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Investigating the impacts of different pitch angles under varying wind speeds is done by performing Computational Fluid Dynamics (CFD) analysis on a horizontal-axis wind turbine

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ABSTRACT

The utilization of modeling software Fluent 2020R1 is implemented for the purpose of conducting computational fluid dynamic simulations. Through the utilization of this software, calculations are performed to determine the torque and power values at varying pitch angles and diverse wind speeds. In the case of horizontal axis wind turbines, a sequence of three distinct aerofoils is employed, commencing with a cylindrical configuration at the base and subsequently transitioning to the aerofoils S818, S825, and S826 for the root, body, and tip sections respectively. The outcomes generated by the software are corroborated by comparing them to both experimental data and analytical findings accessible in existing literature.

Keyword: Horizontal axis wind turbine Blade, angle of pitch, torque, power. computational Fluid Dynamic

1. Introduction

In recent years, Wind power is acknowledged as a sustainable and renewable energy source, displaying a significantly lower environmental impact in comparison to the combustion of fuels in use today. Wind power exhibits variability, necessitating energy storage or other dispatchable generation sources to ensure a dependable electricity supply. Wind energy competes successfully with traditional energy production at favorable, windy locations. Numerous countries possess substantial wind resources that remain untapped. In this work, a blade similar in size to a GE 1.5xle turbine was created in order to verify the results of computational fluid dynamics (CFD). This study's analytical computations and CFD analysis can be compared with the experimental data from the GE 1.5xle turbine.The round hub area of the blade characterizes its beginning section. This hub section seamlessly changes into the S818 airfoil, which is then followed by a change to the S825 airfoil, which changes into the S826 airfoil at the cutting edge. Every facet of the blade's

The WT_Perf analysis was used to determine the geometry, which included measurements for twist length, span, and chord [1-2]. We will graph and compare the tangential velocity at the blade tip to theoretical results. Assessing the effectiveness and potential for electricity generation of wind turbines is one of the study's other main goals [3]. Due to its high level of precision and adaptability, Computational Fluid Dynamics (CFD) garners significant attention from both researchers and design engineers. The multifaceted nature of CFD not only yields dependable results regarding aerodynamic coefficients but also provides intricate insights into flow behavior and wake evolution [4-7] Limited studies have explored the impact of aeroelasticity through the utilization of a nonlinear beam model [8].It is essential to take into account factors like pitch and twist angles while designing wind turbine blades. The crucial function that the pitch angle plays in influencing a wind turbine's operational efficiency is particularly significant [9–11]. The idea of tip plates has been used by certain researchers to optimise the pitch angle for optimal power output at particular wind speeds, improving the performance of wind turbine blades[12]. Furthermore, some researchers have concentrated on modifying the pitch of the blades and the speed of the rotor when there is strong wind. In the face of

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uncertainties present in the wind turbine model, they have presented a resilient sliding mode methodology in which the blade pitch acts as a control input to maintain the rotor speed at a predefined value [13]. A few strategies have been proposed to reduce wear on the wind turbine pitch drive, given the requirement for appropriate monitoring of the blade pitch system[14]. Furthermore, due to the nonlinear dynamics of wind turbines and the uncertainties that accompany them, scientists have developed a variety of pitch control frameworks that enable the simultaneous improvement of power regulation and load mitigation by manipulating the pitch of the blades [15–16]. Numerous techniques, such fuzzy logic and genetic algorithms, which are similar to multi-evaluated logic, have been utilised to control the pitch angle in order to accommodate non-linearities and improve wind turbine system stability by reducing the impacts of loading on the turbine blades [17–18].In comparison to the BEM model, the CFD model incurs greater computational costs, yet it possesses the capability to simulate intricate 3D flow fields accurately and depict realistic fluid dynamics more precisely [19-21].It is standard procedure to depict aerodynamic loads using several aerodynamic models with low order [22, 23]. However, using a higher-resolution approach is necessary to achieve improved accuracy when modelling complicated 3D flows.

The specifics of this analysis can be summed up as follows:
A number of studies have examined the influence of pitch angle on horizontal axis wind turbine output in the literature, either by employing poor fidelity modelling or by using few pitch angle values. This paper uses fluent software to determine aerodynamic load. This article measures aerodynamic load, which is dependent on different pitch angles and wind speeds. There is good agreement between the CFD results and the analytical and experimental results.

2. Analytical Model

The turbulent airflow moves in the direction of negative z at a speed of 12 m/s, a common wind speed for turbines of this magnitude. The motion of this entering airflow is considered to cause the blade to rotate at an angular velocity of -2.22 rad/s around the z-axis (resulting in a clockwise spin when viewed from the front, similar to many practical wind turbines). Consequently, the tip speed ratio (TSR), defined as the ratio between the velocity of the blade tip and the speed of the incoming airflow is 8, a logical value for a large-scale wind turbine. It is important to note that, in order to simulate the blade's connection to a hub, the blade's base is displaced 1 meter from the axis of rotation.

