Modelling of Vertical Axis Wind Turbine

Submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in Mechanical Engineering

by **Abhinav Sagar**

16BME0903

Under the guidance of

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VIT, Vellore.

May, 2020

DECLARATION

I hereby declare that the thesis entitled “Modelling of Vertical Axis Wind Turbine" submitted by me, for the award of the degree of *Bachelor of Technology in Mechanical Engineering* to VIT is a record of bonafide work carried out by me under the supervision of Prof. Jayaprakash Narayan.

I further declare that the work reported in this thesis has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university.

Place : Vellore

Date:
20/05/2020

Signature of the Candidate

Abhinav

CERTIFICATE

This is to certify that the thesis entitled "Modelling of Vertical Axis Wind Turbine" submitted by **Abhinav Sagar (16BME0903)**, **SMEC**, VIT University, for the award of the degree of *Bachelor of Technology in Mechanical Engineering*, is a record of bonafide work carried out by him under my supervision during the period, 01.12.2019 to 20.05.2020, as per the VIT code of academic and research ethics.

The contents of this report have not been submitted and will not be submitted either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university. The thesis fulfills the requirements and regulations of the University and in my opinion meets the necessary standards for submission.

Place : Vellore

Date : **Signature of the Guide**

Internal Examiner

Head of the Department

ACKNOWLEDGEMENTS

I would like to express my gratitude to my mentor Prof Jayaprakash Narayan for his invaluable guidance. Without his advice, this thesis would not have been possible. I am always indebted to my parents for their patience, encouragement and love. I owe gratitude to my girlfriend Shreya Sharma for her countless support. I would further like to thank Luke Da Luz Souza for his helpful comments and discussions throughout my four years at VIT. I am also thankful to all those people who are directly or indirectly associated with me and whose contribution made this project successfully completed.

Executive Summary

This work focuses on simulating the flow around the designed vertical axis wind turbine. Flow over Darrieus type helical bladed NACA 0012 profile is simulated using ANSYS Fluent software. The turbulence model k-epsilon is used for carrying out three dimensional steady simulation. Meshing is done using a tetrahedral meshing approach along with inflation and boundary layer meshing techniques. Freestream wind speed of 10 m/s is taken for inlet and turbine is made to rotate at 400 RPM. The simulation is carried and the velocity vectors, pressure contours are analyzed. The torque and power output values are tabulated at various tip speed ratios. Also the effect of tip speed ratio is studied in detail to maximize the power coefficient of the wind turbine. Using CFD technique for simulation is a good alternative than the traditional wind tunnel testing, thus saving time and cost involved.

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List of Abbreviations

1. VAWT - Vertical Axis Wind Turbine

2. HAWT - Horizontal Axis Wind Turbine

3. RANS - Reynolds Averaged Navier-Stokes

4. URANS - Unsteady Reynolds Average Navier-Stokes

5. CFD - Computational Fluid Dynamics

6. FVM - Finite Volume Method

7. SST - Shear Stress Transport

8. COP - Coefficient of Performance

9. NACA - National Advisory Committee of Aeronautics

10. AR - Aspect Ratio

11. LES - Large Eddy Simulation

12. TKE - Turbulent Kinetic Energy

13. SDR - Specific Dissipation Rate

14. SIMPLE - Semi Implicit Method for Pressure Linked Equations

15. PRESTO - Pressure Staggering Option

16. NSE - Navier Stokes Equation

17. RANS - Reynolds Averaged Navier Stokes

18. RNG - Renormalization Group

19. S-A - Spalart Allmaras

Symbols and Notations

Pw - Wind Power

M - Momentum

ω - Radial Velocity

ρ - Density

S - Surface

Vinf - Upstream Velocity

L - Reference Length

Cm - Momentum Coefficient

λ = TSR - Tip Speed Ratio

R - Wind Turbine Radius

N - Number of Blades

c - Blade’s Chord

H - Wind Turbine Height

k - Turbulence Kinetic Energy

ε - Dissipation

ω - Specific Dissipation Rate

+ Y - Non-Dimensional Wall Distance

Y - Distance to The Nearest Wall

w τ - Wall Shear Stress

υ - Kinematics Viscosity

d - Diameter of Blades

e - Gap (eccentricity)

D - Rotor Diameter

h - Rotor Height

u - Flow Velocity

υ - Kinematic Viscosity

k-ε - Standard k- ε

α - Angle of Attack

Ω - Angular Velocity

μ - Dynamic Viscosity

k - Kinetic Energy

θ - Rotational Angle of Airfoil

λ - Tip Speed Ratio

ε - Turbulence Dissipation Rate

CL - Lift Coefficient

A - Frontal Area of Wind Turbine

CD - Drag Coefficient

Cm - Moment Coefficient

Cp - Power Coefficient

Dθ - Tangential Component of Drag

DR - Radial Component of Drag

Fθ - Total Tangential Force

FR - Total Radial Force

$L\Theta$ - Tangential Component of Lift

LR - Radial Component of Lift

P - Power

p - Pressure

R - Length of the Rotor Arm

Re - Reynolds Number

t - Time

T - Torque

V - Wind Velocity

1. Introduction

1.1 Objective

As the population of the world is increasing day by day, energy problems in many countries have become more and more critical. This effect is especially seen in countries with high population density like those in Asia and Africa. The fossil fuels are limited and predictions claim that they will already be extinct towards the end of this century. Hence for humanity to sustain, we need to look for alternative sources of energy.

Among several renewable energy sources, wind energy has seen a rapid growth worldwide. Wind turbines are typical devices that convert the kinetic energy of the wind into electricity. There are two main categories of wind turbines, namely Horizontal Axis Wind Turbine and Vertical Axis Wind Turbine. Mostly the turbines used in the commercial sector are HAWT type but the interest in VAWT has risen in the last decade.

There are many advantages of using VAWT. Its ability to accept wind from any direction without yawing, ability to provide direct rotary drive to a fixed load, can capture ground level winds and its components (generator and gearbox) can be mounted at ground level. These advantages make VAWT technically feasible for low power generation to be used in residential and office buildings.

1.2 Motivation

Since fossil fuels are limited in nature, we need alternative options for the future. Some of the renewable energy sources are solar, wind, geothermal, nuclear, tidal etc. Wind energy could be the next big thing for the future considering it is unlimited in nature, works 24/7, and is an easy and clean source of energy. However it has its own set of challenges like instability as wind speed fluctuates throughout the day and across seasons, requiring constant maintenance and monitoring of internal components, blades etc, expensive installation and maintenance and low efficiency.

The vertical Axis Wind Turbine has the following advantages

1. Less bulky and hence can be transported from one location to another.

2. Can function in extreme weather conditions especially when wind speed is either too low or too high.

3. Cheaper and hence more affordable for individuals.

4. More environmentally friendly in the sense that it doesn't harm the flying birds and also produce less noise pollution.

5. Installation and maintenance is much easier than HAWT.

6. Ability to accept wind from all directions and even turn on its own according to the direction of the wind.

There are mainly two ways in which researchers work in this domain. One is the traditional wind tunnel testing approach in which a prototype is made using some materials. Nowadays 3D printing is popular to make these prototypes. These are then placed inside the wind tunnel and are simulated by replicating conditions which are present in real life. The flow can be visualized by adding some particles and various flow parameters can be measured by attaching sensors to the geometry. The problem with this approach is that it is too costly from making the prototype to actually doing the simulation. Hence this is not a feasible option for everybody. The second way is much more convenient in which the computers are made to do all the hard work while we work on a Graphical User Interface. Here GUI are simulation software like ANSYS, Simulia etc.

Using CFD, we don't need to worry about the maths and the computational complexity of the problem. All we do is make a model of the geometry, mesh it, simulate it and get the results. Instead of the traditional wind turbine testing approach, in which we actually make a prototype and test it while simulating it in real conditions this approach is much better. Making a prototype and testing it is a costly affair and can only be done in labs which are very few in numbers. These make students and researchers against using this and CFD approach looks like a much better option especially considering the future. This approach helps in saving manual labour, time as well as boosting productivity while focussing on things which really matter.

1.3 Background

1.3.1 Types of Turbine

VAWT is further divided into lift driven VAWT (Darrieus type) and drag driven VAWT (Savonius type). The theoretical maximum power coefficient of wind turbines of any design operating is lower than 59.3%, which is known as the Betz limit.

There are 3 types of darrieus turbine -

a. D type
b. H type
c. Helical type

Each of these turbines have their advantages and disadvantages. As the Darrieus turbines are lift based hence generation of sufficient amount of lift is very important for them to work. The lift force produced should be more than the net resistance which is to overcome for them to work continuously even in fluctuating wind conditions. Taking this into account, helical turbines are the best suited. My work is only focussed towards helical darrieus vertical axis wind turbines.

The 3 types of turbine are shown in Fig 1.

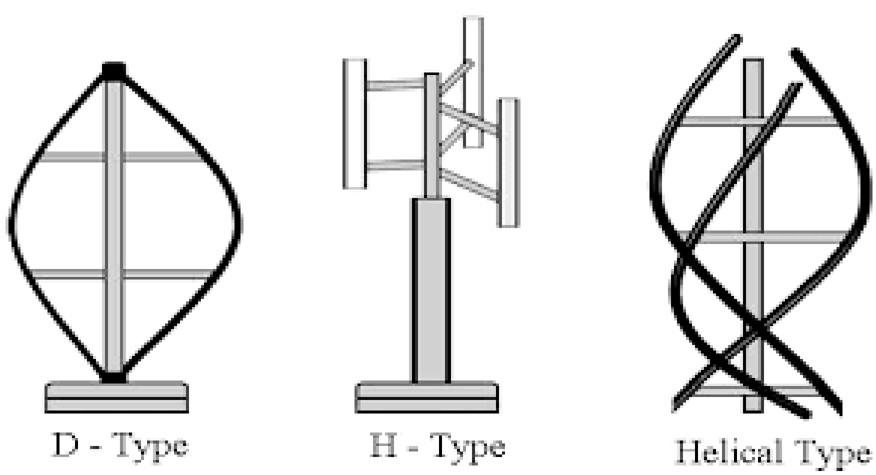


Fig 1. Types of Vertical Axis Wind Turbine [24]

A real world helical darrieus type turbine in operation is shown in Fig 2.

