Vertical Axis Wind Turbine for Low Wind Speed Corridors

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ABSTRACT

As it is well understood that utilizing crude oil or coal for electricity production has adverse effect on environment, due to excess emission of greenhouse gasses. Wind power is one of the most favorable solution for the production of energy as it has least effect when compared with other sources of renewable energy. Wind power generation has so far preferred the multi-megawatt horizontal axis wind turbine (HAWT) over the vertical axis wind turbine (VAWT) technology. Main benefits of the VAWT technology are: (a) Omni-directional operation, which is independent of the directional changes in the wind, (b) heavy components such as the electric generator installed close to the ground, (c) simple design, less manufacturing and maintenance costs, (d) small operating space requirement (high farm power density), and (e) low environmental impact and noise signature. These properties support the application of VAWT in urban environments. However, the VAWT characterizes lower power coefficient C_P compared to the HAWT owing to the presence of dynamic stall and associated blade-wake interaction induced vibrations.

Generally, wind turbines are designed at rated wind speeds of 10-12 m/s. However, for low wind speed corridors such as those in Pakistan, maximum wind speeds of 7-8 m/s are available. For such low wind speeds, a turbine has to be significantly large compared to the ones made for higher wind speed. In addition, a small-scale application will also incur low Reynolds number effects. The current study is therefore focused on designing a VAWT rotor for low wind speeds of 7-8 m/s by considering a number of design variables and parameters.

The double multiple stream tube (DMST) method, the most reliable of all stream tube models is utilized to design the VAWT rotor. The DMST model is coupled to an optimizer in order to obtain optimum rotor geometry for low wind speeds. The chord length, rotor radius and number of blades collectively affects the performance when varied. An optimal selection of different design variables can lead to a smaller yet effective VAWT rotor design in terms of performance. Finally, the results obtain from DMST model are validated with CFD using ANSYS 15.

Key words:

Darrieus, Vertical Axis Wind Turbine (VAWT), Wind turbine, Double Multiple Stream Tube Method (DMST), Computational Fluid Dynamics (CFD).

Symbols

c	chord length [mm]
T	Torque
C_{Tb}	Blade torque coefficient
C_T	Torque coefficient
C_d	drag coefficient [-]
C_l	lift coefficient [-]
C_P	power coefficient [-]
d_w	wakes length
t_c	thickness
P	power [W]
N_b	Number of blades
Fx	component of Force in the direction of flow
u_∞	free stream velocity [m s-1]
$y+$	Non-dimensional distance [-]
α	angle of attack [deg]
θ	azimuthal angle [deg]
ω	angular velocity [min-1]
A	Swept Area
u_r	Relative Velocity
σ	Solidity
$\boldsymbol{\lambda}$	Tip speed ratio
Re	Reynolds number
Δt	Time step size

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GLOSSARY

Blade Pitch	Angle between chord of airfoil and direction in which blade travels.
Drag	During operation, the force exerted on blade by moving air.
H-Rotor	A Vertical Axis Wind Turbine usually with straight blades.
HAWT	Horizontal Axis Wind Turbine.
Angle of Attack (α)	Angle between blade chord and relative wind.
Leading Edge	the end of the blade that is towards the direction of rotation
Lift	The force applied by coming air on asymmetrically-shaped wind generator blades at right angles to the direction of relative movement.
Rotor	The blade, hub and connecting assembly of a wind generator.
Shaft	The middle rotating part at the center of a wind generator or motor that transfers power.
Trailing Edge	The end of the blade away from direction of rotation.
TSR	Tip Speed Ratio. The ratio of blade speed to the free wind speed.
Undisturbed Wind	That wind which occurs freely in nature.
VAWT	Vertical Axis Wind Turbine
Variable Pitch	A type of A rotor angle of attack can be attuned either automatically or manually.
Vertical Axis Wind Turbine	wind turbine shaft is perpendicular to free wind direction.
Yaw	Mechanism where the direction of rotor is adjusted to the wind.
DMST	Double Multiple Stream Tube Model

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LIST OF PUBLICATIONS

- **Naseer Ahmed Khan,** Ali Abdullah, Dr Adeel Javed, “Vertical Axis Wind Turbine for Low Wind Speed Corridors” 1st International Conference 2018 on High Performance Energy Efficient Building & Homes HPEEBH 2018, held on 1 August 2018 at University of Engineering and Technology, Lahore.

