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Design, CFD Analysis and Modelling of Archimedean-Spiral type Wind Turbine

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Abstract

This article presents the preliminary design of Archimedean spiral-type wind turbine, one of the emerging horizontal axis wind turbine (HAWT), with the aid of calculations and observations of various geometric parameters by computational fluid dynamics (CFD) analysis. Through simulations conducted by varying the pitch and opening angle at wind velocity of 3.5 m/s, for a turbine of 150 mm diameter, the geometry of final model was selected to obtain maximum power coefficient. Pitch and opening angle selected for final model was 112.5 mm (1.5 times radius) and 60 degrees respectively. Selected model was scrutinized through CFD analysis in range of wind velocity varying from 3.5 m/s to 12 m/s to estimate the power output. At wind velocity of 8 m/s, 10 m/s and 12 m/s, maximum power output was 1.38 W, 2.72 W and 4.74 W respectively, all obtained at the tip speed ratio of 1.5. Maximum power coefficient of 0.25 was attained at this tip-speed ratio, irrespective of wind velocity.

Keywords

Archimedean spiral-type wind turbine, computational fluid dynamics (CFD), tip speed ratio, power coefficient

1. Introduction

1.1 Need of research

Emission of excessive amount of greenhouse gas (GHG) by human activities is one of the challenging problems threatening humanity. The earth has been showing a rapidly warming trend. This has been primarily caused by the increasing concentration of the GHGs, particularly carbon dioxide. There is worldwide acceptance for the fact that the largest contributor to the increase in CO_2 concentration is the burning of fossil fuels and deforestation.[1] Use of excessive fossil fuel to meet majority of energy demand has threatened the environment and its biodiversity. To secure the energy supply whilst reducing carbon foot print, development of efficient renewable technologies are becoming more important. Among the renewable resources, wind energy is a fairly established technology with huge possibility for commercialization. With much potential and growing energy problems, this small but significant technology can provide much assistance in the households of Nepalese community.

Although few research have been done for analysis of Archimedean spiral-type wind turbine, none has been done, to the best of authors knowledge, to analyze the variation of turbine performance with alteration of turbine parameters.

1.2 Problem Statement

Hydropower is one of the major source of energy in Nepal. Since its introduction in 1911, Nepal was generating 733 MW of hydro-electricity by 2014. However, with the possible impact of climate change on the Himalayas and river systems originating from them, fully depending on hydropower would be unwise. Apart from hydropower, a cheaper and faster alternative renewable energy is wind power. It is clean, effectively infinite and one of the most cost-effective sources of power. A modern large wind turbine is not practical in Nepal as the blades cannot be disassembled and need to be delicately handled, which requires good road access for transportation.[2] So for the time being, small to medium scale wind turbines are ideal for the country.

1.3 Objective

The general objective of the research is to design, conduct CFD analysis and develop a model of Archimedes spiral-type wind turbine. Specific objectives include:

- To perform CFD analysis of wind turbine by varying its pitch and opening angle.
- To select the best model with the help of data obtained from simulation.
- To perform CFD analyses for the best model through range of wind speeds and determine its power coefficient.

2. Methodology

2.1 Literature review

2.1.1 Wind energy in Nepal

Nepal is a mountainous country with high potential for wind energy. The analysis done by the Solar and Wind Energy Resource Assessment concludes that about 6,074 square kilometers of land all over the country has the potential for wind power with density greater than 300 watt per square meter. The analysis established that more than 3,000 MW of power with an installed capacity of 5 MW per sq. km was possible and Kathmandu Valley alone was capable of producing 70 MW, whereas two districts, Mustang and Manang, have a potential of more than 2500 MW.[3]