Fig 2. Helical Darrieus Type Turbine [Wikipedia]

1.3.2 Airfoil

The nomenclature of airfoil is shown in fig 3. Wind turbine blades are 3D projections of airfoils which are 2D in shape. These blades in turn produce lift and drag forces which produce a turning moment on the shaft. The turning moment is responsible for producing the torque which in turn produces the power. Hence it is very important to optimize the shape of the airfoil as per the requirements. Some of the important geometrical parameters which are helpful for designing the airfoil are angle of attack, chord length, thickness, camber and fraction of length at which thickness is maximum. Design of efficient airfoils for vertical axis wind turbines are an active area of research. The main challenge faced in design is increasing lift and lift to drag ratio and at the same time not letting the drag value go below some threshold value.

In this work, the airfoil chosen for the blades is NACA 0012. The choice was made due to its higher lift to drag ratio as compared to other airfoil shapes like NACA 0015, NACA 0018, NACA 2xxx series etc.

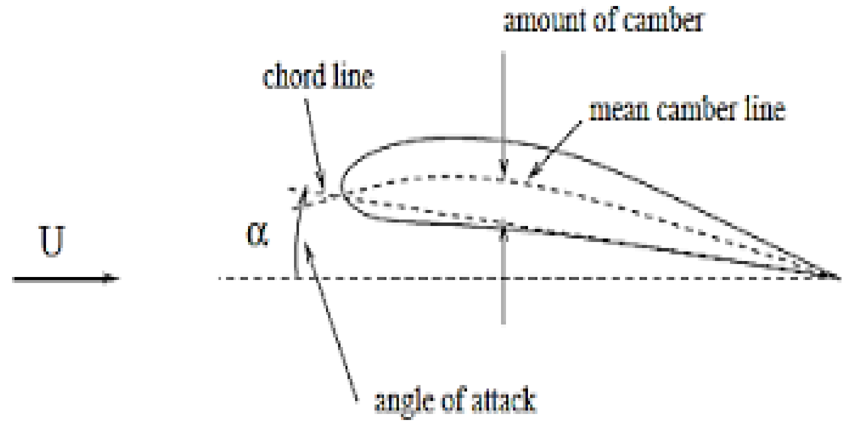


Fig 3. Nomenclature of An Airfoil [17]

1.3.3 Overview

Overview of Darrieus type vertical axis wind turbine is shown in Fig 4. As shown in the diagram, the wind turbine has an upwind side from where the wind is blowing and a downwind side from where the air is coming out. The turbine is rotating in an anti-clockwise direction which is powered by a shaft.

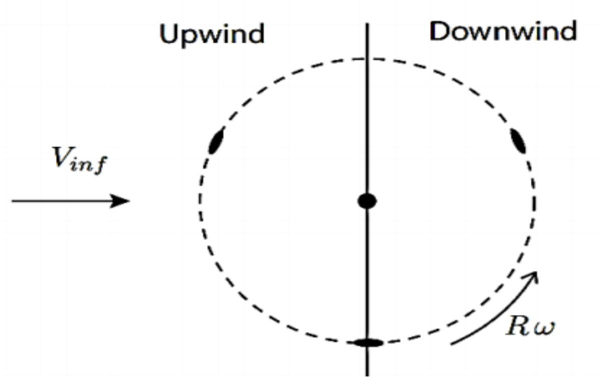


Fig 4. Overview of Darrieus Type VAWT [32]

Velocity diagram for a single blade of a Darrieus turbine is shown in Fig 5. As shown, freestream air is blowing from one side and coming out from the other. The airfoil is inclined at some angle of attack with the freestream air. The velocity at inlet has both axial component which is in the direction of the axis of turbine and a tangential component which is in tangential direction i.e. leaving the circle at that particular instant of time.

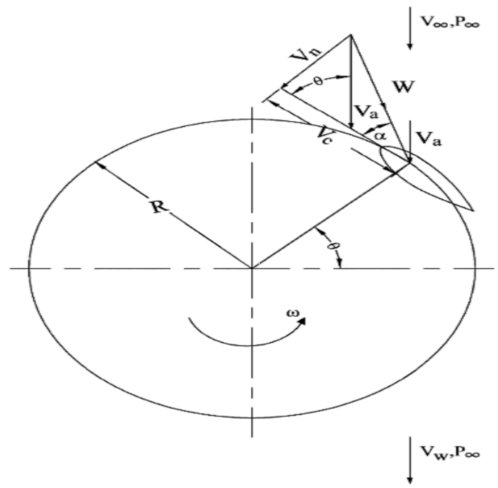


Fig 5.Velocity Diagram For a Single Blade [26]

1.3.4 Physics of Wind Turbines

The basics of wind turbines come down to airfoils which are powered by physics. The fundamental laws of physics which comprises Newton's Laws is the basis on which modern day aerodynamics work. Since wind turbines use similar airfoils as that which are used on airplanes, hence the physics is also similar. Basically, fluid dynamics work on three fundamental equations which are known as continuity, momentum and energy equations respectively.

The continuity equation is derived from the fundamental concept that mass is conserved i.e. the amount of matter which goes in is exactly equal to that which comes out. Applying this concept on a finite volume of fluid gives us the continuity equation. The second equation can be derived by applying Newton’s second law to finite mass of fluid according to which the net force acting on a body at any particular instant of time is equal to the mass time the acceleration of the body which is also equal to the change in the momentum of the control mass. In this case the body is the finite mass of fluid and the equation is known as the momentum equation. The third equation can be derived from the concept of conservation of energy of a fluid element i.e. energy is neither created nor destroyed, it only changes from one form to another.

These three equations when applied to real world problems gives us a set of partial differential equations which are often 6 but sometimes can be more but still be reduced to 6. Since these PDEs are non linear in nature it is almost impossible to solve them by hand. Due to this very reason, research in fluid dynamics came to a stall for a long period in spite of a lot of work being done on the theoretical side. However due to the modern advances in computational architecture, we can instead give the computer all the hard work to do and instead use a GUI to navigate what we want. This is what changed, what was known as fluid mechanics to computational fluid mechanics.

Some of the equations powering the physics of wind turbines are shown along with their description. These equations are later used for calculations in the final section.

Tip speed ratio is a very important parameter while designing the wind turbine which is denoted by Eq (2.1).

$$TSR = \frac{R\omega}{V} \tag{2.1}$$

where
TSR - Tip speed ratio
R - Radius of the turbine
ω- Rotational velocity of the turbine
V - Freestream velocity

The torque can be calculated by using Eq (2.2). Here moment coefficient is calculated numerically.

where
C_m- moment coefficient
T - torque produced
ρ- density of air
A - area swept by the blades
V - freestream velocity

$$C_m = \frac{T}{0.5\rho A V^2 \ R} \qquad (2.2)$$

The pressure coefficient can be calculated by using Eq (2.3).
where
Cp- pressure coefficient
P - freestream pressure

$$Cp = \frac{P}{0.5\rho A V^3} \qquad (2.3)$$

The power output can be calculated using Eq (2.4)
where
P - power output

$$P = T\omega \qquad (2.4)$$

The power coefficient can be calculated using Eq (2.5)
where
C_p- power coefficient

$$C_p = \frac{\omega \times T}{0.5\rho A V^3} \qquad (2.5)$$

1.3.4 Related Work

1. Modeling and Numerical Simulation of a Vertical Axis Wind Turbine Having Cavity Vanes in Fifth International Conference on Intelligent Systems, Modelling and Simulation 2014 by Adhim Suffer,Ryspek Usubamatov, Ghulam Quadir , Khairul Ismaild

The predicted results show that:
1. The drag coefficient increases with the increase in turbine frontal area.
2. The maximum static pressure drop is found in the case of blade angular position of 90° and minimum in the case when the blade angular position is 45°.

2. CFD Analysis of Different Blades in Vertical Axis Wind Turbine in International Journal of Pure and Applied Mathematics
2018 by Dr T.Mothilal, P.Harish Krishna, G.Jagadeesh Babu, Ashwin Suresh, K.Baskar,S.Kaliappan,M.D.Rajkamal

1. The tip speed ratio is better for the Darrieus type of VAWT.
2. For regions with higher wind velocity, Darrieus type VAWT proves to be more efficient.
3. Power coefficient vs tip speed ratio and pressure contours have been shown.

3. Determination of Vertical Axis Wind Turbines Optimal Configuration
through CFD Simulations in International Conference on Future Environment and Energy 2012 by Payam Sabaeifard, Haniyeh Razzaghi, Ayat Forouzandeh

1. A 3-bladed turbine with 35% solidity has the best self-starting ability and efficiency among all geometries.
2. Power coefficient vs tip speed ratio and pressure contours for various angles of attack has been plotted.

4. Analysis of Lift and Drag Forces at Different Azimuth Angle
of Innovative Vertical Axis Wind Turbine in International Journal of Energy and Power

Engineering 2015 by Abhijeet M Malge1, Prashant M Pawar

1. This paper is focused on analysis of drag and lift forces at different tip speed ratios acting at different azimuth angles of the wind turbine.
2. Coefficient of lift obtained was maximum at 35 degrees and minimum at 90 degrees ,drag coefficient was maximum at 60 degrees and minimum at 150 degrees.

5. 2D CFD Modelling Of H –Darrieus Wind Turbine in International Journal of Emerging Technologies in Engineering Research 2016 Komal Rawat, Hina Akhtar, Anirudh Gupta, Ravi Kumar

1. The computational domain was structured with a rotating ring mesh and the unsteady solver was used to capture the dynamic stall phenomena and unsteady rotational effects.
2. Unsteady simulation has been carried out and results show contours as a function of time, lift coefficient vs angle of attack, drag co-co-offecient vs angle of attack, torque, power, pressure coefficient vs tip speed ratio.