2.1 Theoretical calculation

According to the details of the GE 1.5 xle wind turbine specification sheet, a preliminary manual computation that can be conducted prior to commencing the simulation involves determining the theoretical wind speed at the blade tip. Subsequently, a comparison between these findings and the results obtained from the simulation can be executed to ensure their alignment. The velocity denoted by (v) at the blade is expected to adhere to the prescribed formula:

$$V = r \times \omega \qquad (1)$$

The resultant figure is 44.2 m when the angular velocity of 2.21 rad/s is inserted and the blade length of 43.2 metres is combined with an extra one metre to account for the root-to-hub distance.

$V = 2.21 \times 44.2$

$= 98.125$ m/s

2.2 Betz equation and criterion

In the context of a turbine, the Betz Equation relates to the wind velocity upstream, represented by V_0, and the wind speed downstream, represented by V_3. The value of the Betz limit suggests that a wind turbine may extract up to 59.3% of the energy from a stream of wind velocity that is not disturbed.

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Formally, this can be expressed as the Betz coefficient, represented by C_P, which is equal to 16/27 or 0.592593, or 59.3%.

2.3 Power coefficient

A wind stream in motion can be used to generate power, which is defined as the quotient of the power extracted by the wind turbine and the energy contained in the wind stream. This is illustrated in Fig 1. In terms of the induction factor (a), the power coefficient (C_p), which represents the extracted power in respect to the overall power, can be defined as follows:

$$C_p=4a(1-a)^2 \tag{2}$$

where the fractional drop in wind velocity between the free stream and (a) is the Induction factor.

The expression for the rotor plane can be represented as an axial induction factor, a:

$$a=v_0-v/v_0 \tag{3}$$

Where, V is the velocity at the disk and it is defined by:

$$V=½(v_0+v_3) \tag{4}$$

V_0 and V_3 are free stream and downstream velocities respectively. The amount of axial induction factor determines the amount of power extracted by turbine [3].

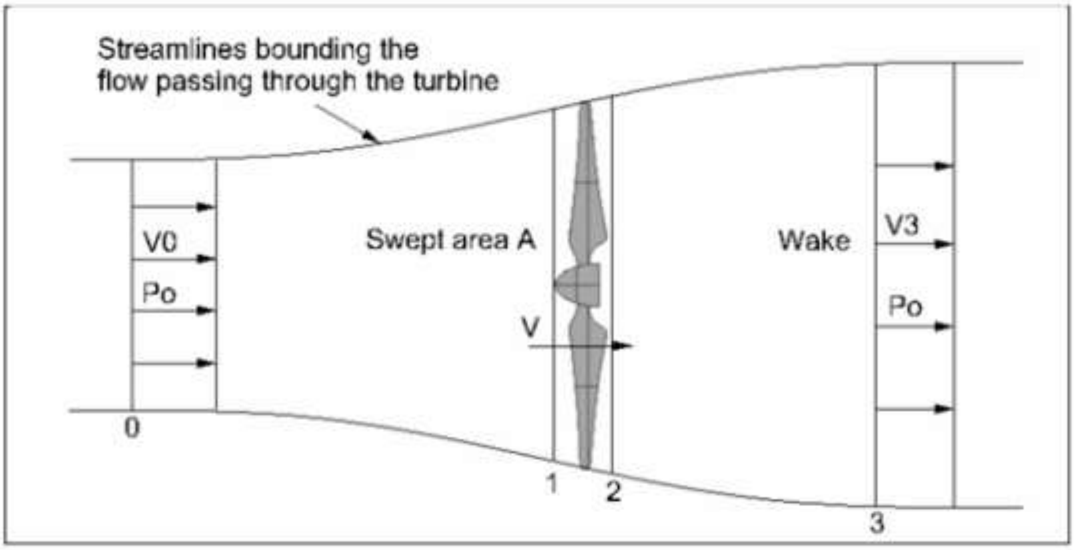

Figure 1 illustrates the control volume utilized in the theoretical actuator disk analysis

3. Methodology

3.1 CFD Modeling

Computational Fluid Dynamics simulation is conducted by employing the FLUENT software. This section is composed of four parts: First is the design of the wind turbine model, second is the computational domain and boundary condition, third is mesh generation, fourth Analysis set up

3.1.1 Design of Wind Turbine Model

Wind turbine blade design is accomplished through the consideration of geometric parameters and technical specifications outlined in references [1] and [2]. The wind turbine in question is a traditional upwind horizontal-axis system with three blades, utilizing control mechanisms that are variable in both speed and pitch angle. Detailed information regarding the WindPACT 1.5MW wind turbine can be located in reference [24], with a comprehensive summary of its primary parameters provided in

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Table 1. The blades consist of three distinct types of aerofoils - thicker airfoils S818 for the root section, medium thickness aerofoil S825 for the primary portion, and thin aerofoil S826 for the tip. The 3D geometry of the blade model is illustrated in Figure 2

