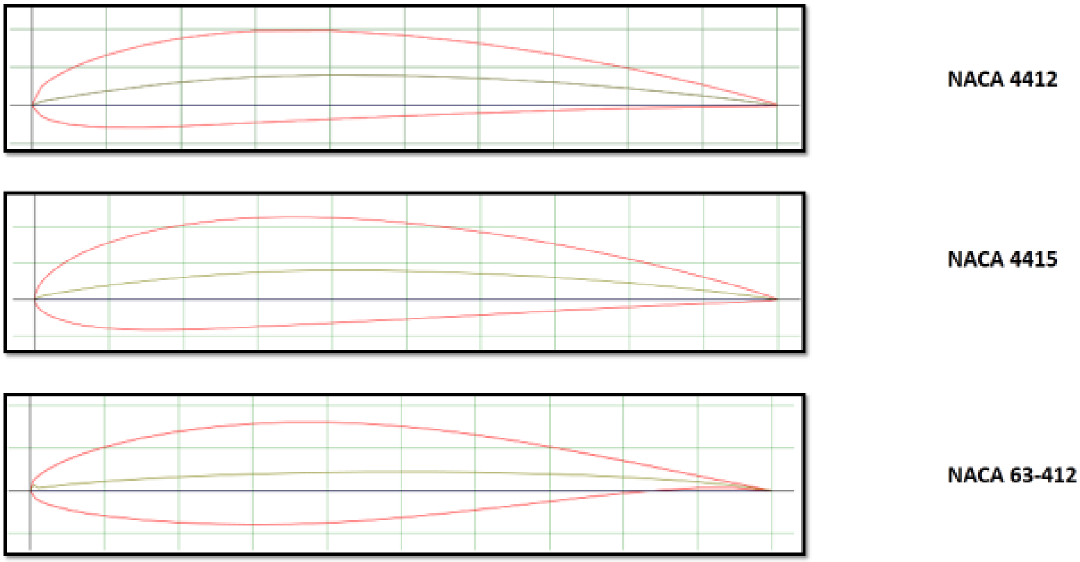


Figure 3-3 Standard Airfoils with Geometry and Identification Codes

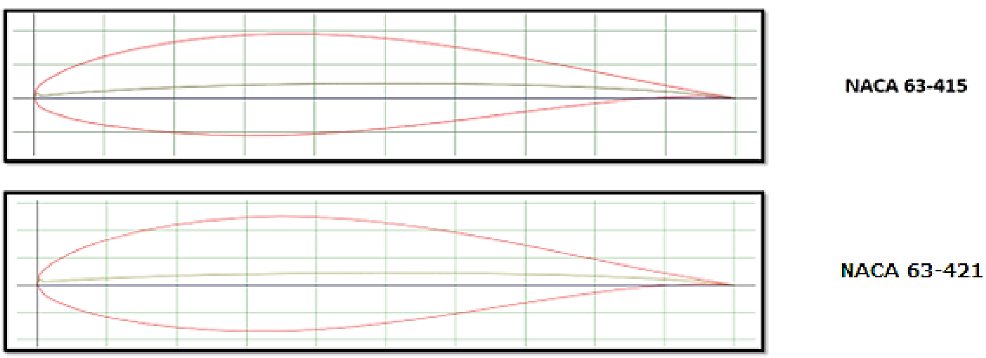
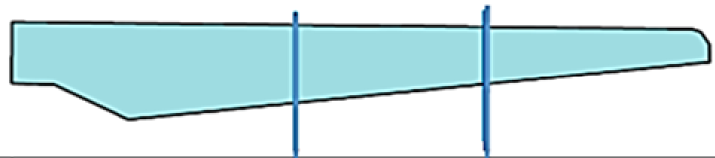


Figure 3-4 Standard Airfoils with Geometry and Identification Codes

Overall Blade Design Goals

The design objectives for turbine blades can be summarized as follows:



Thickness to chord ratio	>0.28	0.28-0.21	0.21>
Maximum lift force ratio to drag force	●	● ●	● ● ●
The beginning of the phenomenon and the delay			● ●
low voice		●	● ● ●
Geometric compatibility	● ●	● ●	● ●
User needs	● ● ●	● ●	●

Figure 3-5 Design Goals for Horizontal Axis Wind Turbine Blades

In designing horizontal axis wind turbine blades, various parameters are considered to achieve an optimal product. The red circles indicate the importance level of each parameter in specific sections of the blade.