6. Velocity Effect On Wind Turbine Blade Using Cfd in International Journal of Creative Research Thoughts 2017 by Ch.Indira Priyadarsini, V.Lakshmi Shilpa, A.Akhil

1. Velocity of the upper surface is higher than the velocity of the lower surface.
2. The pressure coefficient of the airfoil's upper surface was negative and the lower surface was positive, thus the lift force of the airfoil is in the upward direction.
3. The coefficient of pressure was much larger on the front edge, while on the rear edge it was much lower.

2. PROJECT DESCRIPTION AND GOALS

This work focuses to simulate the flow around the designed vertical axis wind turbine. AutoCAD is used for making the 3D model and ANSYS Fluent for carrying out the simulation. Ansys workbench is used for making the bounding box container inside which the designed vertical axis wind turbine is placed. The geometry is transferred to ANSYS meshing in order to carry out the meshing. Meshing is discretization of the partial differential equations consisting of continuity, momentum and energy equations. These values are calculated at various nodes at subsequent iterations until the difference between two values are less than a predetermined threshold. On the simulation side, CFD tests are carried out numerically for the various aerodynamic coefficients of the flow around the wind turbine. In this work, computational fluid dynamics (CFD) is used to model the flow around vertical axis wind turbines. Well known turbulence models — i.e. the k-ε model are used for turbulence modelling. Finally velocity vectors and pressure contours are plotted along with a table depicting the effect of various tip speed ratio on the power coefficient of the wind turbine.

By using computational fluid mechanics and numerical simulation, designers can rapidly simulate their CAD model. This would help them in calculating the various important parameters including the efficiency of the wind turbine before actually making the prototype or model itself. This would likely reduce the time spent and money involved and boost up the productivity.

The goals of this project are:

1. 3D numerical simulation of the flow around the designed vertical axis wind turbine to investigate its aerodynamic performance.

2. The effect of tip speed ratio has been examined which is considered to be a prominent factor in deciding Cp of a wind turbine.

3. Calculate the power coefficient numerically of the designed wind turbine.

4. To study the variation of performance coefficient of VAWT at different tip speed ratios and obtain an optimum value of tip speed ratio at which VAWT produces maximum power output for NACA 0012 airfoil.

5. To study the effect of laminar boundary layer separation on Cp of a VAWT by comparing the results of Laminar viscous model and RANS turbulence model.

6. To study the effect of tip speed ratio on power coefficient, moment coefficient, torque produced and power produced.

3. TECHNICAL SPECIFICATION

The dimensions of the airfoil is taken from the NACA airfoil database. The airfoil shape chosen is NACA 0012. The values of chord length, camber, thickness are taken from the NACA database. In order to compare my work, with the work already done and for the reproducibility, the parameter values are the same. There are some small changes in shaft and end plate dimensions according to the fit with other parts. Rotor is equipped with three airfoil blades each with the chord length of 0.025 m. located at 120◦ from one another. Diameter of the rotor is set as 0.1 m. The length of the blades is 0.2 m measured longitudinally which is also the shortest distance between the end plates. The geometry is completely made in AutoCAD.

The geometry is transferred to ANSYS geometry to enclose the wind turbine with a bounding box in the shape of a cuboid with dimensions of 0.4 m across all three dimensions i.e. length, breadth and height.

Then the geometry is transferred to ANSYS Mesh for meshing. Inflation is used to mesh properly the corners and boundaries. Also the boundary layer meshing approach is used to even out the residuals which will be calculated in subsequent iterations.

Then the mesh is transferred to ANSYS simulation for carrying out the simulation. In this case a steady type of simulation is chosen which means that the time derivative of the various quantities like pressure, velocity etc is constant with respect to time.

The boundary conditions of 10 m/s velocity inlet is given in the positive x axis direction, 0 Pa pressure outlet and no slip wall conditions are applied. Also a rotational velocity of 400 rpm is given to the turbine in the clockwise direction. K epsilon turbulence model and SIMPLE (Semi-Implicit Method for Pressure Linked Equations) solver type chosen. The solution is initialized in a hybrid state with predefined values and the simulation is run for 100 epoch until the residuals for pressure, velocity, turbulence etc begins to stabilize.

Finally the results for contours, vectors, pathlines etc are plotted. Also the x-y graph for tip speed ratio vs pressure coefficient, tip speed ratio vs moment coefficient, tip speed ratio vs torque and tip speed ratio vs power produced by the turbine is plotted.

Some of the design specifications of the vertical axis wind turbine are shown in table 1.

Table 1. Design Specifications

Rotor diameter	0.1m
Blade length	0.2m
Blade chord	0.025m
Density	2.7g/cm^3
No of blades	3

4. DESIGN APPROACH AND DETAILS

The following points highlight the detailed design approaches used in this work.

1. Make the individual parts including shaft, blades and end plates in AutoCAD. The dimensions of the airfoil taken from the NACA airfoil database. The individual part dimensions are taken from the previous research papers.

2. Mate the parts to make the 3D CAD model for vertical axis wind turbines in AutoCad.

3. To mesh the model appropriately using the inflation and boundary layer meshing approach.

4. Carry out numerical simulation of the flow around the designed vertical axis wind turbine to investigate its aerodynamic performance.

5. Plot the vectors, contours and pathlines for velocity, static pressure and turbulent kinetic energy for the flow around the wind turbine.

6. Plot the x-y graph for tip speed ratio vs pressure coefficient, tip speed ratio vs moment coefficient, tip speed ratio vs torque produced and velocity vs power produced.

7. Finally calculate the power coefficient of the wind turbine numerically.

Rotor is equipped with three airfoil blades each with the chord length of 0.025 m. located at 120◦ from one another. Diameter of the rotor is 0.1 m. The boundary conditions of 10 m/s velocity inlet, 0 Pa pressure outlet and no slip wall conditions are applied. Also a rotational velocity of 400 rpm is given to the turbine. K epsilon turbulence model and SIMPLE (Semi-Implicit Method for Pressure Linked Equations) solver type are chosen.

The geometrical domain for 3-bladed Darrieus turbines is shown in Fig 6. The face of the container from which the flow is coming is known as the velocity inlet, the face from which the flow is coming out is known as a pressure outlet. The other faces of the container are denoted by a moving wall. The domain in the inner portion of the turbine is denoted by a steady inner domain while that containing the rotating blades is denoted by a rotating domain. The area outside the turbine but inside the container is denoted by steady outer domain

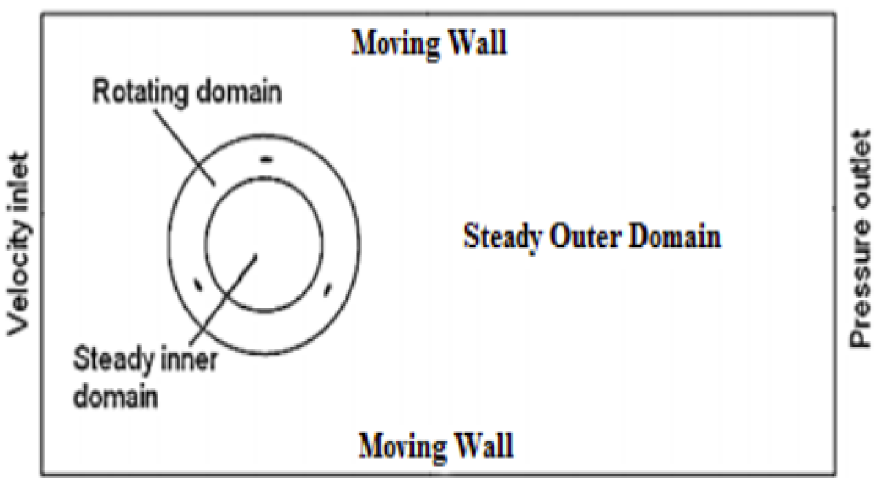


Fig 6. Problem Domain Of a 3-bladed Darrieus Turbine

5. SCHEDULE, TASKS AND MILESTONES

The following timeline was followed for doing this work -

1. Dec 1 - Dec 15 Read research papers
2. Dec 16 - Dec 31 Design the CAD model
3. Jan 1 - Jan 20 Do the simulation
4. Feb 1 - Feb 15 Read research papers
5. Feb 16 - Feb 29 Mesh and carry out second round of simulation
6. Mar 10 - May 15 Write the thesis

6. PROJECT DEMONSTRATION

Frontal view of the designed vertical axis wind turbine is shown in Fig 7. As shown there is a central shaft through which external rotation is given to the turbine. There are two end plates attached to the opposite ends which houses three spiral blades.

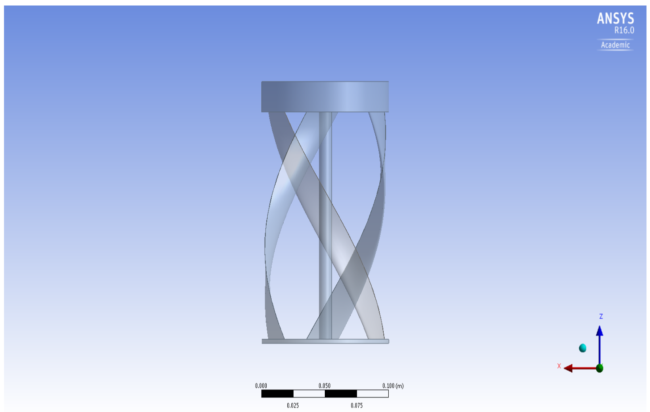


Fig 7. Front View of Turbine

The top view of the designed vertical axis wind turbine is shown in Fig 8.