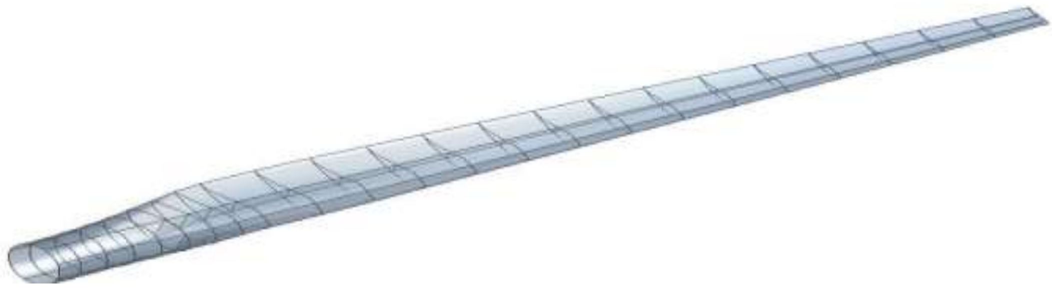

Figure 2 1.5 MW WindPACT wind turbine blade's 3D geometry model

Table 1

Key characteristics of the 1.5 MW Wind PACT wind turbine

Parameters	value	Unit
Rated power	1.5	MW
No. of blades	3	-
Rotar diameter	86.5	Meter
Rated wind speed	11.5	m/s
Rotational velocity	21.21	Rpm
Pitch angle	0,4,8,12,16	Degree
Velocities	8,10,12,16,20,24	m/sec

3.1.2 computational domain and boundary condition

Periodic boundary conditions are applied within the computational domain to minimize the computational time required for finding a solution. The domain exhibits a symmetrical design with respect to its center of rotation, enabling the representation of three blades by a single blade within a radial stream tube domain spanning 120 degrees. A depiction of the computational domain and the boundary conditions employed in the model can be observed in Figure 3.

The spatial distance between the inlet and outlet regions of the domain is 270 meters. In the domain design stage, the global reference point is located at the central position of the blade's root. Specifically, the distances from the blade to the velocity inlet and pressure outlet are 90 meters and 180 meters, respectively. Uniform inlet velocity is assigned to the upper region of the domain. Additionally, the arc angles at the velocity inlet and pressure outlet are set at 120 and 240 degrees. The conical shape of the domain facilitates the expansion of the wake behind the turbine blade.

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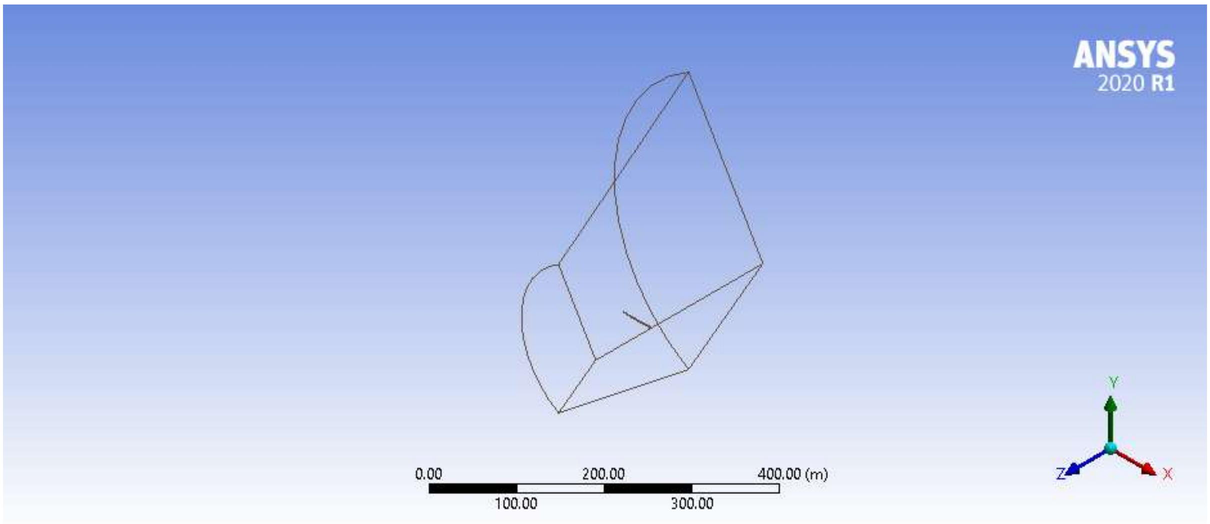

Fig 3. computational domain and boundary condition for CFD modelling

3.1.3 Meshing

In CFD simulation mesh generation is mostly time consuming part. Inside the mesh setting We naming various faces of our geometry shown in Figure 3