Modelling parameters

- **Physical conditions governing the problem**

In order to choose the physical conditions governing the problem, some things should be considered

In horizontal axis turbines, due to the increase in wind speed, its power also increases, this power has an upward trend up to a certain speed, and after that the power is fixed and the amount of power does not change with the increase in wind speed.

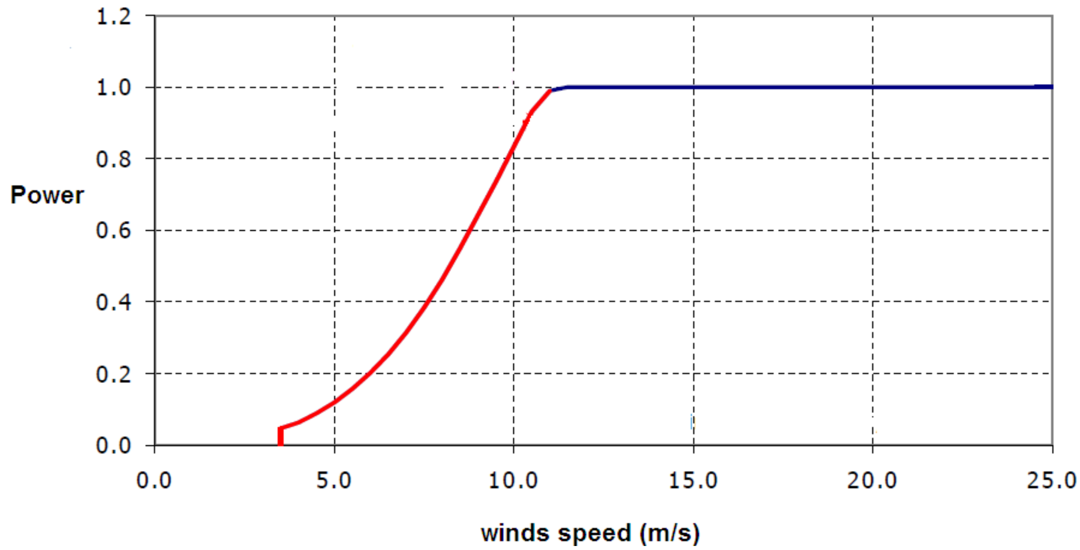


Figure 4-1 standard curve of horizontal axis turbine power to wind speed

As you can see in the figure above, the target turbine starts to increase its power when the wind speed is about 4 m/s, and it goes up to a speed of about 11 m/s, afterwhich its power is fixed.

Therefore, choosing a speed of 30 m/s for wind blowing can be reasonable for modeling, because at this speed, the turbine has a constant power. And the simulation results are closer to reality.

The physical conditions of the flow are chosen as follows:

Target fluid: air
Wind speed: 30 m/s
Pressure: one atmosphere
Density: 1.2250 kg/m3
Temperature: 288.16 K

