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DESIGN AND FLOW SIMULATION OF AN ARCHIMEDEAN SPIRAL-TYPE WIND TURBINE BLADE FOR DETERMINING VELOCITY AND PRESSURE PROFILE

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ABSTRACT

The objective of the paper is to design a turbine blade of Archimedean Spiral-Type Wind Turbine (ASWT) and to conduct an external flow analysis to determine the variation of velocity and pressure of air while it flows through the blade. The design and Computational Fluid Dynamics analysis is performed with the aid of SOLIDWORKS 18 software. The design of turbine is enhanced to improve the power coefficient by studying the effect of various parameters such as pitch, opening angle and tip speed ratio (wind velocity). The turbine blade design is optimized for achieving optimum power coefficient. Simulation is conducted at a wind velocity of 4 m/s for the blade with 750 mm radius. Pitch and opening angle of the blade are 1125 mm (1.5 times radius) and 60^o respectively. The maximum, average and minimum values of velocity and pressure is also found out through simulation.

INTRODUCTION

Wind turbines are devices which can convert kinetic energy of wind into electrical energy with a mechanical rotor, drive train and a generator. Wind turbines are broadly classified into two on the basis of their blade arrangement with shaft, Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). (Cao, 2011)

The Archimedean Spiral-Type Wind Turbine (ASWT) is a small Horizontal Axis Wind Turbine (HAWT) that is based on the Archimedean spiral principle. It captures energy from the wind by deflecting it 90 degrees from its initial path. Unlike standard HAWTs, which rely on lift force to extract energy from the wind, the ASWT employs both lift and drag forces. The advantage of ASWT is that it can operate at low wind speeds. (Kim *et al.*, 2014).

The Archimedes rotor has both resistance and lift type turbine characteristics. The turbine blades are flat sheets, can work with a huge margin of error, create very little noise, and are lightweight. The turbine rotor, can work with a tip speed ratio greater than 1 and has a high efficiency, like the lift type rotor. The rotor is designed according to the Archimedean Spiral. The spiral design of the blade allows air to flow freely through the blade, enabling it to utilise both drag and lift force. The rotor is made up of three blades that are 120 degrees apart. (M. Mieremet, 2014)

The general objective of the research is to design and conduct a Computational Fluid Dynamics analysis of an Archimedean Spiral-Type Wind Turbine blade using SOLIDWORKS 2018. The design will be enhanced through the study of variation of power coefficient with pitch, opening angle and wind speed. SOLIDWORKS is a Design and Simulation software used to create 3D structures from 2D drawings and can be used as a CFD tool as well. Since the wind turbine blades are subjected to wind at all times, it is necessary to perform simulation tests to study the effect of pressure and velocity on blades. If the pressure acting on a blade is too high, the chances of its failure will be high as well. Analysis is done to find out the velocity and pressure profile of wind passing through the turbine blade.

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LITERATURE REVIEW

2.1 PREVIOUS RESEARCH

The first patent, issued in 2006, featured a 30° opening angle and pi number of revolutions. TU Delft conducted a test of the model in March 2007 and found it to be around 10% efficient. At the Peutz wind research centre in 2009, an upgraded model was tested, and it broke at 21 m/s. From pi number of revolutions, the number of revolutions along the rotor axis was reduced to one, resulting in a smaller shaft. This brought in a 15% boost in efficiency. In 2012, a rigorous research was conducted at Pusan University in Korea, which confirmed the calculations done previously, and the theoretical efficiency for the 0.5 KW model was determined to be 25%. (M. Mieremet, 2014)

2.2 DESIGN AND FLOW SIMULATION

Safdari created a scaled-model of an Archimedes spiral wind turbine and used CFD analysis to determine its aerodynamic efficiency. The maximum power coefficient of 0.25 was predicted in his research. (Safdari and Kim, 2015)

The features of wind turbine power performance and the flow field around the rotor are analysed through modelling in the research by using a CFD simulation to predict the performance of wind turbines. The proposed theoretical model was compared to CFD simulation. The power coefficient of the Archimedes spiral wind turbine was calculated using both approaches, producing a mechanical efficiency of 0.25. (Kim *et al.*, 2014)

The performance prediction of an Archimedes Spiral wind turbine has been re-investigated by CFD simulations. The target wind turbines were similar to previous models, but the dimensions were altered. (Lu, Qian *et al.*, 2012)