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Chapter # 1

INTRODUCTION TO WIND ENERGY

1.1 Introduction

The need of continuous, reliable and clean energy is one the ultimate challenges in the modern world. Presently most of the world's energy requirement is being fulfilled by resources utilizing the crude oil (fossil fuels). The energy production using these fossil fuels is costly and CO_2 emissions associated with these fuels is causing environmental concerns. On the other hand, the usage of these fuels at such a large scale has increase the depletion rate of resources of these fuels. Annual production of fossil fuel has been continuously decreasing form last decade. Therefore, falloff of greenhouse gases emissions and replacement of fossil fuel-based energy sources with sustainable and renewable energy sources has been need of hour. The need for a sustainable and efficient source of renewable energy is highly in demand, especially for developing countries. As these renewable energy resources are everywhere to be utilized, therefore, recent year have seen

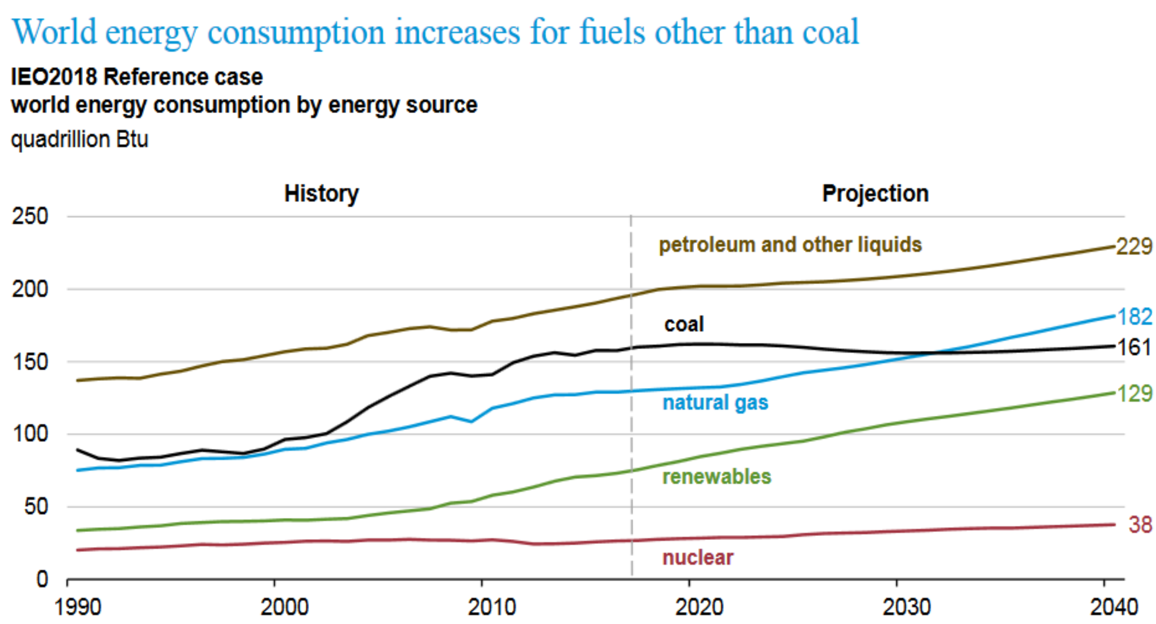

Figure 1 world energy Consumption EIA [2]

more interest in developing these resources. There are, number of renewable energy resources can be exploited, such as solar, wind, geothermal, hydro, biomass and tidal.

Among these renewable energy resources, the wind energy can be termed as the cleanest, reliable and cost-effective resource. Wind energy is often compared to solar energy. But one of interesting feature of wind energy compared to solar energy is its availability during all times of the day. Therefore, wind energy shows enormous potential as a sustainable solution. Moreover, its production has grown tremendously in recent years. In UK, 10 GWh of energy was produced from wind alone in the year 2010. In China, the wind energy has become the third largest contributor to energy mix. Therefore, these international trends show glimpse of a brighter future of wind energy.

Wind is basically the result of fluctuation in the atmospheric pressure. When there is a difference in atmospheric pressure, air will move from the higher to the lower pressure area, thus resulting in winds of various speeds. Moreover, wind is basically tons of air moving around the earth's surface in different direction. For the first time wind was used to sail boats to explore other areas of the world. Later on, wind mills were invented to extract energy from the wind and used it for pumping water and smashing wheat [1].