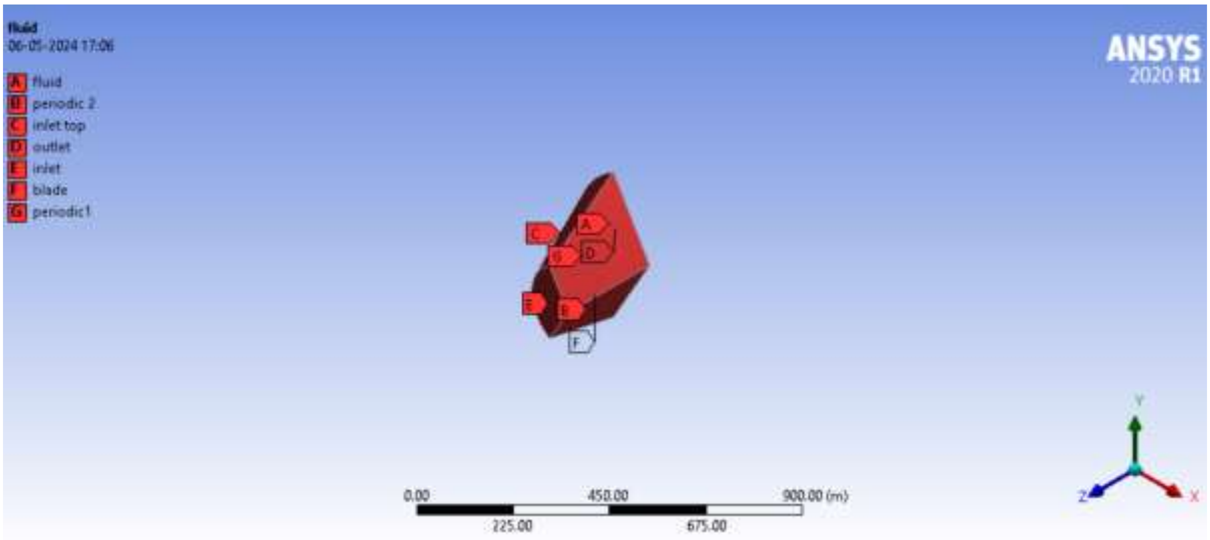

Fig 4 Final fluid domain with various faces of geometry

Fig 4 shows the mesh used in the CFD modeling. After So many attempts to create mesh geometry. generated mesh geometry has high quality of mesh which give a sufficiently precise solutions. By implementing specified global mesh sizes ranging from medium to coarse, a more precise outcome is achieved. For faster calculation, we set the surface size of blade as .3 m and hard. The meshing procedure outlined in this study commences with central mesh control, followed by local mesh control.

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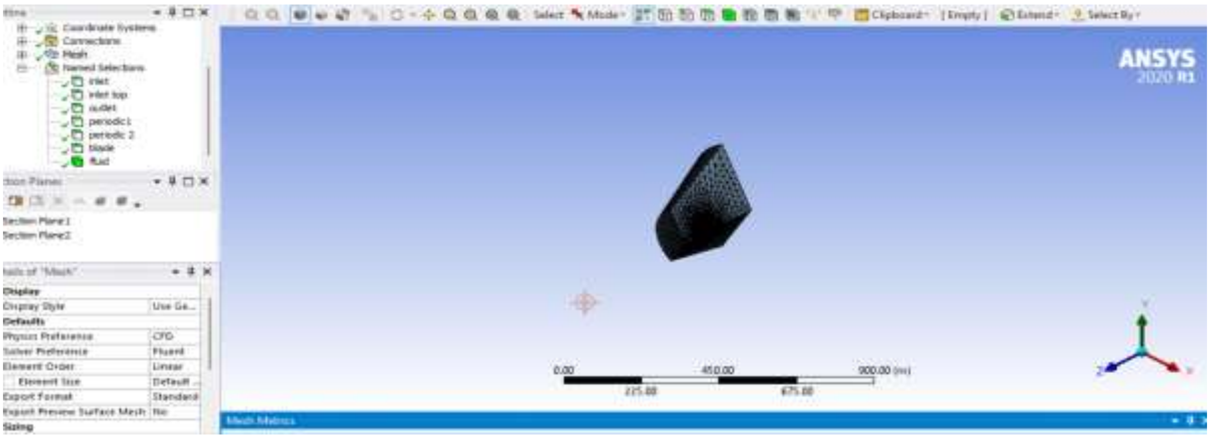

Fig 5 mesh of the computational domain

3.1.4 Analysis Setup

The k -w SST (shear-stress transport) model is employed in this research. The rationale behind selecting this particular model for the final analysis is its efficiency compared to other models that require a significantly longer computational time. This specific model has found extensive application in numerous research endeavours focusing on the aerodynamic characteristics of wind turbine blades. The transport equations governing the SST model are utilized for the determination of turbulent kinetic energy (k) and specific dissipation rate (w). A rotating frame of reference with a magnitude of 2.21 rad/sec is established around the negative z-axis, accompanied by an inlet wind velocity of 12 m/s. The outlet condition is defined as a pressure outlet with an initial gauge pressure of 0 Pa, simulating atmospheric conditions. The computational process commences with an initial iteration set at 1500, upon which the results are computed.