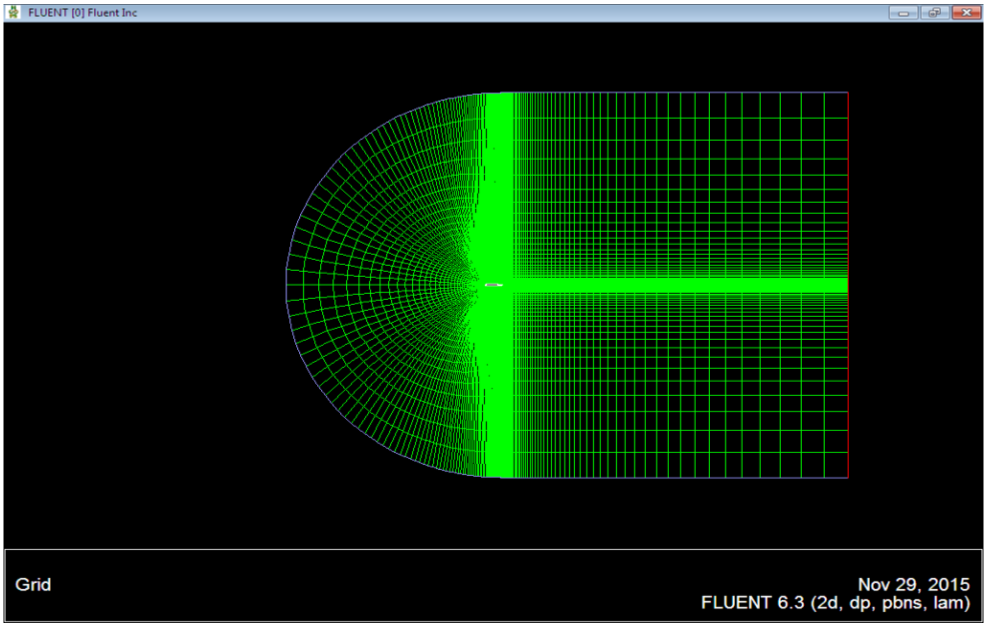
Kinematic viscosity: 1.4607e-5 m2/s

The above conditions are chosen according to standard sea level conditions. Also, the two-dimensional flow, stable, incompressible (due to the low flow speed), and the equations obtained by the finite volume method have been discretized. And for the discretization of the momentum and energy equations, the quadratic upper handscheme has been used.

- **Design and analysis of airfoils**

After choosing the airfoils, we design them in Gambit software and then analyze them in Fluent software to get the important characteristics of each airfoil. It should be noted that for the design of the solution space around the airfoil, organized networks have been used for a more detailed analysis of the flow around the airfoil. Organizational networks are networks that have two characteristics; 1- They should have four sides. 2- The number of meshes on opposite sides should beequal.

In the figure below, you can see the geometry designed by Gambit.



✓ **Result:**

- **Analysis of Lift Coefficient in Airfoils**
  As observed in the above curves, the highest lift coefficient at a zero-degree angle of attack corresponds to the NACA 4412 airfoil.