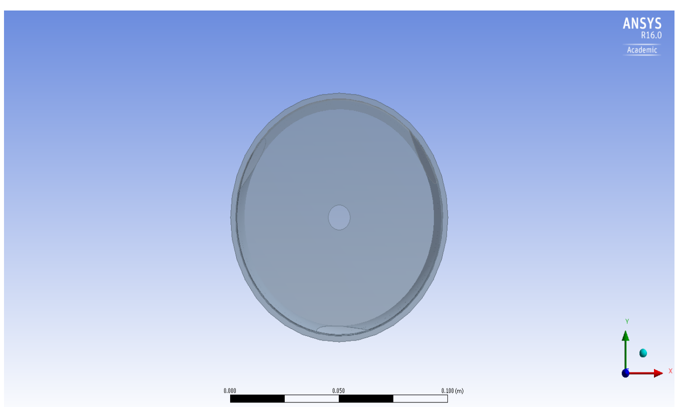


Fig 8. Top View of Turbine

The side view of the designed vertical axis wind turbine is shown in Fig 9.

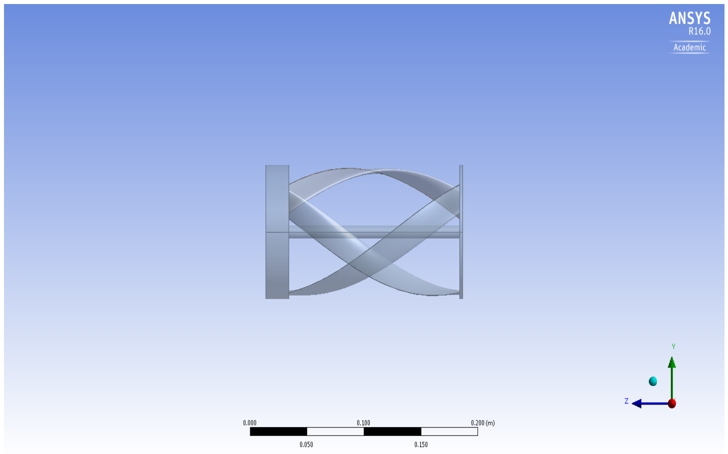


Fig 9. Side View of Turbine

The blades which are made up of NACA 0012 shape are shown in Fig 10.

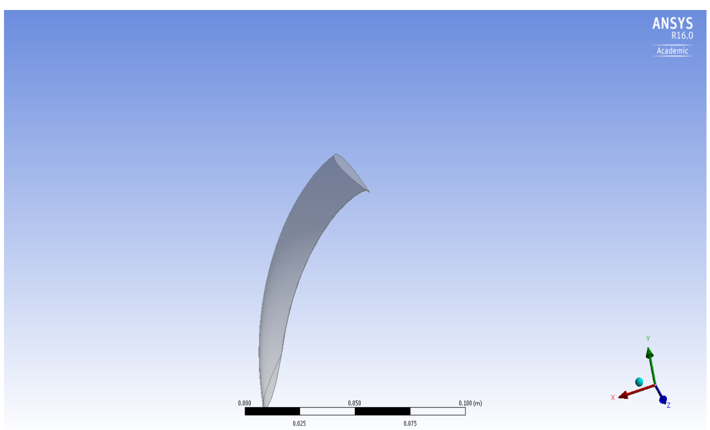


Fig 10. Blades NACA 0012

The inlet face of the container is shown in Fig 11.

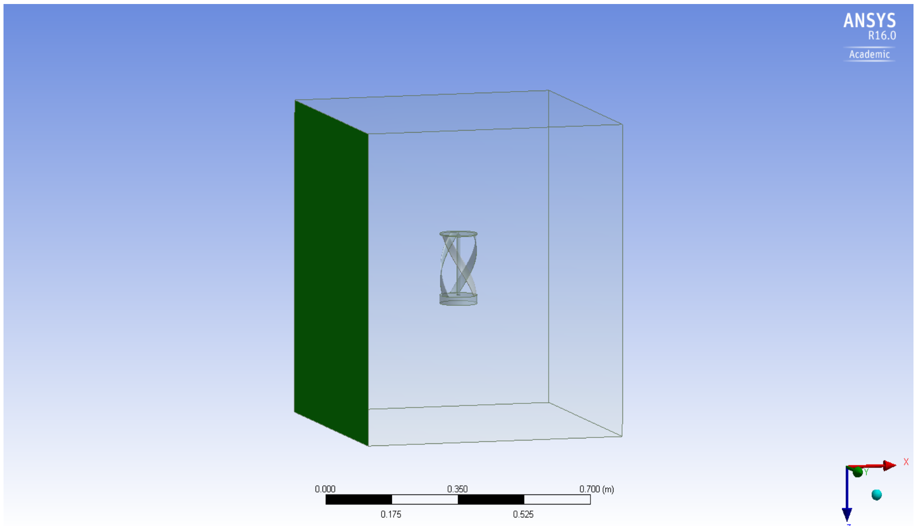


Fig 11. Inlet Face of Enclosure

The outlet face of the container is shown in Fig 12.

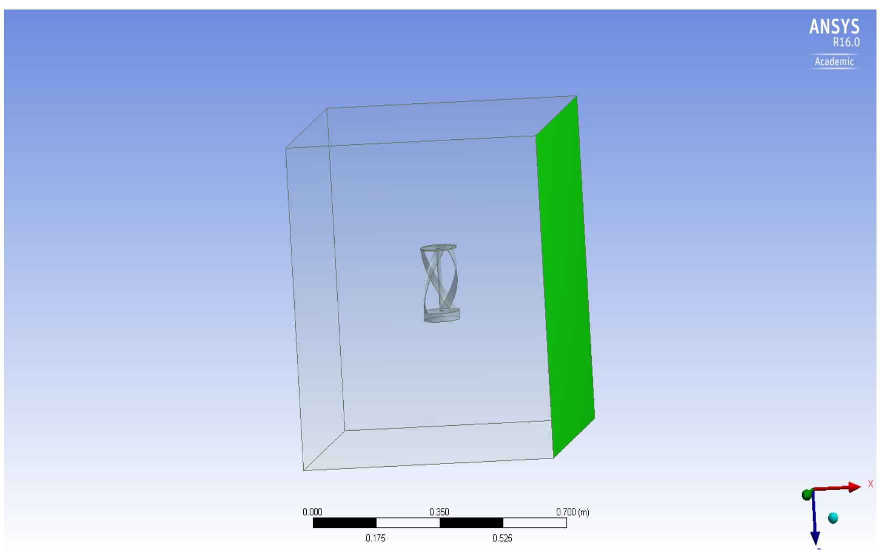


Fig 12. Outlet face of Enclosure

6.1 Mesh

Mehing is very important in simulation where complex 3D geometry are approximated to simple elements on which discretization is carried out. Since the flow quantities like pressure, velocity are continuous in nature, hence the resulting continuity, momentum and energy equations are differential in nature. These second order partial differential equations which are non linear in nature are almost impossible to solve by hand. Hence we discretize these differential equations and calculate the flow parameters like pressure, velocity etc on every iteration until the values have converged.

The mesh has a very important role to play in accuracy, convergence and speed of simulation. The more time it takes to do a meshing, the more accurate the results are produced, hence it is very important to give time in this step. The various types of meshing are tetrahedral, hexahedral, polyhedral etc. The meshing in this work has been done using parallel processing i.e. making use of multiple cores present in the CPU. The number of cores used in this case is 8 which helps is speeding up the whole operation multiple times. The mesh specifications are given in Table 2.

Table 2. Mesh Specifications

Advanced size	Function proximity and curvature
Relevance Center	Fine
Smoothing	Medium
Max size (m)	0.01
Max face size (m)	0.005
Growth rate	1.05

The mesh details are given in Table 3. This work has used 4 different types of meshes with different sizing parameters going from fine to coarse.

Table 3. Mesh Details

Name	Length (m)	Domain Elements
Mesh 0	0.0005	44627
Mesh 1	0.001	25904
Mesh 2	0.002	16411
Mesh 3	0.004	10953

The corresponding mesh in order from fine to coarse around the turbine is shown in Fig 13.

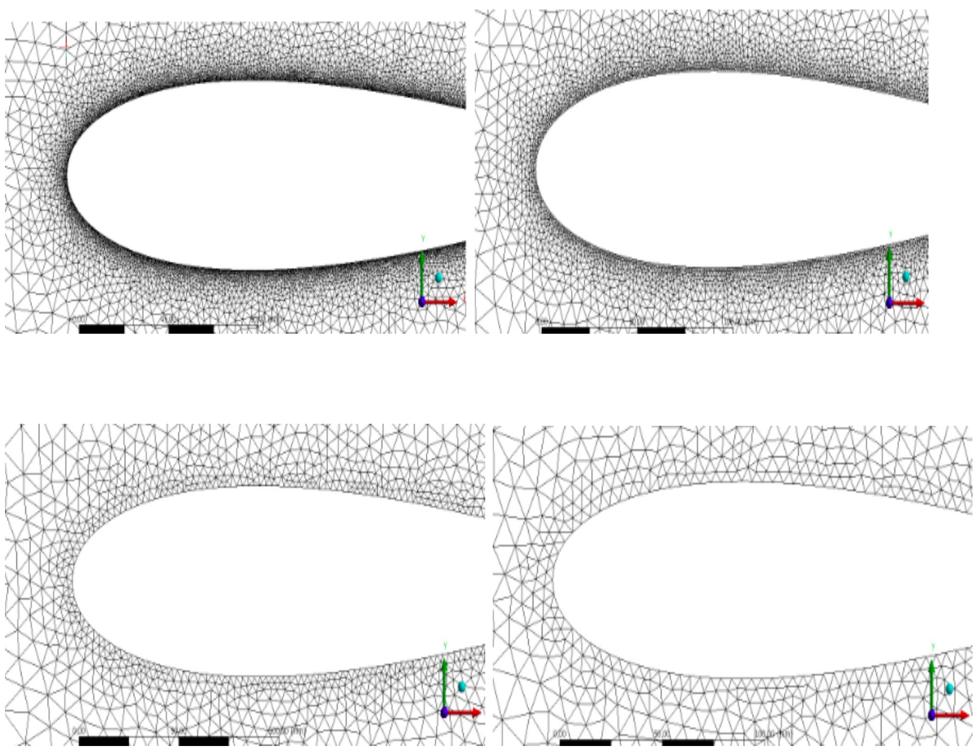


Fig 13. Mesh Discretization Along the Airfoils

This work uses a boundary layer meshing approach which uses the concept that the first layer which is adjacent to the boundary of a surface is finest. As we move away from the boundary, the mesh becomes coarse. In this method, two important parameters to be tuned are first layer thickness and number of rows through which boundary layer meshing will be applied. The first layer thickness as shown in Table 4 is function of chord length of the airfoil.