2.1.2 Archimedean Spiral

Archimedean spiral is a spiral named after the 3rd century BC Greek Mathematician, Archimedes. It is the locus of points corresponding to the locations over time of a point moving away from a fixed point with a constant speed along a line which rotates with constant angular velocity. In polar coordinates (r, θ) spiral can be described by the equation,

$$r = a + b\theta^{1/c}$$

Changing the parameter 'a' will turn the spiral, while 'b' controls the distance between successive turnings. The normal Archimedean spiral occurs when c = 1.[4]

2.1.3 Archimedean Spiral type Wind Turbine (ASWT)

Archimedean Spiral-Type Wind Turbine (ASWT) is small scale horizontal axis wind turbine (HAWT) designed on Archimedean spiral principle. It harvests energy from the wind by redirecting its flow 90 degrees relative to the original direction. Unlike traditional HAWTs, which use lift force to take power from wind energy, the ASWT uses both lift and drag force. In particular, the advantage of ASWT lies in operation at low wind speeds.[5]

The Archimedes rotor has the characteristics of both resistance and lift type turbine. Resistance characteristics are that the turbine blades are flat sheets, can work under a large margin of error, produce very low noise and is lightweight. Likewise, the turbine rotor can work with tip speed ratio greater than 1, and its efficiency is high, which are the characteristics of the lift type rotor. The rotor is designed on the basis of Archimedean Spiral. The spiral shape given to the blade enables the air to flow thoroughly within the blade and use both drag and lift force. The rotor consists of three blades connected with each other at 120°.[6]

2.1.4 Betz's law

Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow system. It was published in 1919, by the German physicist Albert Betz. According to Betz's law, no turbine can capture more than 59.3% of the kinetic energy in wind. The factor 0.593 is known as Betz's coefficient.[7]

2.1.5 Previous works

First patented model, granted in 2006, had an opening angle of 30 degrees and pi number of revolutions. In March 2007, Tu Delft carried out a test of the model which showed the efficiency of approximately 10%. In 2009 an improved model was tested at the Peutz wind research center which broke at 21 m/s. The number of revolutions along the rotor axis was reduced to one from pi number of revolution, also reducing the length of the shaft. This increased efficiency to about 15%. In 2012 a very detailed study at Pusan University, Korea was carried out which confirmed the calculations made earlier and the theoretical efficiency was determined at 25% for 0.5 KW model.[6]

2.2 Design, drawing and simulation

Design, drawing and simulation of turbine blade were done on various ranges of turbine parameters to obtain the criteria for maximum efficiency. Initially, simulation was performed at wind speed of 3.5 m/s. After defining the criteria for maximum efficiency, simulation was performed for the best model in range of wind speed above 3.5 m/s. Drawing was done using SOLIDWORKS 15. CFD was conducted with Academic CFD solver, ANSYS FLUENT 16.0 and mesh was generated using ANSYS MESHING 16.0.

3. Design and Simulation

3.1 Design Parameters estimation

In order to define the system used in simulation, various parameters are used that give the turbine and its surroundings their virtual existence. Different parameters considered for design process are discussed as follows:

3.1.1 Wind Velocity

Velocity of air at the inlet of turbine is known as the wind velocity which is the velocity of free stream. Power of the wind is proportional to the third power of velocity. So, even though no beneficial energy is available at lower wind velocity, it grows exponentially with increase in velocity. Initially, simulation is performed at wind speed of 3.5 m/s. For the best geometry obtained simulation is performed on range of wind speed to study the variation in power coefficient.

3.1.2 Tip speed ratio (TSR)

TSR, denoted by λ of a wind turbine is the ratio of tangential speed of the tip of a blade to the actual velocity of free stream, v. It is related to the efficiency of the turbine, with the optimum value depending on the geometry of the turbine blade. Tangential speed is the product of angular velocity of blade, ω and radius of the blade, R. Mathematically, λ can be represented by the following formula.

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

3.1.3 Pitch of the blade

Pitch of the blade is the axial distance measured when the spiral turns one complete rotation. The estimation of the proper pitch becomes an essential factor for producing maximum power coefficient. The pitch is varied and studied in the simulation process.