Vertical axis Savonius wind turbine of 2m diameter and 4m height was designed using SOLIDWORKS and CFD analysis and FEA were done. Computational Fluid Dynamics analysis was done to obtain the pressure difference between concave and convex surface of blade and Finite Element Analysis for obtaining the structural response of blade. (Sai and Rao, 2016)

A modified version of ASWT was designed and fabricated by implementing NACA 2412 using CATIA and OPENSCAD software package. The upgraded version was fabricated by 3D printing with Acrylonitrile-Butadiene-Styrene as its material. Comparison study was conducted between traditional Archimedean wind turbine using experimental and Computational Fluid Dynamics analysis. (S, Sandeep *et al.*, 2017)

2.3 SUMMARY

The Archimedean Spiral-Type Wind Turbine (ASWT) is a small scale wind turbine, which has the characteristics of both lift and drag type wind turbines. Relatively new, many studies over the year have improved the efficiency of the turbine. Through Computational Fluid Dynamics simulations, the performance and flow field can be predicted.

METHODOLOGY

This chapter discusses the designing of the Archimedean Spiral-Type Wind Turbine (ASWT) and its external flow simulation. A literature study was conducted to collect information regarding ASWT. A 3D geometric model of ASWT was created using SOLIDWORKS 18 and an external flow simulation was performed.

3.1 DESIGN PARAMETERS

Various parameters are employed to define the simulation system, which gives the turbine and its surroundings their virtual existence. Some of the parameters that are considered during the design process are:

3.1.1 Wind Velocity

The wind velocity, which is the velocity of air at the turbine's inlet. The wind's power is proportional to its velocity to the third power. So, while there is no useful energy available at lower wind speeds, it increases exponentially as the wind speed increases. The simulation is run with a wind speed of 4 m/s.

3.1.2 Tip Speed Ratio (λ)

Tip speed ratio of a wind turbine is the ratio of tangential speed of the tip of a blade to the actual velocity of free stream. The optimum value of **λ** depends on the geometry of turbine blade. It is closely related to the efficiency of the turbine and can be Mathematically expressed by

$$\lambda = \frac{\omega R}{v}$$

3.1.3 Pitch of the blade

Pitch of the blade is the axial distance measured when the spiral turns one complete rotation. Determining the proper pitch becomes a crucial factor in maximising power coefficient. In the design, the pitch is taken as 1.5 times radius of the blade.

3.1.4 Opening Angle

The opening angle of the turbine, represented by θ, defines the angle at which air exits the turbine in relation to incoming air. The tip vortex formed at the end of the turbine blade is determined by this angle. Similarly, when the opening angle of the turbine changes, so does the pressure difference formed along the blades. The opening angle in the design is taken as 60°.

3.1.5 Radius

Radius is the maximum distance of the turbine blade from the center of the shaft. It influences the turbine's swept area during rotation, which determines how much air interacts with the turbine. For all geometry, a constant radius of 750 mm is used to deliver the same input power.

3.1.6 Power Coefficient (C_p)

Power coefficient is the measure of the capability of wind turbine to convert kinetic energy of wind into rotational energy of turbine. It is the ratio of output rotational power of shaft to the input power of the wind. Power coefficient is the function of tip speed ratio for a given geometry of turbine blade and is independent of the wind speed. It can be calculated from the following formula.

$$C_p = \frac{T\omega}{\frac{1}{2}\rho A v^3}$$

Where,
ρ - Density of air
A - Swept area of turbine blade
v - Free stream velocity
T - Torque exerted on turbine by fluid
ω - Angular velocity of turbine

3.2 CFD ANALYSIS OF THE TURBINE

3.2.1 Modeling of Geometry

The turbine consists of three blades of 1500 mm diameter attached to a shaft at an angle of 120°. The turbine is drawn using SOLIDWORKS 18. The major parameters used for designing are mentioned in the table below.

Parameter	Value
Radius	750 mm
Opening Angle	60^{o}
Pitch	1125 mm

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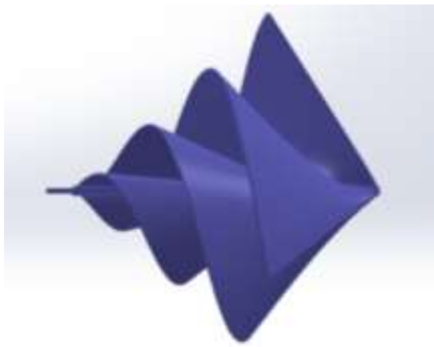

Fig 3.1 Side view of the turbine

Fig 3.2 Front view of the turbine

3.2.2 External Flow Simulation

The external flow simulation of the designed turbine was performed by SOLIDWORKS flow simulation tool. The CFD analysis led to the understanding of the variation of wind velocity and pressure as it flows through the turbine blade with an inlet velocity of 4 m/s.