4. Results and discussions

A model for the blades of a horizontal axis wind turbine is developed, and the aerodynamic elements are verified using computational fluid dynamics (CFD) outcomes along with mathematical computations and experimental data from the GE1.5xle turbine. Subsequent to the verification process, the aerodynamic element is integrated into the Wind PACT 1.5 MW wind turbine blade for the purpose of analyzing its power and torque under different pitch angles and varying wind velocities.

4.1 Validation of Computational Fluid Dynamics Model

The blade velocity at the tip, where the velocity reaches its highest value of roughly 98.04 m/s, must be measured in order to validate the Computational Fluid Dynamics (CFD) model shown in Figure 6. Subsequently, a comparison between the CFD outcomes, mathematical computations, and data from experiments presented in Table 3 can be performed.

Pitch angle (Degree)	velocity (m/s)	Tangential velocity (m/S)		
		Analytical calculations	GE1.5 xle turbine	CFD analysis
4	12	98.12	97	98.04

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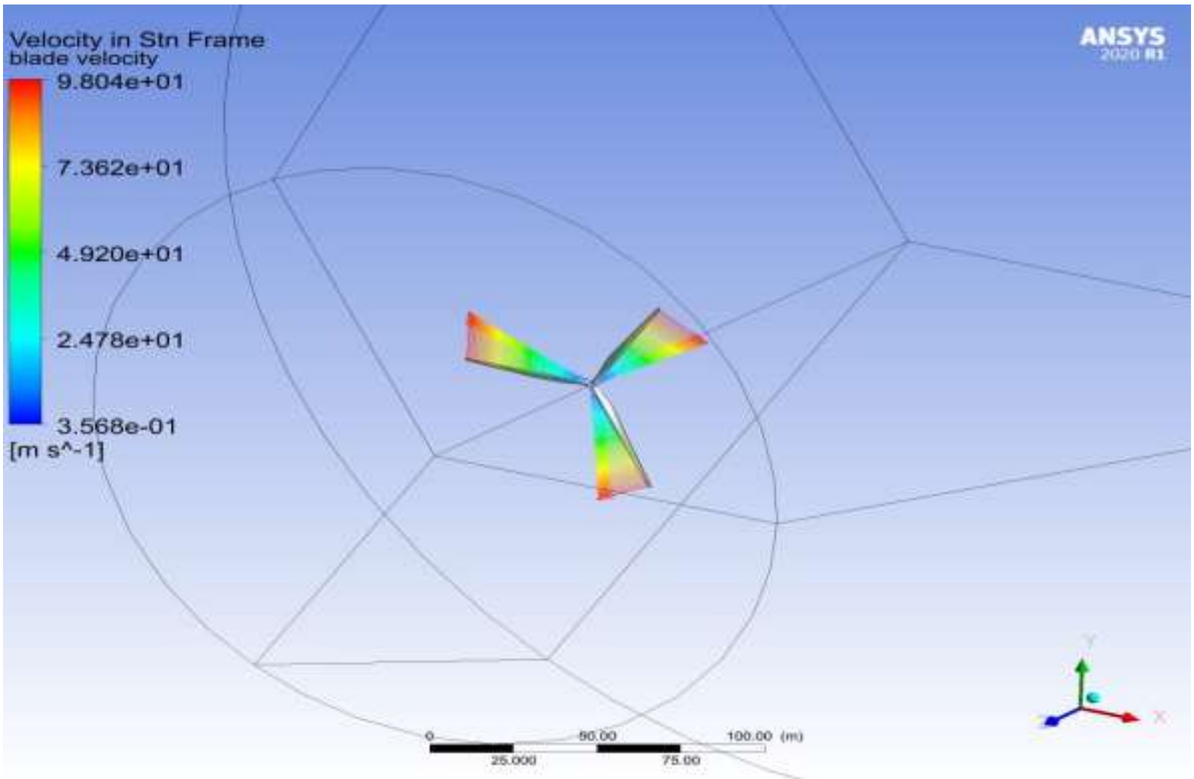

Fig 6 Blade velocity

To authenticate the CFD model illustrated in Figure 7, the power coefficient (c_p) is derived from the CFD analysis. CFD simulations are used to calculate the downstream velocity (v_3) and free stream velocity (v_0) and substituted into equations (2) to (4) to yield a c_p value of .297. Subsequently, a comparison can be made between the CFD outcomes, mathematical computations, and experimental findings presented in Table 4.