Table 4. Boundary Layer Parameters of Each Mesh

Mesh	First layer thickness	Number of rows
Coarse	0.001 c	20
Medium	0.0005 c	30
Fine	0.0001 c	50

The mesh domain is shown in Fig 14.

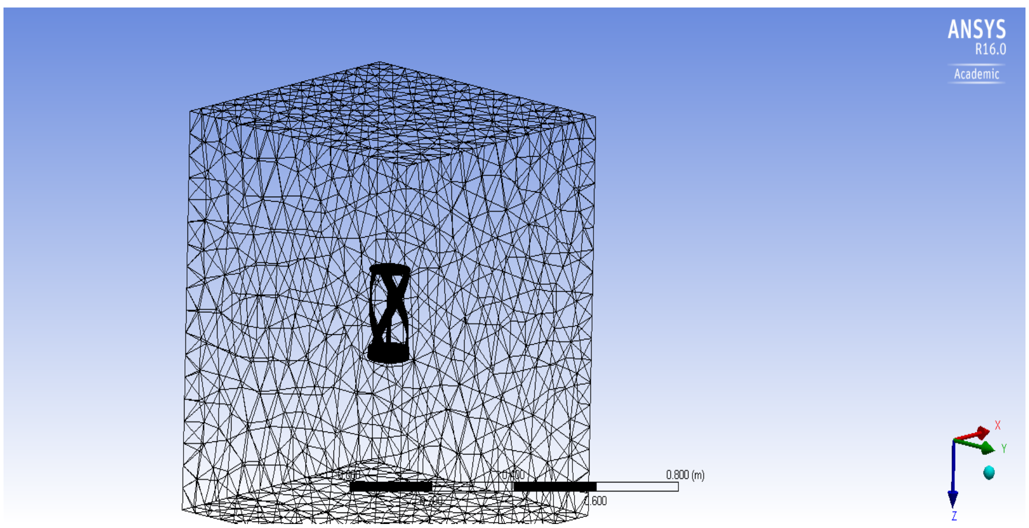


Fig 14. Mesh Domain

The mesh is shown on the vertical axis wind turbine in Fig 15.

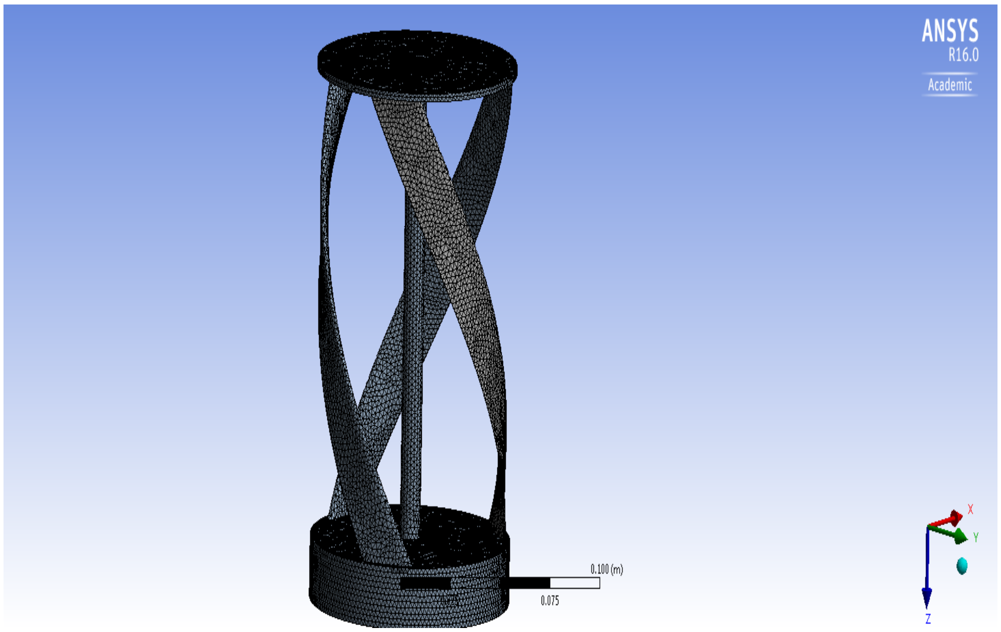


Fig 15. Mesh on Turbine

Meshing is time taking and at the same time very important operation to get better results. While meshing, there is often speed vs accuracy tradeoff involved which means that if we want better results then we need to give enough time to optimize the various parameters, handle interactions like boundaries etc. The more the number of elements and nodes, the greater the accuracy which is generally the trend but this is only applicable till a particular value. After this point an increase in the number of elements, does not affect the accuracy. As a tradeoff the processing time is also increased, as we increase the number of elements which can be taken care of using multiple cores present in the CPU.

6.2 Simulation

After getting satisfied with the mesh, the next step was to simulate the model. The model was transferred to ANSYS simulation. The simulation used parallel processing i.e. using multiple processors to speed up the computation. 8 cores were used for simulation in a steady state. Different types of turbulence models were tried like k- epsilon, k-omega, shear state transport, large eddy scale etc. The best results were obtained with a k-epsilon model with standard wall functions. Most of the simulation parameters and specifications were taken in the default mode. The boundary conditions were given appropriately with velocity inlet at 10 m/s, pressure outlet at net 0 Pa ie atmospheric pressure and no slip wall conditions at other boundaries. The model was initialized in a hybrid state and the simulation was run for 100 iterations.

The specifications which are used for simulation are shown in Table 5.

Table 5. Simulation Specifications in Ansys Fluent

Turbulence Model	SST k-epsilon
Modeling of Rotating Cell Zone	Moving Reference Frame
Pressure-Velocity Coupling Scheme	SIMPLE
Gradient Discretization	Green-Gauss Node Based
Pressure Discretization	PRESTO
Momentum Discretization	First Order Upwind
Turbulent Kinetic Energy (TKE) Discretization	First Order Upwind

The reference values in Fluent while carrying out the simulation is shown in Table 6.

Table 6. Reference Values

Enthalpy	0 joule/kg
Pressure	1 atm at the Velocity Inlet
Density	1 kg/m3
Temperature	288 K
Reynolds number	1.086×10^6
Viscosity	1.8421×10^−5 kg-s/m
Turbulent Kinetic energy	1.5 m2/ s 2
Turbulent dissipation rate	1386 s −1

The simulation is made to run for 100 iterations. The residuals which comprise of the six unknown parameters in Navier Stokes equation are solved in each and every iteration. These values are stored in every iteration and the solution is said to have converged when the difference between two consecutive values is lesser than some threshold. The residuals vs iteration plot is shown in Fig 16.

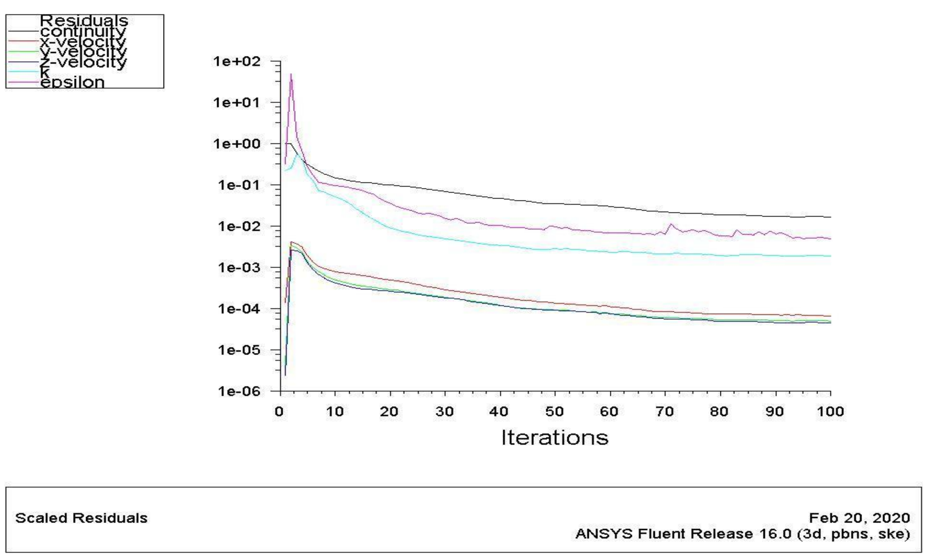


Fig 16. Residuals vs Iteration

The coefficient of drag vs iterations plot is shown in Fig 17.

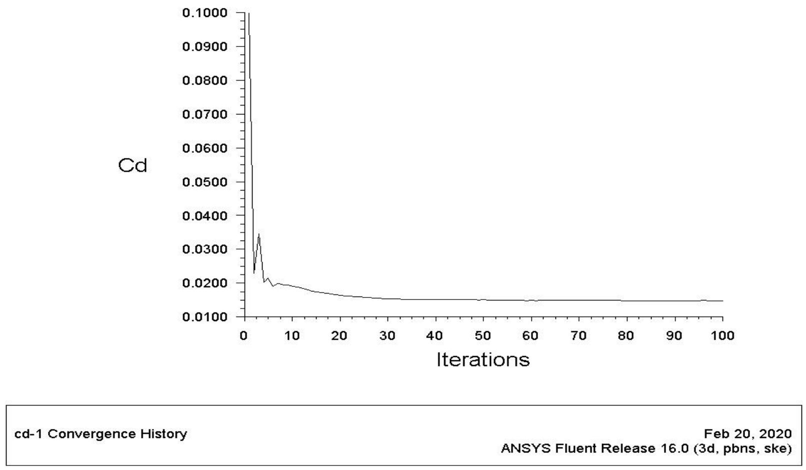


Fig 17. Coefficient of Drag vs Iterations

The coefficient of lift vs iterations plot is shown in Fig 18.