3.1.4 Opening angle

The opening angle, denoted by θ of the turbine determines the angle at which air exits the turbine with respects to the incoming air. It also determines the tip vortex created at the end of the turbine blade. Likewise, the pressure difference created along the blades of the turbine also gets affected with the change in opening angle. The opening angle is varied and studied in the simulation process.

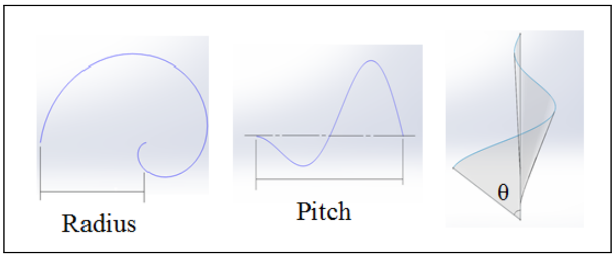

Figure 1: Blade parameters

3.1.5 Radius

Radius is the maximum distance of the turbine blade from the center of the shaft. It determines the swept area of the turbine during rotation which dictates the amount of air interacting with the turbine. To provide same input power, constant radius of 75 mm is considered for all geometry.

3.1.6 Power coefficient (C_p)

Power coefficient is the measure of capability of wind turbine to convert kinetic energy of wind to 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 virtually independent of the wind speed. It can be calculated by using 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 incorporates three blades of 150 mm diameter attached to a shaft at an angle of 120°. The turbine is drawn using SOLIDWORKS 15. 3D geometries of various dimensions were constructed for simulation of turbine with various parameters.

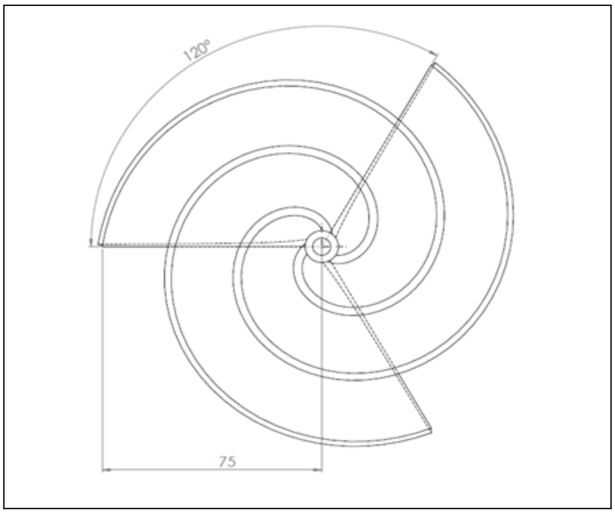

Figure 2: Front view of the turbine

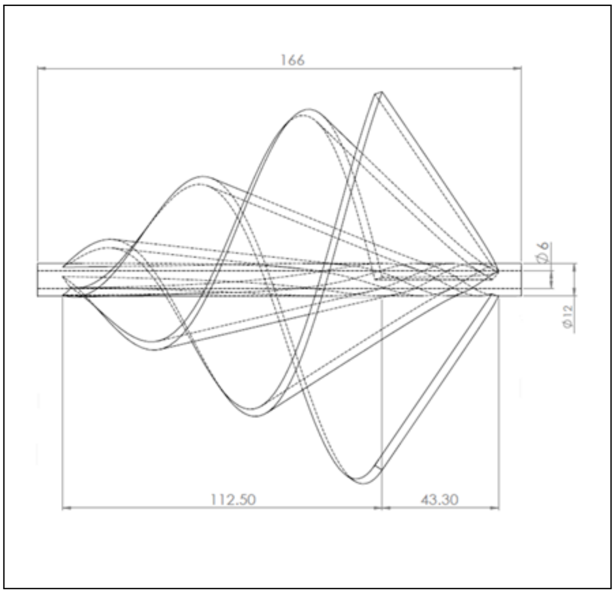

Figure 3: Side view of the turbine

3.2.2 Grid Generation (Mesh Geometry)

The geometry is imported in ANSYS MESHING 16. A single cylindrical domain, with radius five times that of the turbine, is created where the turbine is incorporated. Around the turbine geometry, an O-grid is created. The O-grid facilitated us with the advantages of dense mesh around the turbine and proper inflation. Wall distance is calculated using following parameters:

- Free stream Velocity
- Fluid density
- Dynamic viscosity
- Boundary layer length
- Non-dimensional wall distance(Y^+)

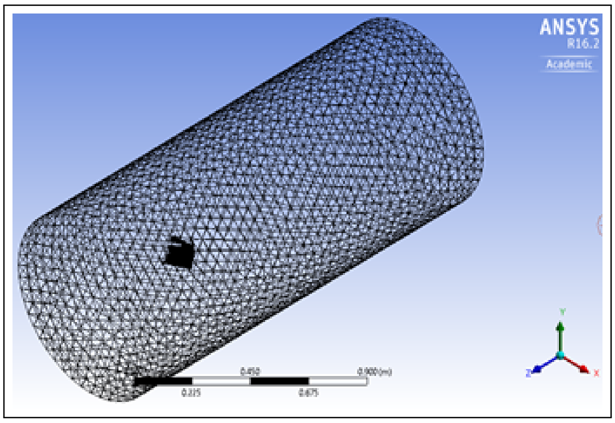

Figure 4: Grid generation using ANSYS Meshing

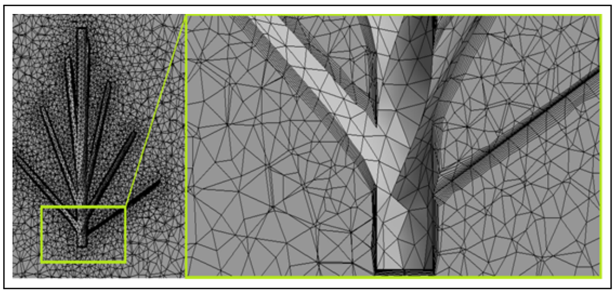

Figure 5: Inflation layer on the turbine's surface

The wall distance value of the model is found to be between 0.2 mm to 0.32 mm, depending upon velocity of the wind, for the desired Y^+ value of approximately 4, for SST $k-\omega$ model. The estimation tool was taken from online source: `www.cfdonlinetools.com`

Sphere of influence, the size of turbine, is created around the turbine and very fine grids were used within the sphere to address the high pressure and velocity gradient near the turbine surface. Grid tests were performed to confirm the grid independency.

3.2.3 Fluent Simulation

The developed mesh is imported to ANSYS Fluent and the setup is done. During setup, the fluid properties and the turbulence model are chosen. Inlet flow velocity and outlet pressure values are supplied for boundary conditions. The cell conditions are changed to fluid in the ANSYS MESHING itself. The setup is then initialized and calculation is done.

3.2.4 Fluent setup parameters

For the relevant comparison of different geometry, fluent setup parameters are kept same for each trail. The models selected are as follows:

- Viscous model: Shear stress transport (SST) k-ω with all parameters kept by default
- Material: Air (Incompressible)
- Density: 1.225 kg/m^3 (Constant)
- Dynamic viscosity: 1.875e-5 kg/ms (Constant)
- Ambient pressure and temperature: Standard atmosphere (101325 Pa and 288.15K)

3.2.5 Governing Equations

The governing equations are the continuity and Navier-Stokes equations. Reynolds Averaged form of continuity and momentum equation are used. SST k-ω turbulence model is used to close the equation set. These equations are written in a frame of reference rotating with the blade. This has the advantage of making our simulation not require a moving mesh to account for the rotation of the blade. [8]

Finite volume method (FVM) is used to evaluate partial differential equations in the form of algebraic equation. This huge set of algebraic equations is inverted through an iterative process in ANSYS Fluent. Inverting these algebraic equations gives the value of u, v, w, k and ω at the cell centers. Everything else is derived from the cell center values.