U.S Energy Information Administration (EIA's) report shows the worldwide energy consumption in Figure 1. According to this report, as readers can see most of the worldwide energy comes from crude oil and coal [2]. On the other hand, many countries including Denmark are planning to switch 100% of their energy supply to renewable sources till 2050 [3]. The goal of this work is to contribute to the renewable energy research for production of clean energy.

1.2 Wind Energy in Pakistan

Electric power is a basic human necessity in the modern-day world. However, Pakistan is facing vast challenges in the energy sector. For instance, the electricity shortfall has terribly stalled the economy and everyday life in the last decade or so. In addition, one third of Pakistan's population lives in the rural areas that does not have access to electricity at all. The principal supply of our energy comprises of fossil fuels costing billions of US dollars in oil import bills every year. These fuels contribute to about 85% of the total electricity supply of the country, while coal, nuclear and hydroelectric resources account for only 4.5%, 1.1% and 9.2% of contribution, respectively [4]. Nonetheless, Pakistan is globally positioned in a rich renewable energy corridor with one of the highest solar irradiance, wind and hydro power potential in the world. This energy potential has to be exploited to the fullest in the coming years for human development and economic progress of the country.

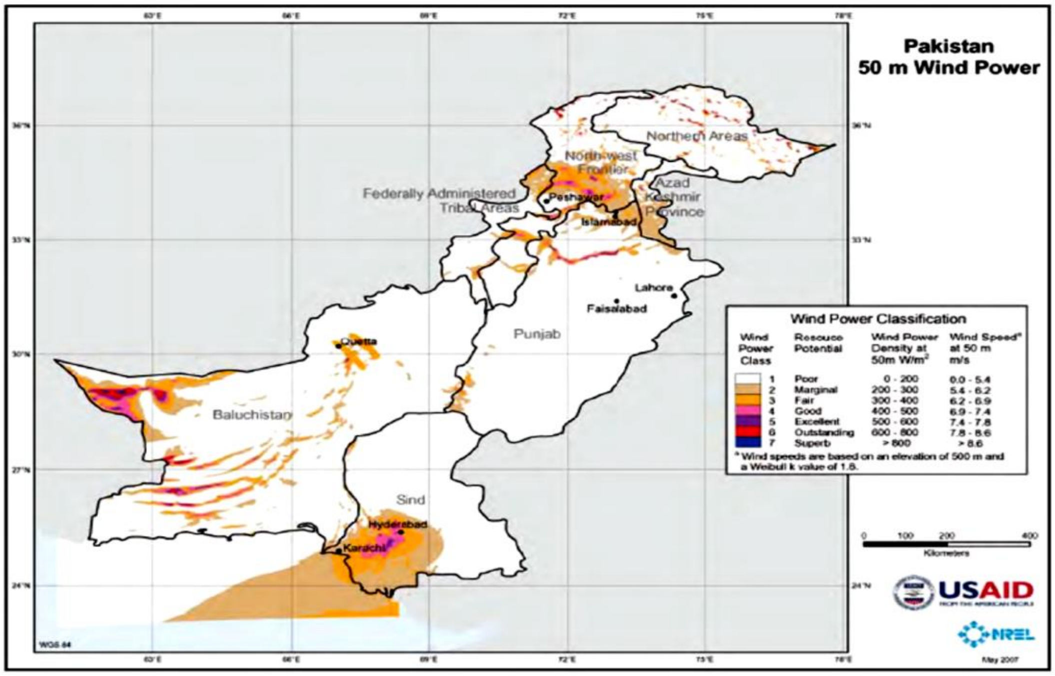

Figure 2 National renewable energy laboratory (NARL) wind survey map [5]

Considering the wind energy potential, up to 130 GW of electricity can be generated across Pakistan from wind alone [5]. The potential wind corridors are situated mainly at the coast lines of Sindh province's, northern Punjab and Khyber Pakhtunkhwa (KPK) province, and eastern Balochistan as illustrated in Fig. 2. The average wind speeds shown in Fig. 2 were recorded in the mapping range of 7-8 m/s. This kind of potential supports the installation of both small-scale and large-scale wind turbine units. Many projects are already underway to extract this 20 GW of wind energy potential from the Sindh province using large-scale HAWT units. The flat lands in Sindh supports large-scale wind farms for power generation. On the small-scale i.e., smaller and decentralized wind power generation, no effort is being made so far. The northern Punjab and KPK sites, especially, can benefit from the small-scale VAWT units due to the hilly landscape where HAWT units can be difficult and costly to install and maintain. Because of the case in mobility and maintenance, the VAWT can also be installed in unconventional sites such as urban area buildings and highways/motorways of Pakistan. A study of VAWT design and characteristics along with unconventional installation on different sites is, therefore, desirable.