Pitch angle (Degree)	velocity (m/s)	power coefficient(C_p)		
		Analytical calculations	GE1.5 xle turbine	CFD analysis
4	12	.59	.265	.297

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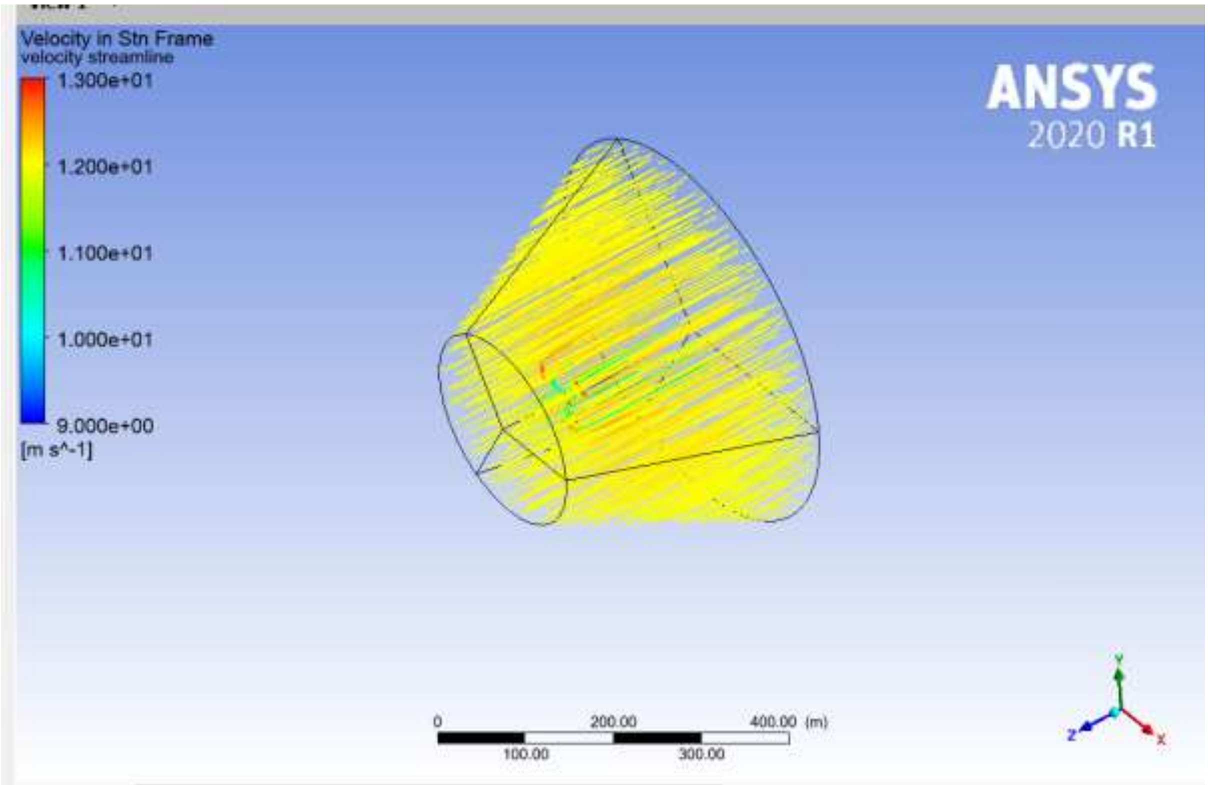

Fig 7 Blade velocity streamlines

4.2 Estimation Toque and power from CFD Analysis

Figures 8 to 13 illustrate the influence of pitch angle and wind speed on key performance parameters such as power and torque in wind turbines. According to wind turbine physics, there is an ideal torque and power output for a given wind speed that is reached when the free stream velocity precisely hits the blade span and the blade pitch angle aligns at a particular value.

This study considers five pitch angles (0, 4, 8, 12, 16 degrees) and six wind speeds (8, 10, 12, 16, 20, 24 m/s) to determine the wind turbine's power output reaching its maximum potential.

The torque fluctuation with varying wind speeds at a pitch angle of 0 degrees is shown on the chart in Figure 8.The torque demonstrates a decline as the wind speed transitions from 8 to 10 m/s, followed by an increment up to 24 m/s. Figure 9 exhibits that at 4 degrees of pitch angle, the torque rises for the initial velocities of 8 and 10 m/s, then declines until 12 m/s, but subsequently ascends up to 24 m/s. Figure 10 depicts an increase in torque at an 8-degree pitch angle beyond 16 m/s, while Figure 11 indicates that at a 12-degree of pitch angle, the torque commences an ascent after 20 m/s. Notably, Figure 12 highlights a consistent decrease in torque with the rise in wind speed at a pitch angle of 16 degrees.

The power generated by the wind turbine blades is calculated using Computational Fluid Dynamics (CFD) analysis, and the component of torque is an important factor in this process. The power output can be easily determined by applying the following mathematical formula:

$$P = T\,\omega \tag{5}$$

Here, P represents power (in megawatts), T denotes torque (in Newton-meters), and ω signifies angular velocity (in radians per second).