Second order discretization upwind is used to solve the problem with a pressure based solver. Two pressure-based solver algorithms are available in ANSYS FLUENT, a segregated algorithm, and a coupled algorithm. A coupled algorithm or scheme is selected for the problem.

3.2.6 Boundary conditions

- Initially constant wind speed of 3.5 m/s is used at inlet and after the determination of best model wind speed was gradually increased to study the variation in power coefficient.
- Fluid is at normal atmospheric pressure at far outlet for all geometries.
- No slip conditions are applied to turbine blades to account for viscosity of the fluid.
- Free slip condition is applied to the cylindrical domain.

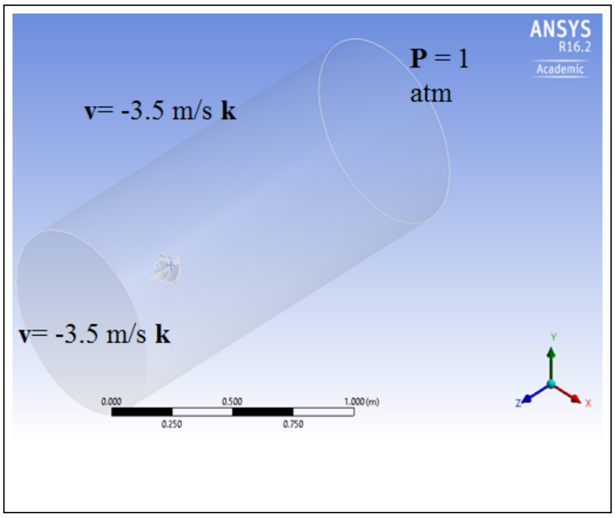

Figure 6: Boundary conditions

4. Result and Discussion

4.1 Verification and validation

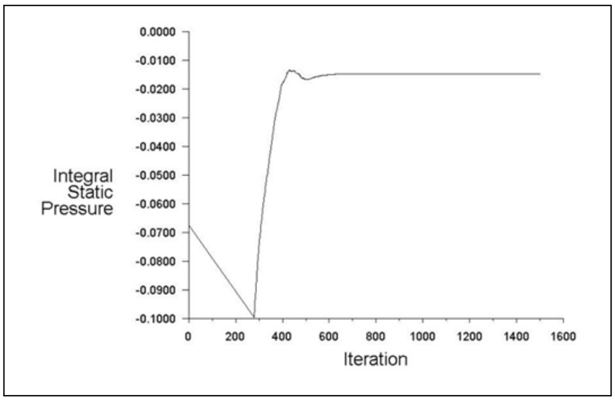

Figure 7: Convergence History of Static Pressure

Verification of simulation is done in ANSYS using fluent and CFD post. One of the essential condition is to verify that sufficient number of iterations have been done to obtain the result. Convergence of various parameters can be observed while performing the simulation as seen in figure 7, which shows that the value of Integral static pressure is converged after 600 iterations. Different component of velocities were converged after about 2500 iterations. Mass flow rate at inlet and outlet is checked after the simulation to validate continuity.

4.2 Variation of power coefficient with pitch

Simulation was performed in a range of pitch starting from pitch of 0.25 times the radius. While varying the pitch, constant opening angle of 60 degrees is used for all model. When increasing the pitch, the value of power coefficient began to rise. Highest power coefficient was obtained at pitch value of 1.5 times the radius. Further increase in pitch resulted in decrease of power coefficient. So pitch of 1.5 times the radius was chosen for the best model.