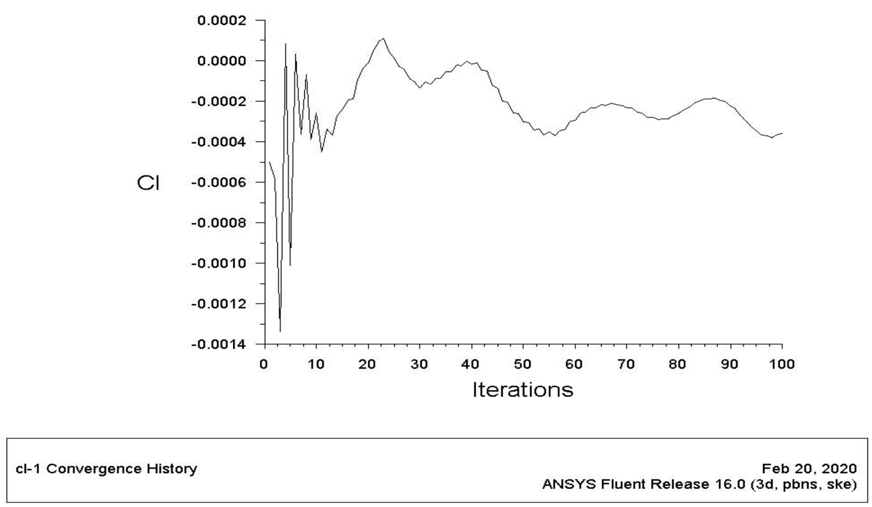


Fig 18. Coefficient of Lift vs Iterations

The simulation was done using different values of boundary conditions i.e. varying the Reynolds number of the flow. The goal was to see if any abrupt changes happen at a very low Reynolds number or at high Reynolds number. There was not any visible change as some of the earlier studies had shown of large wake region creation behind the turbine. The reasoning could be the steady nature of simulation in this work. Also other flow parameters were tested in different rounds to see if any appreciable changes come in results. But again this wasn't the case as some papers have stated due to the addition of randomness to simulation which would probably be the case with carrying out unsteady simulation.

Some of the other simulation parameters used are specified in Table 7.

Table 7. Simulation Parameters

Solver type	Pressure, steady
Turbulence model	K epsilon (2 equation), standard wall function
Material	Solid - Aluminium, fluid - air
Solution method	SIMPLE
Initialization type	Standard

7. Results

7.1 Velocity Vectors

The velocity vectors are useful for studying the flow around the geometry. These can be useful in providing visualization of the flow, areas where velocity of the flow is higher or lower. Further velocity vectors are also important for turbulence modelling and studying wake around the geometry.

The velocity vectors around the turbine as seen from the top is shown in Fig 15.

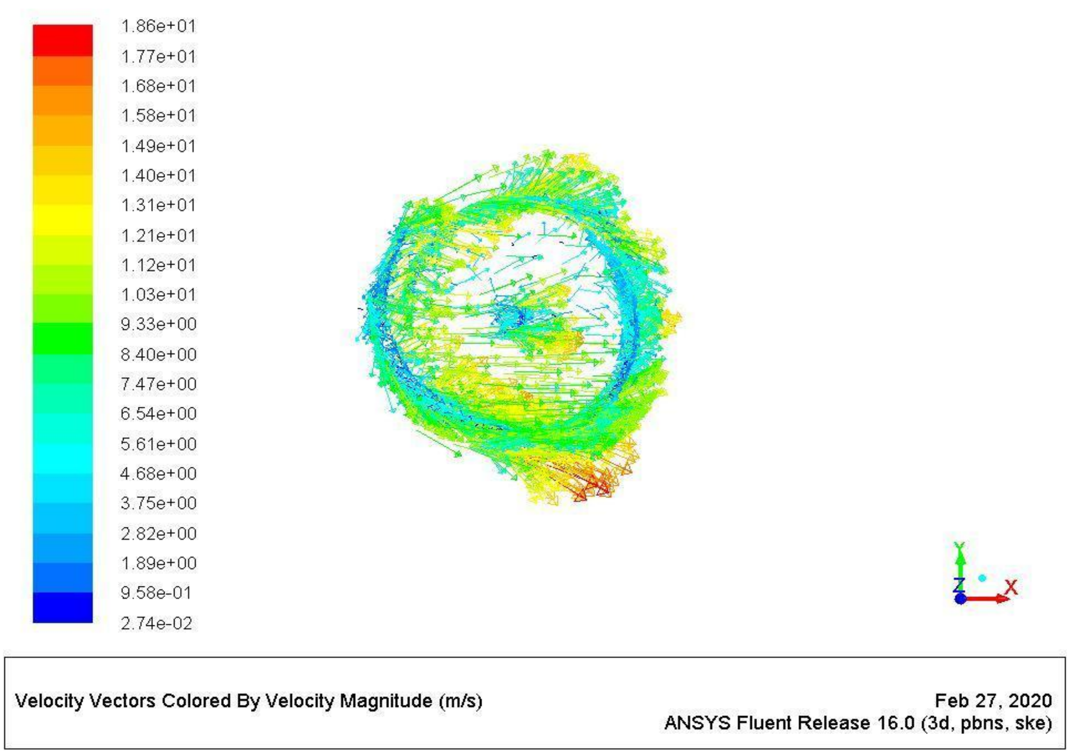


Fig 19. Velocity Vectors

7.2 Pressure contours

Pressure contours are lines of constant magnitude. The plot draws these contours projected off the surface along a reference vector by an amount proportional to the value of the plotted variable at each point on the surface. These contours help us know in advance which parts of the turbine experience higher pressures and the given flow conditions. Using this information, the designer can make appropriate changes to the geometry as required.

The pressure contours on the turbine is shown in Fig 16.

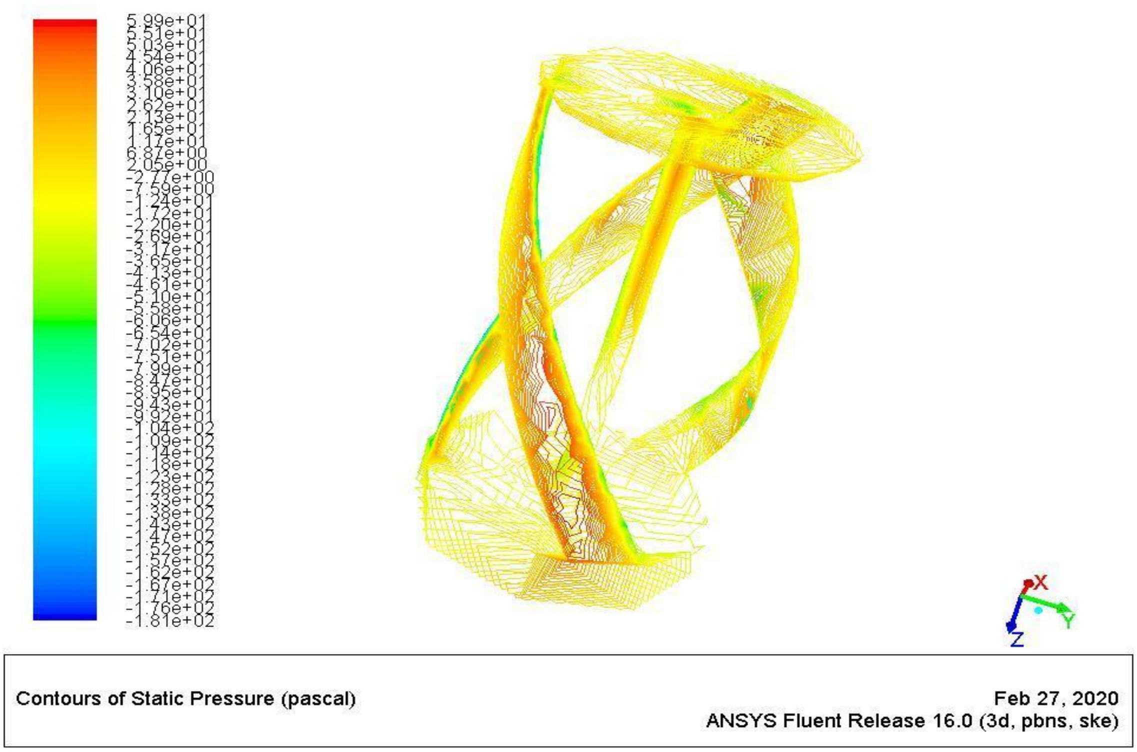


Fig 20. Pressure Contours

7.3 Final Results

For fixed diameter of 0.1m and rotational velocity of 400 rpm, the results are depicted in Table 6. The table shows the moment coefficient variation with various tip speed ratio values. Here tip speed ratio only depends on the velocity of the freestream air as the rotational velocity of the turbine and its diameter is constant. Moment coefficient is calculated by summing the individual moment produced by summing up the lift and drag forces. Torque is calculated from the moment coefficient and hence power output of the turbine is calculated. Finally the power-coefficient is calculated which denotes the efficiency of the turbine.

Table 8. Results

Velocity(m/s)	Tip speed ratio	Moment coefficient	Torque(Nm)	Power(W)	Power coefficient
5	4	0.046	0.001	0.38	0.36
10	2	0.054	0.002	0.83	0.42
15	1.33	0.047	0.006	2.28	0.45
20	1	0.042	0.013	4.08	0.36
25	0.8	0.036	0.018	7.02	0.31

As the tip speed ratio value increases, power coefficient increases till a fixed value which in this case is 1.6 and then decreases from that point onwards. The highest value of power coefficient obtained is 0.45 at a tip speed ratio of 1.6.

As the tip speed ratio value increases, moment coefficient increases till a fixed value which in this case is 2 and then decreases from that point onwards. The highest value of moment coefficient obtained is 0.05 at a tip speed ratio of 2

As the tip speed ratio increases, torque produced by the turbine decreases.