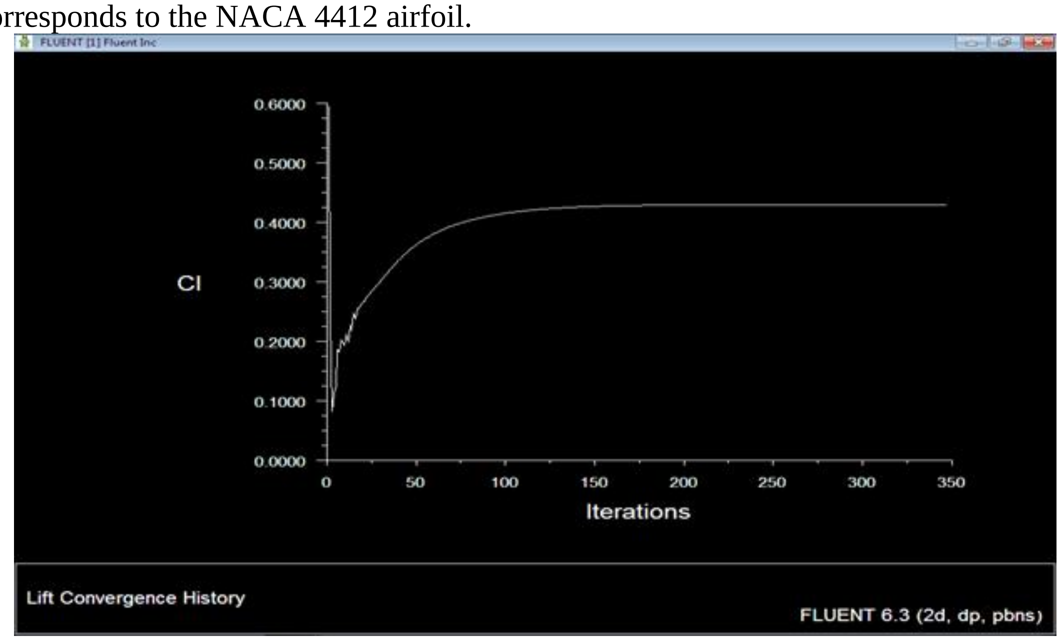


Figure 4-7 Lift Coefficient Variation Curve During Solution for NACA 4415 at Zero Angle of Attack

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Based on the curves 4-8 to 4-16, it can be concluded that at a 5 and 15 degree angle of attack, the highest lift coefficient is also associated with the NACA 4412 airfoil.

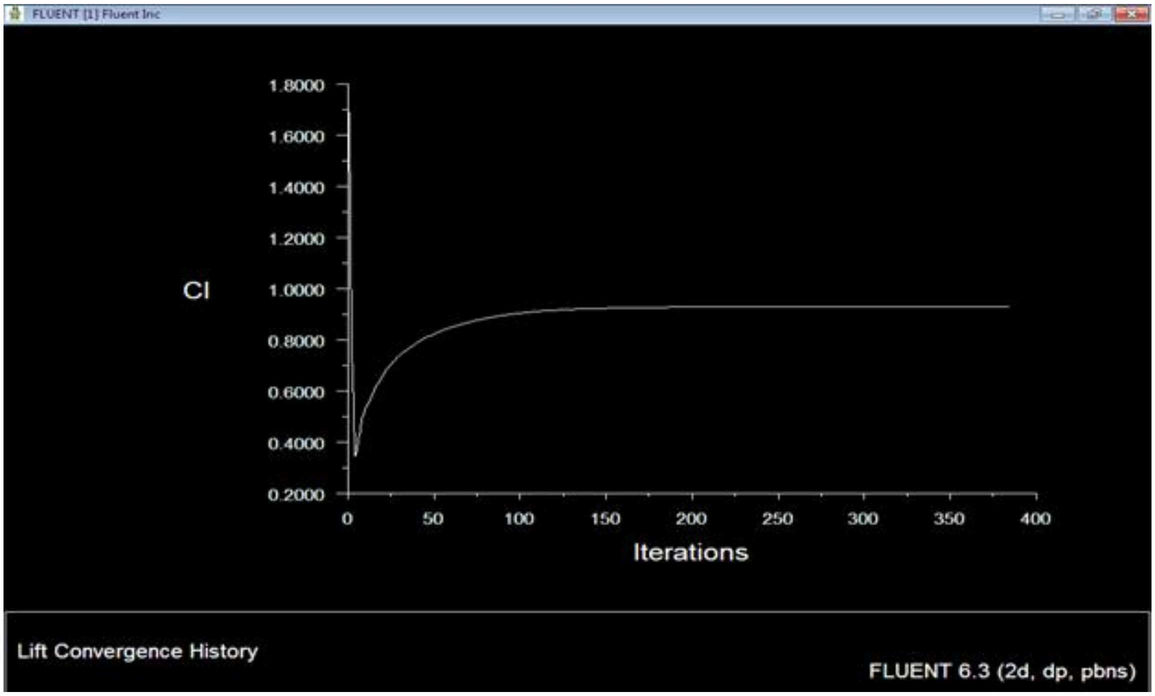

Figure 4-10 Lift Coefficient Variation Curve During Solution for NACA 4412 at 5-Degree Angle of Attack

Analysis of Drag Coefficient for NACA 4412 and NACA 63-415 Airfoils

After examining the lift coefficients, we identified that the NACA 4412 and NACA 63-415 airfoils possess the highest lift coefficients. Therefore, we will now study the drag coefficients for these two airfoils to determine the most suitable airfoil at the optimal angle of attack.

The drag coefficient for both airfoils is at its lowest at a zero-degree angle of attack(as shown in fig 4-17 to 4-22.