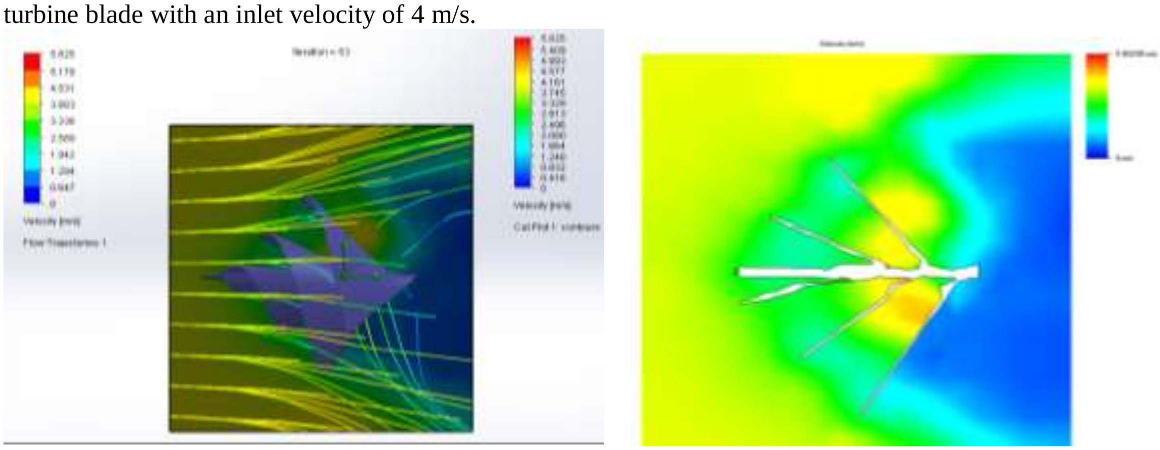

Fig 3.3 Velocity profile of flow through ASWT blade

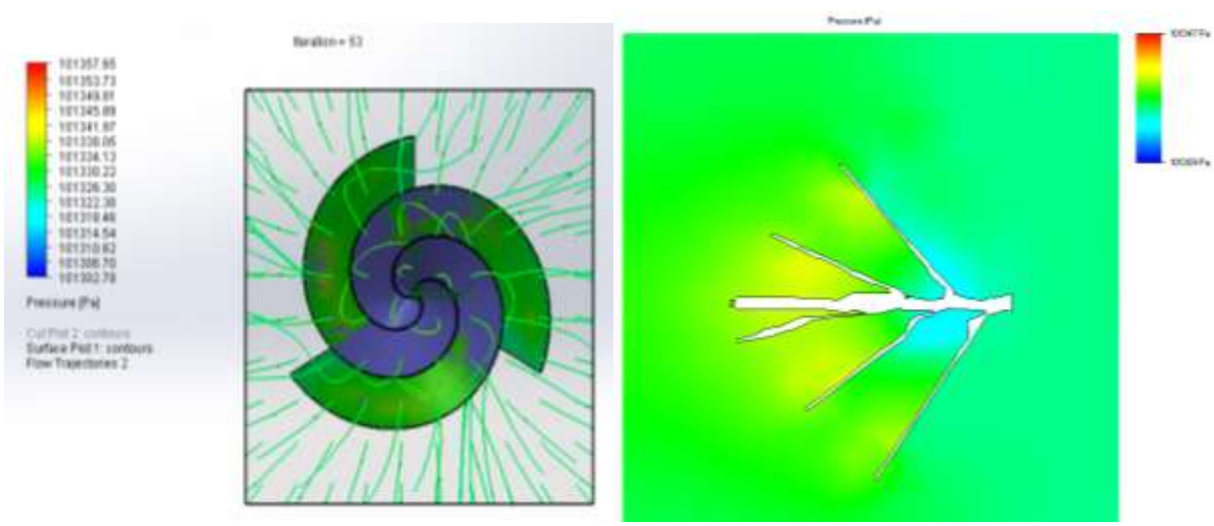

Fig 3.4 Pressure distribution on ASWT blade

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RESULTS AND DISCUSSION

4.1 PARAMETRIC STUDY

The variation of power coefficient (C_p) with respect to different turbine parameters are discussed in this section. Changes in Pitch, opening angle and tip speed ratio can impact the power coefficient (C_p). The design of Archimedean Spiral-type Wind Turbine is enhanced by the study. (Sapkota and Bhattarai, 2019)