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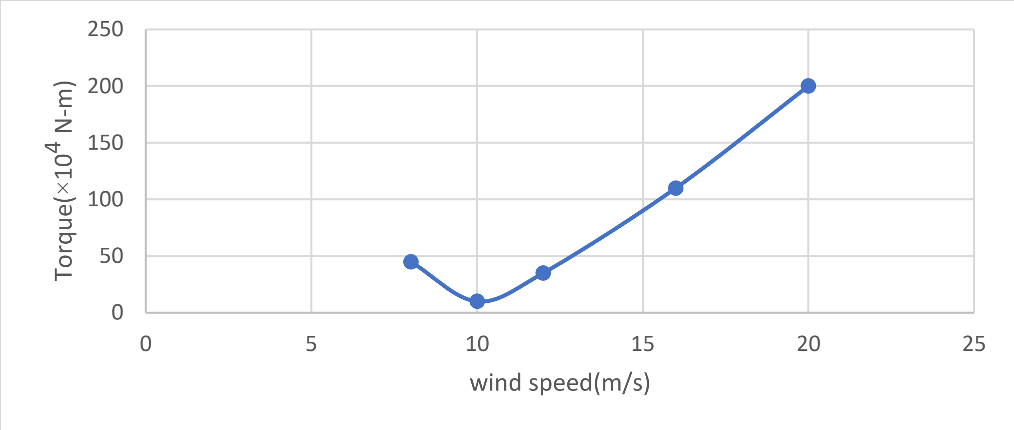