From the lift and drag coefficient curves, we can conclude that the NACA 4412 airfoil demonstrates the best performance in smooth flow and under the specified conditions. Therefore, we proceed with a more detailed analysis of the NACA 4412 airfoil's characteristics.

Analysis of NACA 4412 Airfoil Characteristics

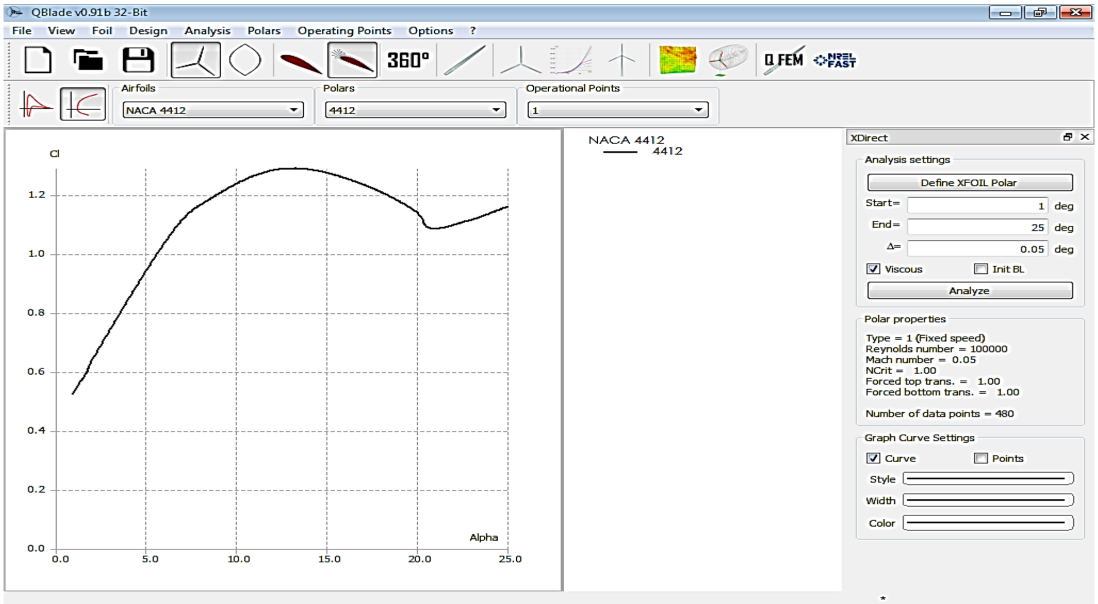

Figure 4-30 Lift Coefficient vs. Angle of Attack Curve for NACA 4412 Airfoil

In the above curve, a higher stall coefficient indicates that airflow separates from the airfoil surface later, delaying the stall phenomenon. In this curve, stall occurs at an angle of attack of approximately 13 degrees.