4.1.1 Variation of power coefficient with pitch

The simulation was performed over a range of pitches, starting at 0.25 times the radius. For all models, a constant opening angle of 60 degrees is used while varying the pitch. The value of the power coefficient began to rise when the pitch was increased. At a pitch of 1.5 times the radius, the highest power coefficient was obtained. With further increase in the pitch, the power coefficient decreased. As a result, a pitch of 1.5 times the radius was chosen as the best model.

SN	Pitch (xR)	Max. C_p	Corresponding λ
1	0.25	0.109	1.5
2	0.5	0.145	1.75
3	0.75	0.188	1.75
4	1	0.214	1.75
5	1.25	0.228	1.5
6	1.5	0.236	1.5
7	1.75	0.235	1.25
8	2	0.232	1.25

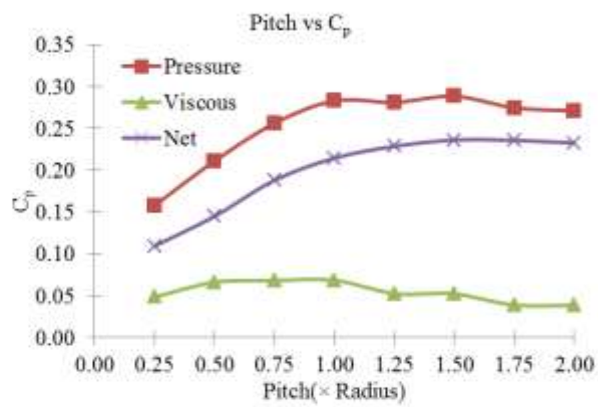

Fig 4.1 Pitch vs Power Coefficient (C_p) [7]

4.1.2 Variation of power coefficient with opening angle

After selecting the pitch, simulation was performed for the turbine at a variety of opening angles ranging from 30 to 90 degrees. The maximum power coefficient was found at 60-degree, as shown in the figure.

SN	θ (degrees)	Max. C_p	Corresponding λ
1	30	0.171	1.5
2	45	0.220	1.75
3	60	0.236	1.75
4	75	0.219	1.75
5	90	0.163	1.5

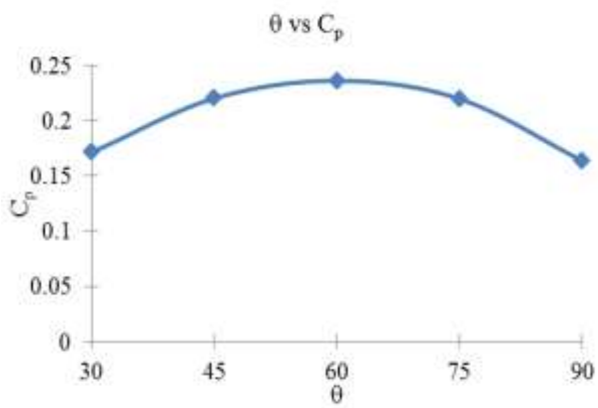

Fig 4.2 Opening angle vs Power Coefficient (C_p) [7]

4.1.3 Variation of power coefficient with tip speed ratio

After determining the pitch and opening angle of the turbine blade, simulation is performed at various wind speeds exceeding 3.5 m/s. It can be seen that the power coefficient is not a function of wind speed, but depends on the tip speed ratio.

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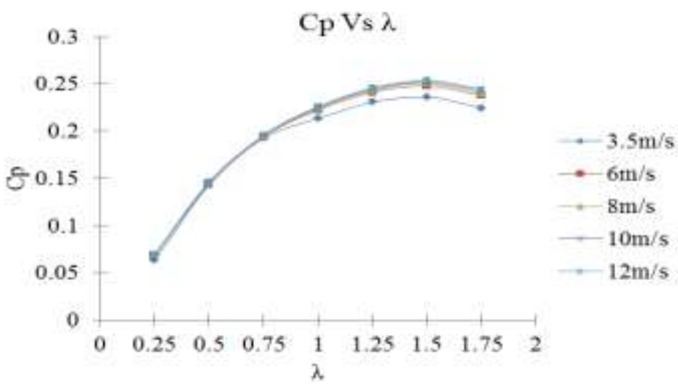

Fig 4.3 Tip speed ratio vs Power Coefficient (C_p) [7]

In figure, the maximum power coefficient is obtained at a tip speed ratio of 1.5, irrespective of wind speed. This shows that ASWT is effective at low tip speed ratios. The following are some of the benefits of having a high-power coefficient at low tip speed ratios:

- Turbines can run at high efficiency even when the wind speed is low.
- Lower centrifugal force on the root of the blade due to rotation of the blade.
- High torque output, which results in low cut-in speed.
- Lower noise production.