Table 1: Pitch vs Power coefficient (C_p)

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

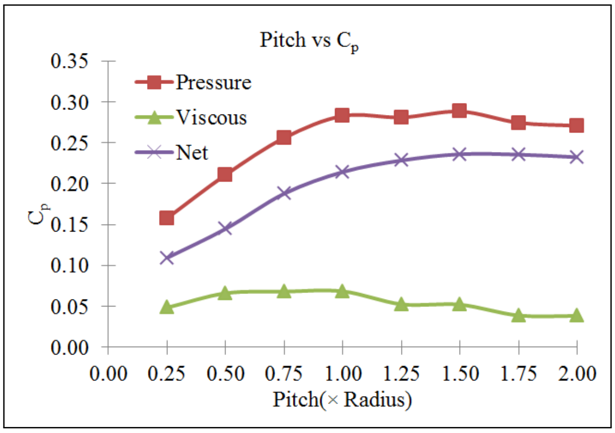

Figure 8: Pitch vs. power coefficient (C_p)

4.3 Variation of power coefficient with opening angle

Table 2: Pitch vs power coefficient (C_p)

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

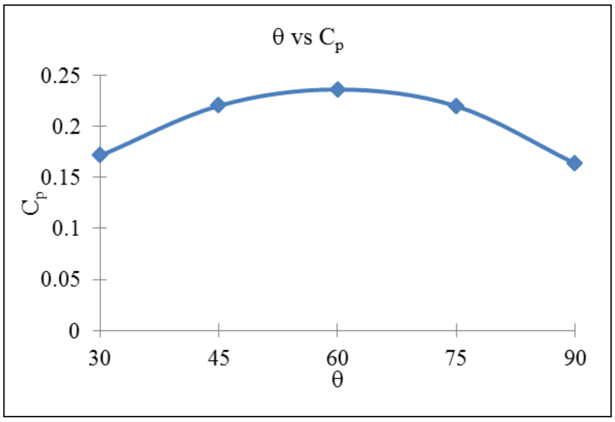

Figure 9: Opening angle vs. power coefficient (C_p)

After selecting the pitch, simulation was performed for the selected pitch at range of opening angle varying from 30 to 90 degrees. As seen in figure 9 maximum power coefficient was obtained at an angle of 60 degrees.

4.4 Variation of power coefficient with wind speed

After determination of pitch and opening angle of turbine blade, simulation was performed for the best model at different wind speed above 3.5 m/s. It can be observed that the power coefficient is independent of wind speed, rather it is a function of tip speed ratio.

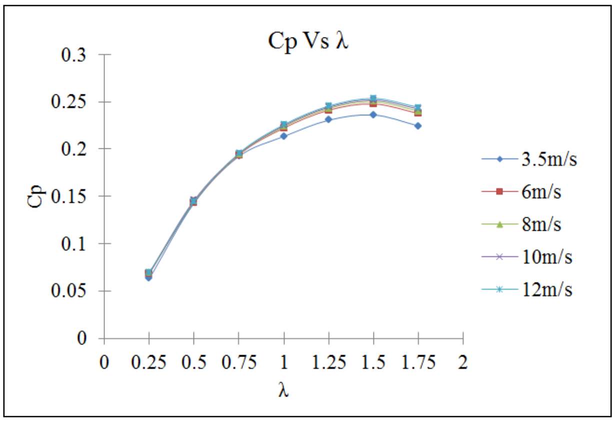

Figure 10: Tip speed ratio vs. power coefficient

In figure 10 we can observe that maximum power coefficient is obtained at tip speed ratio of 1.5 irrespective of the wind speed. This confirms the literature that ASWT is efficient at low tip speed ratio. Modern urban-usage 3-blade wind turbines have high rotor efficiency at higher tip speed ratio range.[9] Advantages of having high power coefficient at low tip speed ratios are as follows:

- Turbine can operate at high efficiency at low wind speed condition.
- Lower centrifugal force on the root of the blade due to rotation of the blade.
- High torque output, as torque and rotational speed are inversely proportional, which results in low cut in speed.
- Noise produce at the tip of the blade is lower.