Figure 8 Torque at 0 degree pitch angle

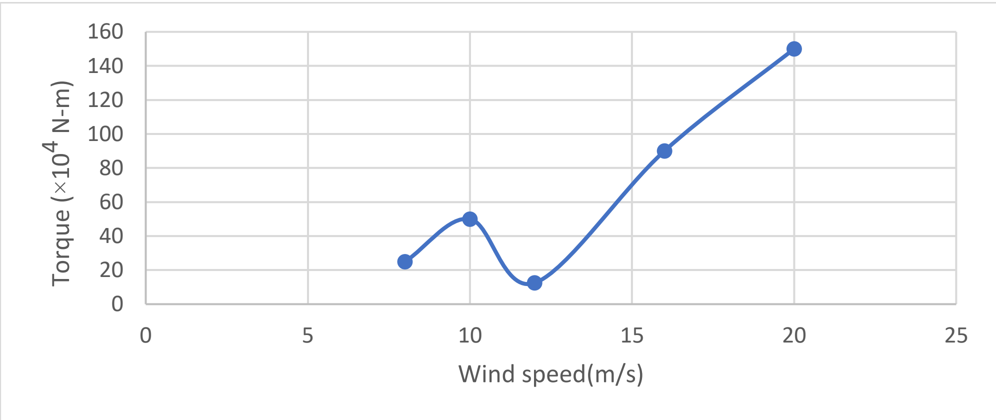

Figure 9 Torque at 4 degree pitch angle

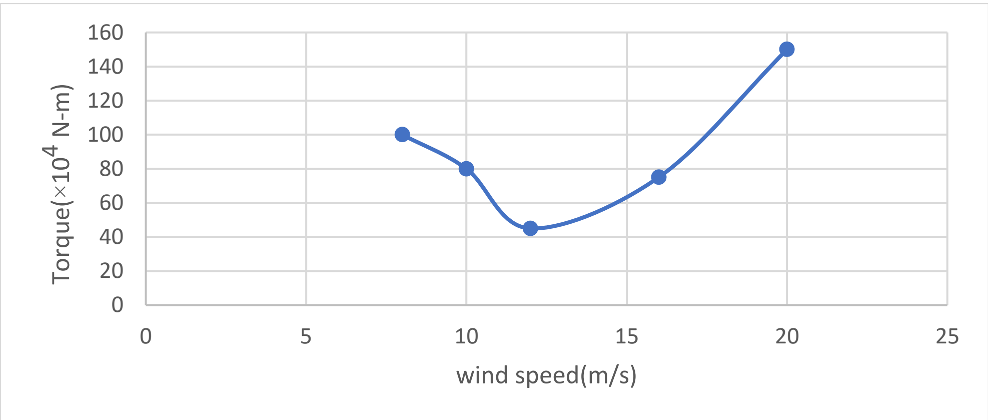

Figure 10 Torque at 8 degree pitch angle

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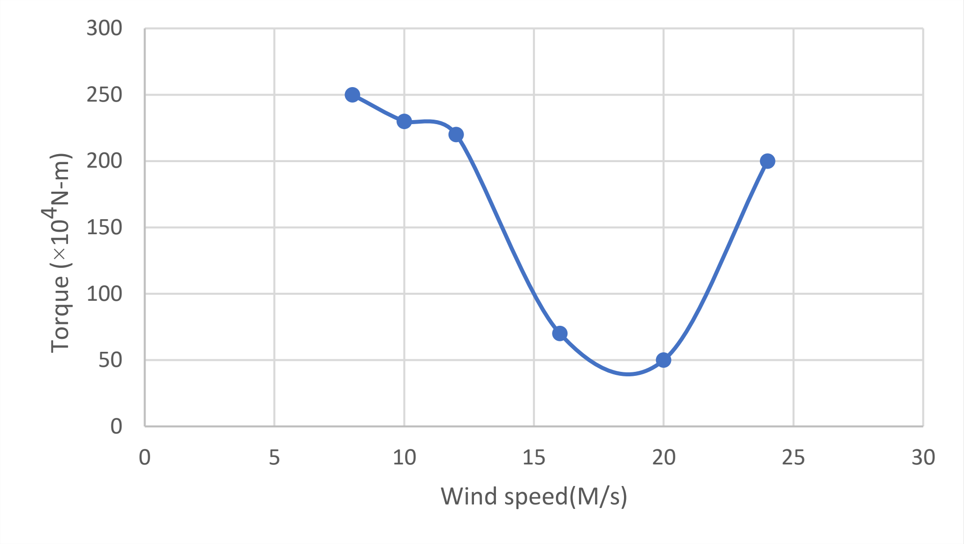

Figure 11 Torque at 12 degree pitch angle

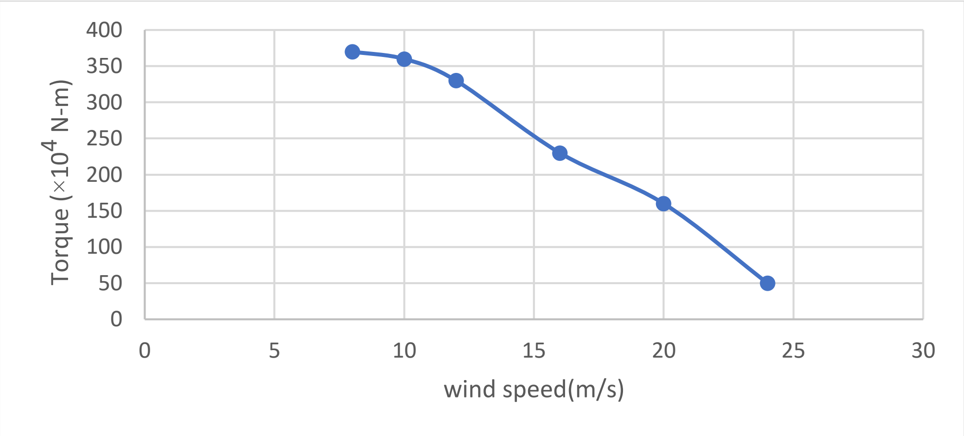

Figure 12 Torque at 16 degree pitch angle

The trend of power curve given in Figure 13

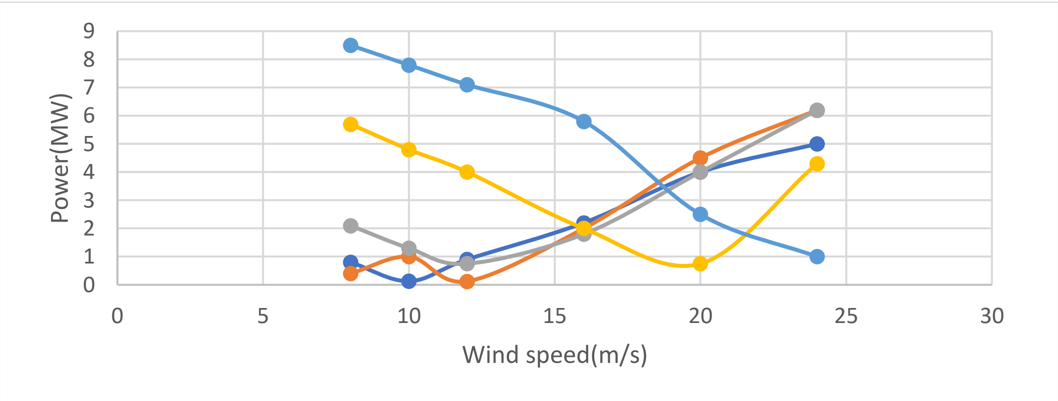

Figure 13 power curve at different pitch angle

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5. Conclusion

The examination in this research focuses on investigating the aerodynamic load on a horizontal axis wind turbine through the application of computational fluid dynamics methods. A comparison is made between the CFD outcomes and the GE1.5 xle turbine's mathematical calculations and experimental findings. This investigation has illustrated that the CFD techniques validate the experimental data and have the potential to refine and validate the turbine's shape requirements. Based on the findings of this study, it can be inferred that

1) The utilization of a 16° pitch angle is unsuitable for analysis and experimental purposes due to a reduction in power output at varying wind speeds.

2) The power output is more favorable with pitch angles of 0°, 4°, and 8° compared to other angles.

3) The maximum power exerted on the wind turbine blade occurs when utilizing pitch angles of 4 and 8 degrees.

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