4.2 FLOW SIMULATION RESULTS

From the external flow analysis of ASWT, the variation of velocity and pressure of the air while passing through the turbine is found to be;

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
Min Total Pressure	[Pa]	101309.437	101308.5237	101307.2049	101309.437
Av Total Pressure	[Pa]	101333.4422	101333.4699	101333.44	101333.5656
Max Total Pressure	[Pa]	101351.1972	101351.7443	101351.1972	101352.534
Min Velocity	[m/s]	0	0	0	0
Av Velocity	[m/s]	3.204111023	3.210734132	3.195952755	3.267098492
Max Velocity	[m/s]	5.902954887	5.96609723	5.901908415	6.073321683

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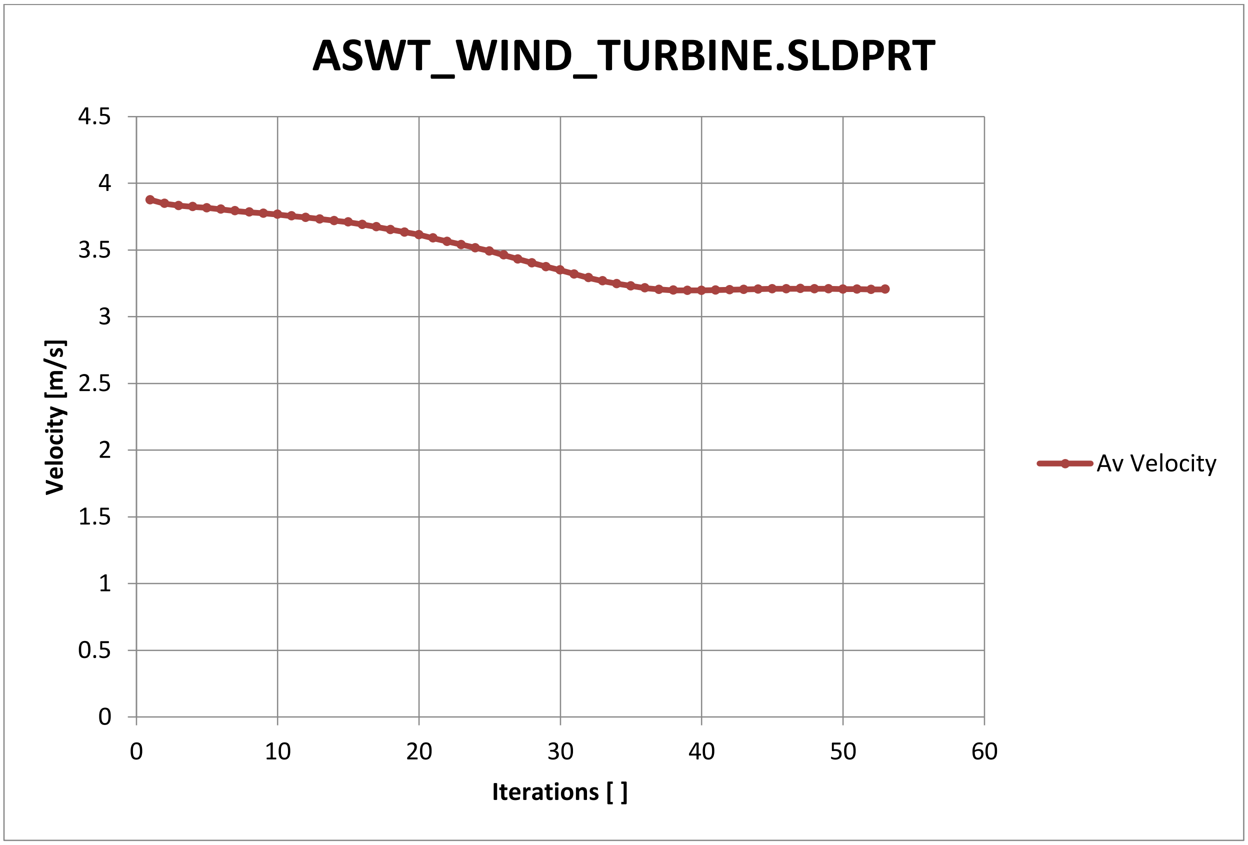