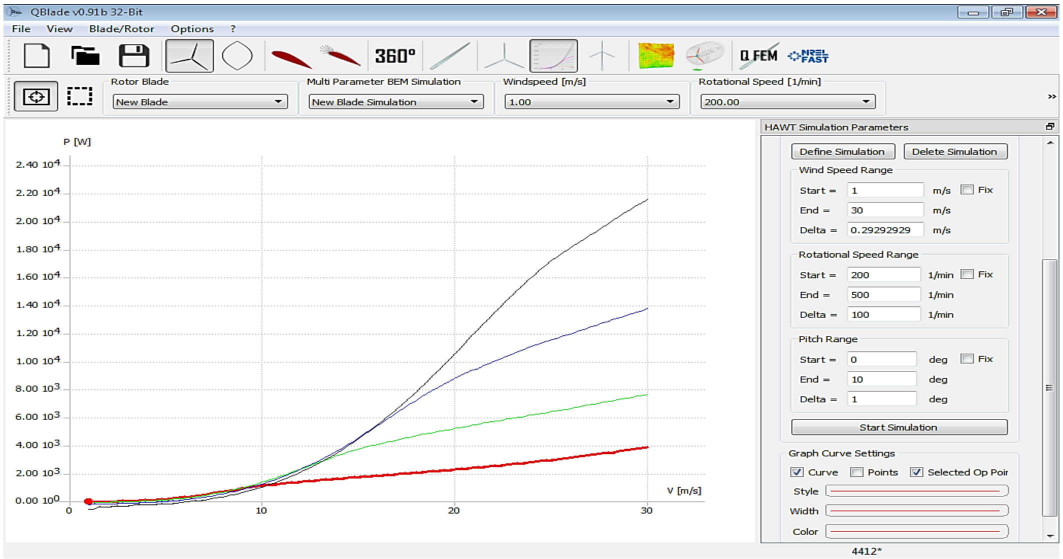

Figure 4-35 Rotor Power Curve vs. Wind Speed up to 30 m/s

In the curve above, the gray line represents the power at the blade tip, the blue line represents the power at the mid-blade section, and the green line corresponds to the power at the blade root. The red line indicates the total rotor power, which is the key metric. As observed, beyond a wind speed of 10 m/s, the turbine reaches a stable power output, which then continues to increase.

Validation of present work

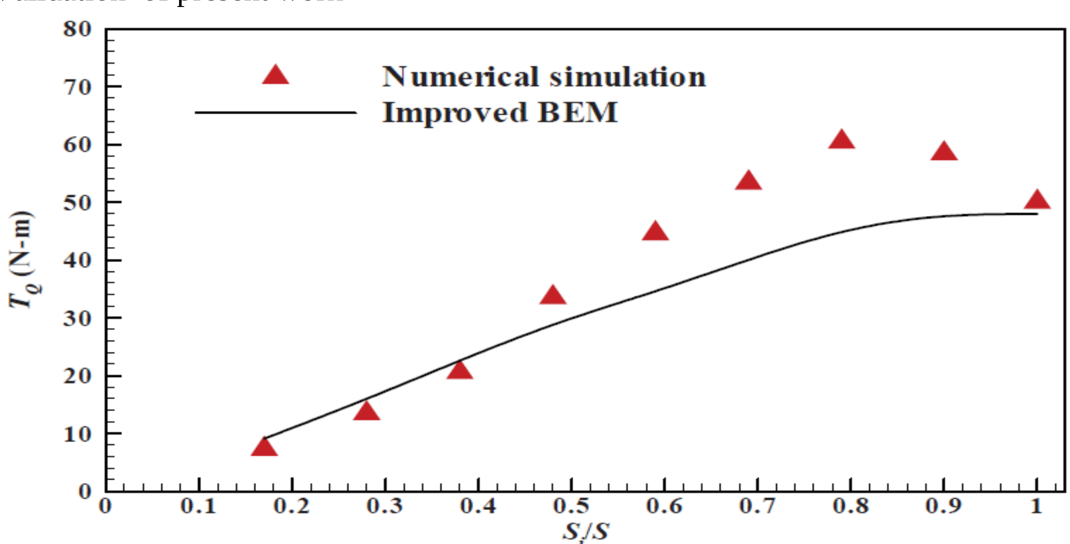

Figure 4-37 Torque Curve of a 10 kW Turbine Blade by C. G. Bai and Colleagues [27]

Conclusion:

It can be concluded from the present research that the type of airfoil used in horizontal axis wind turbines has a great impact on the output power and efficiencyof the turbine. Also, the wind speed that hits the turbine can have a significant impact on the efficiency of the turbine. Therefore, in order to design a wind turbine, the wind speed of the desired area should be calculated and according to it,the airfoil that has the highest lift coefficient at that speed should be selected or designed.

In order to design and predict the performance of horizontal axis wind turbines, theories have been presented, which are of great importance among blade element theory, momentum theory and blade momentum element theory. In this project, theblade momentum element theory has been used to design the blade. In relation to the flow around the airfoil, it can be concluded that, due to the low speed of the air flow, the flow can be considered incompressible when solving. This in itself causes a better convergence of the simulation with the real model and as a result theanswers are close.

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