4.5 Drag force on turbine

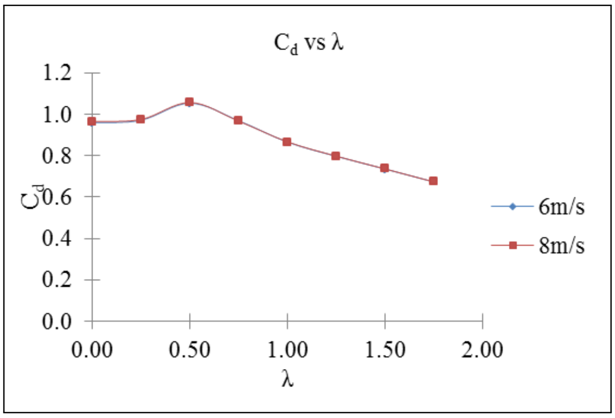

Figure 11: Drag coefficient vs. tip speed ratio

Drag force (D) also referred to as thrust force is experienced by the turbine in the direction of the wind. It can be represented by the following equation:

$$D = \frac{1}{2}\rho A v^2 C_d \tag{1}$$

Where C_d = Drag Coefficient

Figure 11 shows the plot of C_d and λ for wind speed of 6 m/s and 8 m/s. Maximum drag force is obtained at tip speed ratio of 0.5, above which drag force gradually decreases. Indeed, the graph shows that C_d is independent of wind speed and varies according to tip speed ratio. Compared to airfoil turbines, ASWT experience greater drag force because of larger surface area of the blade.

4.6 Velocity and pressure contours

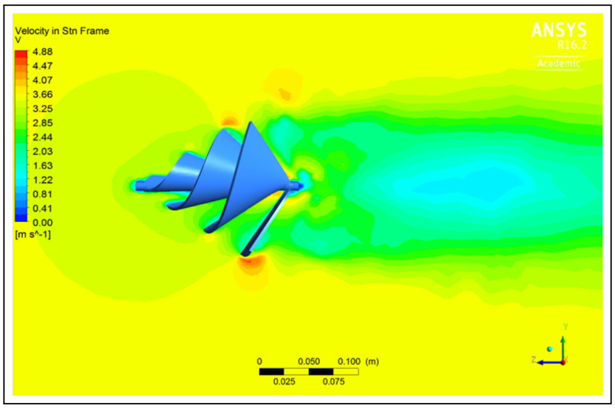

Figure 12: Calculated averaged velocity fields of the overall flow field on the central plane at 3.5 m/s wind speed and 1.5 tip speed ratio.

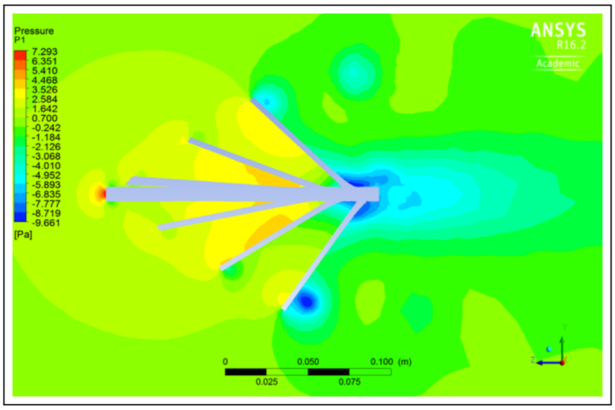

Figure 13: Calculated static pressure distribution of the overall flow field on the central plane at 3.5 m/s wind speed and 1.5 tip speed ratio.