Fig 4.4 Variation of the Velocity with flow

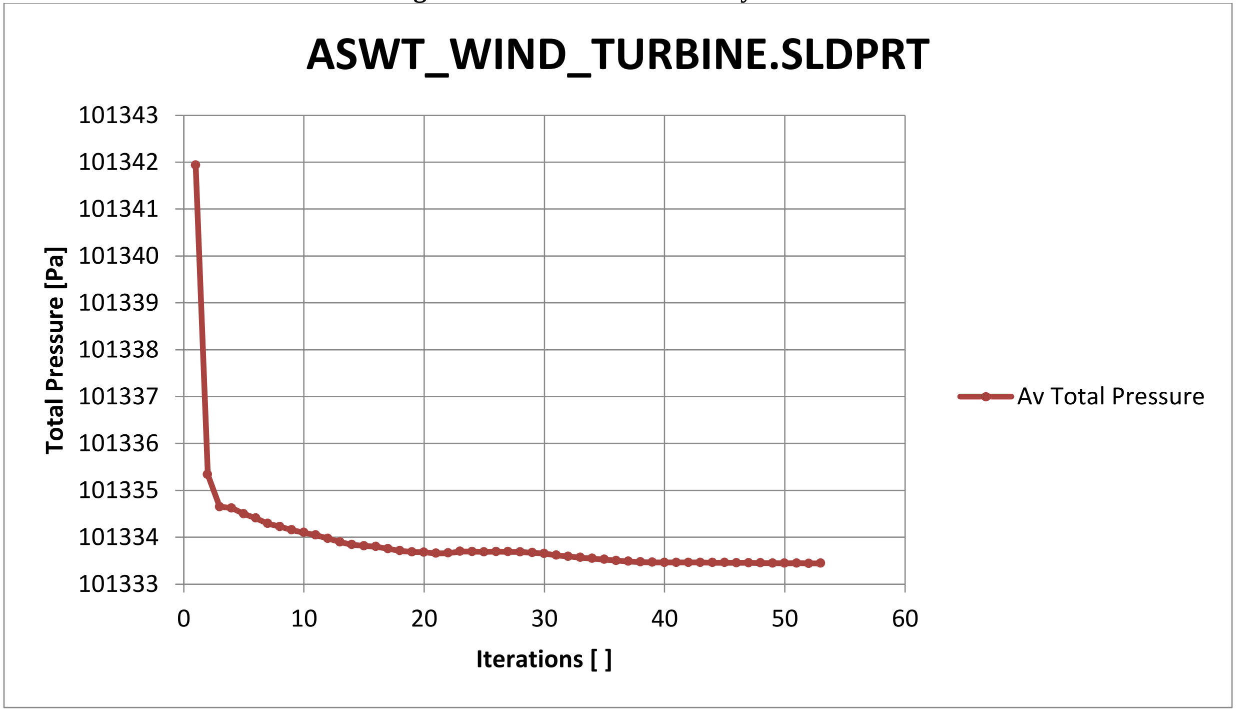

Fig 4.5 Variation of the Total Pressure with flow

CONCLUSION

A new type of HAWT that accepts the Archimedes spiral blade layout was familiarized. The turbine blade's design, CFD analysis, and the study of wind turbine parameters influencing the power coefficient led to the following conclusion:

- The power coefficient of the turbine is influenced by the parameters of turbine like pitch, opening angle and tip speed ratio. The design of ASWT was optimized for improving performance, by selecting pitch as 1125 mm (1.5 times radius of turbine) and an opening angle of 60°.
- The Computational Fluid Dynamics analysis of the turbine blade helped in understanding the fluid flow characteristic such as the velocity variation and pressure distribution of the air flow through the blade profile.
- The maximum and minimum pressure from external flow analysis were 101352.534 Pa and 101307.2049 Pa respectively.
- The maximum and minimum velocity from external flow analysis were 6.073321683 m/s and 3.195952755 m/s respectively.
- Further studies can be conducted for analysing the strength and stiffness of turbine blade to determine whether it can withstand pressure generated due to high wind speed. This includes stress and strain analysis of the blade.

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