As the tip velocity increases, power produced by the turbine increases.

The power coefficient vs tip speed ratio plot is shown in Fig 21.

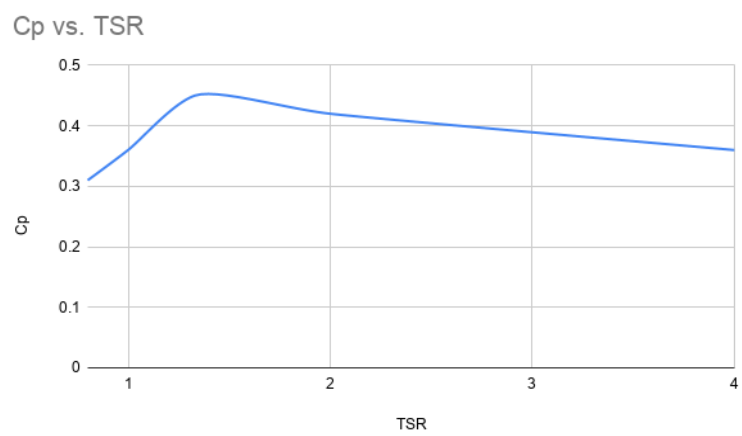


Fig 21. Cp vs TSR

The moment coefficient vs tip speed ratio plot is shown in Fig 22.

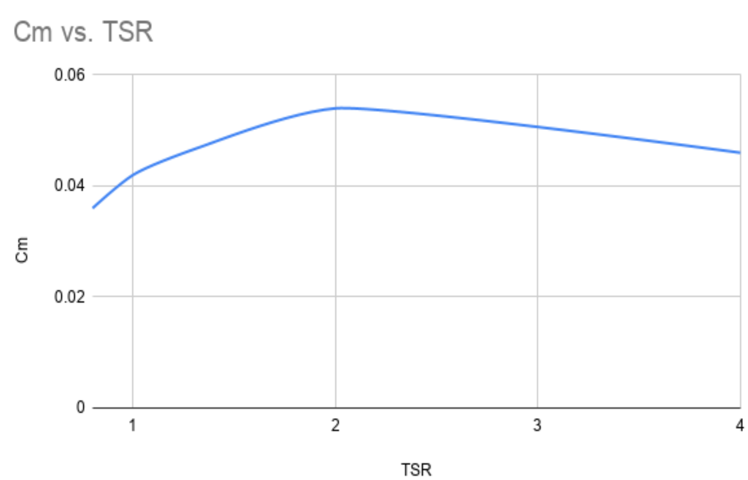


Fig 22. Cm vs TSR

The torque vs tip speed ratio plot is shown in Fig 23.

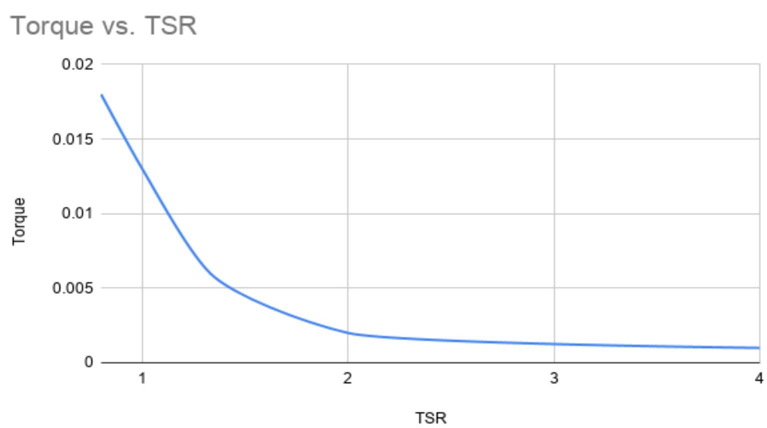


Fig 23. Torque vs TSR

The power produced vs velocity plot is shown in Fig 24.

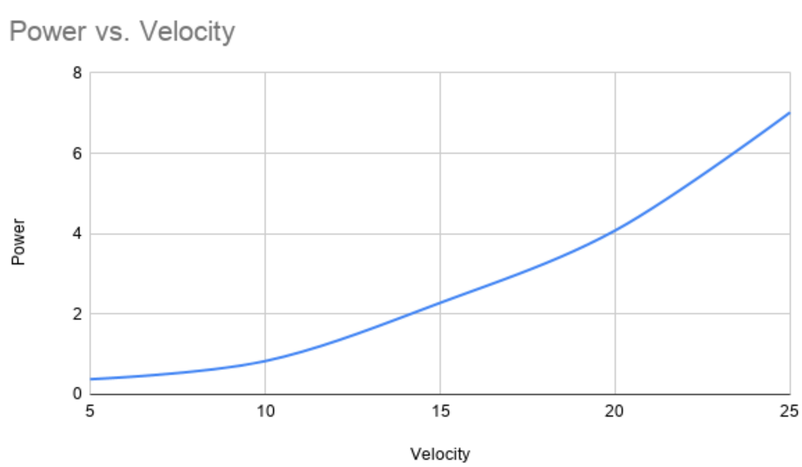


Fig 24. Power vs Velocity

8. Summary

The conclusions are highlighted in the following points:

1. The vectors, contours for velocity, static pressure for the flow around the wind turbine shows the variations. These values can be used for a designer to simulate the results early on thus saving time and cost involved.

2. Tip speed ratio is one of the influential factors on which the power coefficient of a wind turbine depends.

3. For Laminar flow at low Reynolds number power coefficient was found to be low due to the less lift-to-drag ratio value.

4. For a particular range of tip speed ratios, the turbine produces positive power output and for the rest of the values of tip speed ratio it generates negative power. It proves the earlier work done by others that Darrieus type VAWT with fixed blades is unable to start by itself. Hence it is necessary to rotate the turbine with the help of an external power source.

5. The major problem with VAWT is the negative power coefficient at low tip speed ratios. A positive power coefficient shows that the turbine is able to rotate independently and produce power, whereas a negative power coefficient means the turbine needs extra power to be able to rotate.

6. The power produced of the wind turbine can be calculated using torque calculated numerically. Torque is the sum of torque produced by both lift and drag forces. Finally the power-coefficient of the turbine can be calculated which gives us the measure of the efficiency of the wind turbine.

8.1 Future Ideas

To finish, here are some of the future work ideas that can be used to improve the current study -

1. Turbines with both two blades and more than three blades can be simulated. The power output can be compared with the present work and it would be interesting to see which turbines are more efficient for a particular tip speed ratio value.

2. Alternative design choices can be used like changing the geometrical dimensions of the parts involved, airfoil choice, use of flaps, spoilers etc on airfoil. A lot of similar work has been done with great success for airplane blades and it will be interesting to see if similar positive results are seen in the case of wind turbines.

3. The turbine can be scaled up to get higher power values, in the order of 1-5 kW. It's important to make a bigger model and see the performance to check if a vertical axis wind turbine is feasible for scalability.

As a conclusion, CFD modelling for vertical axis wind turbines seems to be a perfect alternative to the traditional wind tunnel testing approach which requires making a physical model. This would not only reduce the labour and cost involved but also boost up the productivity.

9. References

1. A. A. J. Arturo, G. Muñoz. and B. F. Manuel, “Experimental and numerical analysis of vertical axial wind turbines applying the dynamic mesh method”, ASME 5t International Conference on energy sustainability, August, 2011, Washington, DC, USA, pp 7-10.

2. Huimin Wanga, Jianliang Wanga, Ji Yaoa, Weibin Yuanb, Liang Caoa, “Analysis on the Aerodynamic Performance of Vertical Axis Wind Turbine Subjected to the Change of Wind Velocity” Procedia Engineering, vol. 31, 2012, pp. 213 – 219.

3. Fluent tutorial no.5, "Modeling compressible flow over an airfoil", Fluent Inc. 2007
M.F.White, "Fluid mechanics", pag. 467, Ed. McGraw-hill, ISBN 9780072831801

4. Tang, J., Viieru, D. and Shyy, W., “A Study of Aerodynamic of Low Reynolds Number Flexible Airfoils”, 37th AIAA Fluid Dynamics Conference and Exhibit, 2007, Florida.
Marini, M., Massardo, A. and Satta, A., “Performances of Vertical Axis Wind Turbines With Different Shapes”, Journal of Wind Engineering and Industrial Aerodynamics, 1992, Vol. 39, pp. 83-93

5. Islam, M., Ting, D. SK., and Fartaj, A., “Aerodynamic Models for Darrieustype Straight-Bladed Vertical Axis Wind Turbines”, Renewable and Sustainable Energy Reviews, 2006, Vol. 12, pp. 1087-1109.

6. Cetin, N. S., Yurdusev, R. A., and Ozdemir, A., “Assessment of Optimum Tip

7. Speed Ratio of Wind Turbines”, Mathematical and Computational Applications, 2005, Vol. 10.

8. Cetin, N. S., Yurdusev, R. A., and Ozdemir, A., “Assessment of Optimum Tip Speed Ratio of Wind Turbines”, Mathematical and Computational Applications, 2005, Vol. 10, pp. 147-154.

9. Chen, W. and Zhou, C. Y., “Application of Numerical Simulation to Obtain the Optimization Pitch Angle for VAWT”, IEEE, 2009, pp. 4244-4702.

10. Guerri, O., Sakout A. and Bouhadef, K., “Simulations of the Fluid Flow Around a Rotating Vertical Axis Wind Turbine”, Wind Engineering, 2007, Vol. 31, pp. 149-163.

11. ANSYS FLUENT 12.0.16 manual, 2009.

12. Tang, J., Viieru, D. and Shyy, W., “A Study of Aerodynamic of Low Reynolds Number Flexible Airfoils”, 37th AIAA Fluid Dynamics Conference and Exhibit, 2007, Florida.

13. Marini, M., Massardo, A. and Satta, A., “Performances of Vertical Axis Wind Turbines With Different Shapes”, Journal of Wind Engineering and Industrial Aerodynamics, 1992, Vol. 39, pp. 83-93.