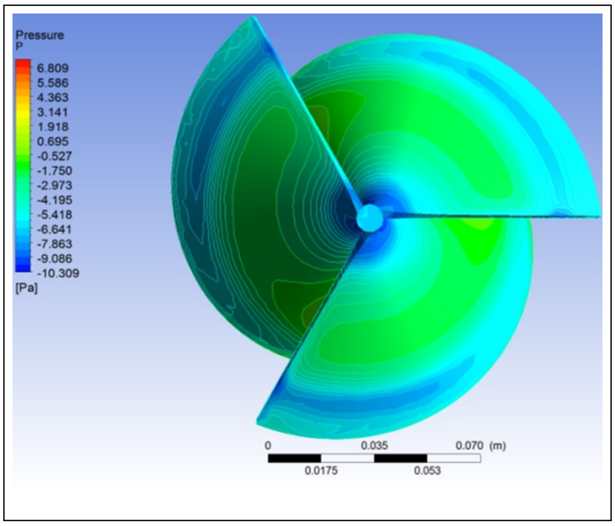

Figure 14: Static Pressure field distribution on rear side of Wind Turbine at wind speed of 3.5 m/s

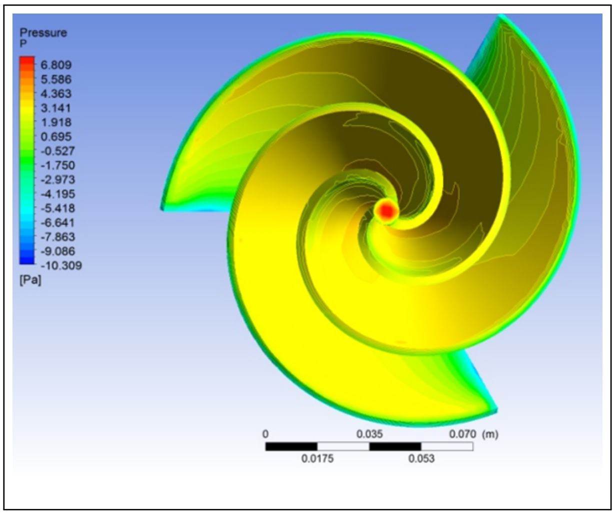

Figure 15: Static Pressure field distribution on front side of Wind Turbine at wind speed of 3.5 m/s

Figure 12 shows the calculated ensemble averaged velocity fields of the overall flow field on the central plane of the turbine at inlet wind speed of 3.5 m/s. Contour shown in this figure correspond to the turbulent wake shape. Highest velocity of about 4.9 m/s was obtained in the vicinity of rotor tip. The re-circulation zone in the wake region has significant reduction in velocity due to blockage of airflow by the turbine.

Figure 13 shows pressure distribution in the central plane of the turbine. In this figure, maximum pressure difference can be observed at the tip region. This suggests that maximum energy is extracted from the tip region of the blade. Figure 14 and 15 shows pressure distribution on opposite sides of the turbine blades. The highest pressure difference of about 14 pa can be observed at the tip of the blade, and the highest pressure of course is seen at the inlet due to blockage of air by the turbine rotor. The pressure difference on front and rear side of turbine is responsible for generating torque and drag force on the turbine.

5. Conclusion

An innovative kind of HAWT accepting the Archimedes spiral blade layout was familiarized. Design, CFD analysis and modeling of the turbine blade led to following conclusion:

- The optimum geometry for the model obtained from the analysis was with pitch of 1.5 times the radius (112.5 mm) and opening angle of 60 degrees.
- The performance characteristics of the best selected model of Archimedes wind turbine by 3D CFD analysis showed power coefficient, C_p of 0.25.
- Highest power coefficient was obtained at tip speed ratio of 1.5, which confirmed the literature that ASWT works best at low tip speed ratio.
- CFD analysis confirmed that power coefficients and drag coefficients are independent of wind velocity and are function of tip speed ratio.

6. Recommendations

Due to the limitation of maximum number of cells (512,000) in ANSYS Student license for a CFD model, simulation was only performed for a model of diameter, 150 mm. This size of model required about 350-500 thousand cells depending upon the pitch, which determines the length of the turbine. Further analysis could be performed to study the variation of turbine performance with increasing turbine diameter. Furthermore, a sophisticated experimental study could be performed to verify the results obtained in this research.

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