14. Islam, M., Ting, D. SK., and Fartaj, A., “Aerodynamic Models for Darrieustype Straight-Bladed Vertical Axis Wind Turbines”, Renewable and Sustainable Energy Reviews, 2006, Vol. 12, pp. 1087-1109.

15. Howell, R., Qin, N., Edwards, J. and Durrani, N., “Wind Tunnel and Numerical Study of a Small Vertical Axis Wind Turbine”, Renewable Energy, 2009, Vol. 35, pp. 412-422.

16. Guerri, O., Sakout A. and Bouhadef, K., “Simulations of the Fluid Flow Around a Rotating Vertical Axis Wind Turbine”, Wind Engineering, 2007, Vol. 31, pp. 149-163.

17. V. Kevat B. Patel. Performance prediction of straight bladed darrieus wind turbine by single streamtube model. International Journal of Advanced Engineering Technology, 2013.

18. D.C. Wilcox. Turbulence Modeling for CFD. DCW Industries, 2nd edition, 1994.

19. M. Messina R. Lanzafame, S. Mauro. 2d cfd modeling of h-darrieus wind turbines using a transition turbulence model. Energy Procedia, 45:131–140, 2014.

20. E. Benini M.R. Castelli, A. Englaro. The darrieus wind turbine: Proposal for a new performance prediction model based on cfd. Energy, 36:4919–4934, 2011.

21. J. Kjellin, F. B¨ulow, S. Eriksson, P. Deglaire, M. Leijon, and H. Bernhoff. Power coefficient measurement on a 12 kw straight bladed vertical axis wind turbine. Renewable Energy, 36, 2011.

22. R. Howell, N. Qin, J. Edwards, and N. Durrani. Wind tunnel and numerical study of a small vertical axis wind turbine. Renewable Energy, 35:412–422, 2010.

23. Sabaeifard P.,Razzaghi H., Forouzandeh A. Determination of Vertical Axis Wind Turbines Optimal Configuration through CFD Simulations. 2012 International Conference on Future Environment and Energy IPCBEE vol.28.

24. Mazharul Islam etal (2008), "Aerodynamic models for Darrieus-type straight-bladed vertical axis wind turbines", Renewable and sustainable Energy Reviews, Vol. 12,pp-1087-1109.

25. Ghosh, A., Biswas, A., Sharma, K. K., & Gupta, R. (2015). Computational analysis of flow physics of a combined three bladed Darrieus Savonius wind rotor. Journal of the Energy Institute, 88(4), 425–437.

26. Huimin Wanga, Jianliang Wanga, Ji Yaoa, Weibin Yuanb, Liang Caoa, "Analysis on the Aerodynamic Performance of Vertical Axis Wind Turbine Subjected to the Change of Wind Velocity" Procedia Engineering, vol. 31, 2012, pp. 213 – 219.

27. S. Rolland, W. Newton, A.J. Williams, T.N. Croft, D.T. Gethin, M. Cross, "Simulations Technique for the Design of Vertical Axis Wind Turbine Device with Experimental Validation", Applied Energy vol. 111, 2013, pp. 1195–1203.

28. A. A. J. Arturo, G. Muñoz. and B. F. Manuel, "Experimental and numerical analysis of vertical axial wind turbine applying the dynamic mesh method", ASME 5t International Conference on energy sustainability, August, 2011, Washington, DC, USA, pp 7-10.

29. A. M. Biadgo, A. Simonovic, D. Komarov and S. Stupar, "Numerical and Analytical Investigation of Vertical Axis Wind Turbine", FME Transactions, vol. 41, 2013, pp 49-58.

30. Izli, N. A. Vardar and F. Kurtulmn, "A Study on aerodynamic properties of some NACA profiles used on wind turbine blades". Applied Sci., vol. 7, 2007, pp. 426-433.

31. S. Mathew, Wind Energy Fundamentals Resource, Springer, Analysis and Economic, 1st ed., 2006.

32. Tu J, Yeoh GH, Liu C. Computational fluid dynamics: a practical approach. India: Elsevier India Private Limited; 978-81-312-16 85-9.

33. Castelli R.C., Englaro A. and Benini E., 0 , “The Darrieus Wind Turbine: Proposal for a New Performance Prediction Model Based on CFD”, Energy, 6, pp.4919-4934

34. Graham H.Z.,Panther C.,Hubbel M.,Wilhelm J.,Angle J.M. and Smith J.E.,2009, “Airfoil Selection for a Straight Bladed Circulation Controlled Vertical Axis Wind Turbine”, Proceedings of the ASME 009 rd International Conference of Energy Sustainability, San Francisco,USA, July 19-23

35. Islam M., 00 , “Analysis of Fixed-Pitch Straight-Bladed VAWT with Asymmetric Airfoils”, Ph.D. Thesis, University of Windsor, Ontario, Canada

36. Howell R., Qin N., Edwards J. and Durrani N., 0 0, ”Wind Tunnel and Numerical Study of a Small Vertical Axis Wind Turbine”, Renewable Energy, 5, pp.412-422

37. Castelli M.R., De Betta S. and Benini E., 0 , “Effect of Blade Number on a Straight Bladed Vertical Axis Darrieus Wind Turbine”, World Academy of ScienceEngineering and Technology, 61, pp. 305-311

38. Biadgo A.M.,Simonovic A.,Komarov D. and Stupar S., 0 ,”Numerical and Analytical Investigation of Vertical Axis Wind Turbine”, FME Transactions, 4 , pp.49-58

39. Dumitrescu H. and Cardos V., 009,”A Free Wake Method for Vertical Axis Wind Turbine Performance Prediction”, Roum. Sci. Techn. – Méc. Appl., Tome 54, No 2, P. 87–100

40. Islam M., David S.,Ting K. and Fartaj A., 006,”Aerodynamic Models for Darrieus Type Straight Bladed Vertical Axis Wind Turbines” , Renewable and Sustainable Energy Reviews, Vol.12, pp. 1086-1109

41. Ponta F.L. and Jacovkis P.M., 00 , “A vortex model for Darrieus turbine using finite element techniques”, Renew Energy, 4: –18

42. Goude A., 0 ,”Fluid Mechanics of Vertical Axis Turbines: Simulations and Model Development”, Acta Universitatis Upsaliensis

POSTER

Modelling of Vertical Axis Wind Turbine

Abhinav Sagar| 16BME0903 | Prof Jayaprakash Narayan | SMEC

Motivation/ Introduction

Since fossil fuels are limited in nature, we need alternative options for the future. Wind energy could be the next big thing for the future considering it is unlimited in nature, works 24/7, and is an easy and clean source of energy. However it has its own set of challenges like instability as wind speed fluctuates throughout the day and across seasons, required constant maintenance and monitoring of internal components, blades etc, expensive installation and maintenance and low efficiency.

Scope of the Project

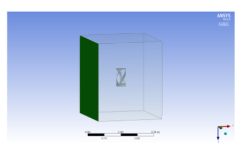
The following steps are involved:

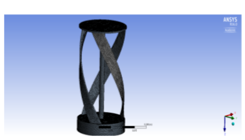
1. 3D numerical simulation of the flow around the designed vertical axis wind turbine to investigate its aerodynamic performance.
2. To study the effect of tip speed ratio on pressure coefficient, moment coefficient, torque produced and power produced.
3. Calculate the power coefficient numerically of the designed wind turbine.

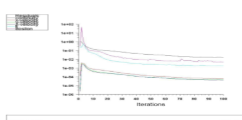
Methodology

1. Make the individual parts including shaft, blades and end plates in AutoCAD.
2. Mate the parts to make the 3D CAD model for vertical axis wind turbines in AutoCad.
3. To mesh the model appropriately using the inflation and boundary layer meshing.
4. Carry out numerical simulation of the flow around the designed vertical axis wind turbine to investigate its aerodynamic performance.
5. Plot the vectors, contours and pathlines for velocity, static pressure and turbulent kinetic energy for the flow around the wind turbine.
6. Plot the x-y graph for tip speed ratio vs pressure coefficient, tip speed ratio vs moment coefficient, tip speed ratiovs torque produced and velocity vs power produced.
7. Calculate the power coefficient of the wind turbine.

The following figures shows the CAD model, flow domain, mesh and residuals plot respectively.

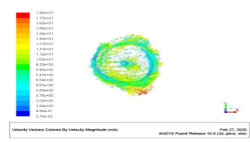


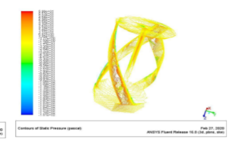


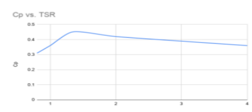


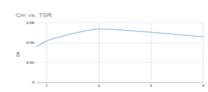
Results

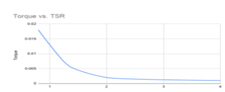
The followind diagrams show velocity vectors, pressure contours, tip speed ratio vs power co-offecient, tip speed ratio vs moment co-offecient, torque vs tip speed ratio and power vs velocity plots respectively.

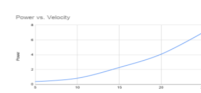












Conclusion/ Summary

1. The vectors, contours for velocity, static pressure for the flow around the wind turbine shows the variations. These values can be used for a designer to simulate the results early on thus saving time and cost involved.

2. Tip speed ratio is one of the influential factors on which the power coefficient of a wind turbine depends.

3. The power produced of the wind turbine can be calculated using torque calculated numerically. Torque is the sum of torque produced by both lift and drag forces. Finally power-coefficient of the turbine can be calculated which measures the efficiency of the wind turbine.

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Acknowledgments/ References

1. V. Kevat B. Patel. Performance prediction of straight bladed darrieus wind turbine by single streamtube model. International Journal of Advanced Engineering Technology, 2013.
2. Biadgo A.M.,Simonovic A.,Komarov D. and Stupar S., 0 ,"Numerical and Analytical Investigation of Vertical Axis Wind Turbine", FME Transactions, 4 , pp.49-58