1.3 Wind Turbines

The two main types of turbine used to harness wind energy into other form of energy most notably electrical energy is, a) Horizontal Axis wind turbine and, b) vertical axis wind turbine as shown in figure 3. Much of the work is done on horizontal axis wind turbine but due to high maintenance and manufacturing cost, in addition to more complex design, vertical axis wind turbine has been the focus of research for many scientists.

Wind turbines are devices that are basically used for electricity generation using wind as source of Energy. The working principle of these turbine is to transfer the momentum in the wind to the wind turbine blades. The rotor in-turn is attached to some gearing system that is coupled with an electrical energy generator. Some wind turbine which operates in closed circuits, for low power requirement might use DC generator coupled directly to rotor.

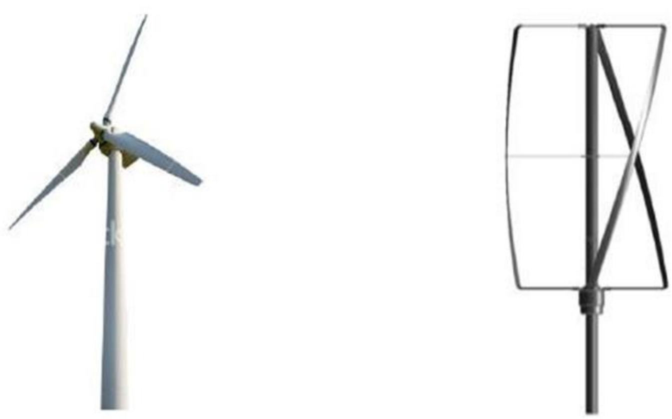

Figure 3 HAWT (left) and VAWT (right**)**

Small-scale wind turbines are being developed (rated power outputs <50 kW) for decentralized power generation. For small-scale applications, VAWT offers a practical option due to its Omni-directional operation and relatively easy installation and maintenance. A comprehensive review on the VAWT technology has been presented in ref. [6, 7]. The strong blade-wake interactions and the dynamic vortex shedding together with the vibrations caused by these aerodynamic factors increases the complexity of the VAWT design for aerodynamic and structural designers. Nonetheless, the complexity of VAWT operation also provides an opportunity for advance research and development in order to increase the energy output from the available wind corridor.

In this regard, different methods to enhance the VAWT rotor aerodynamic characteristics have been highlighted in ref. [8-11]. Studies have also shown that a number of VAWT when operated in close proximity can aerodynamically supplement each other resulting in a superior synergic performance and power density [10, 11]. Couples of co-rotating and counter-rotating VAWT has resulted in generating more power (between 50 and 100% of power augmentation) compared to a lonely VAWT by taking assistance of the beneficial induced velocity field [12]. Such an arrangement of multiple wind turbines would be advantageous for limited area urban population.

Momentum models are extensively applied in the aerodynamic calculation of Darrieus VAWTs. Moreover, there are three momentum models used, although all are based on the same principle, i.e. to calculate flow velocities passing through a turbine by calculating the stream wise aerodynamic force on the blades, with the variation in rate of air momentum based on momentum models [13]. This work mainly employs Double Multiple Stream-tube Model which is one of the momentum models used vastly to predict the performance of Vertical Axis Wind Turbine (VAWT), that will be suitable for low wind speed corridors where wind speed is not more 7-8 m/s.

1.4 Power Coefficient/Turbine Efficiency:

The maximum power coefficient (C_p) that a turbine can attain is defined by Betz limit as,

$$C_P = \frac{P_{max}}{\frac{1}{2}\,\varrho\, A\, U_\infty^3} = \frac{16}{27} = 0.593$$

This result is achieved by using continuity, momentum and energy conservation in any type of turbine. If any simulation model gives value which is higher than Betz limit, it is certainly wrong. The characteristic power coefficient outputs of different wind turbines against their tip-speed ratios are shown in fig.4. The ideal maximum is the Betz limit.

The figure clearly shows that high speed propellers leads all other wind turbine in term of efficiency. This is the reason that much of the research so far has been carried out on Horizontal axis wind turbine or high-speed propeller, but the advantages of vertical axis wind turbine on accounts of maintenance and operating cost compel researcher to work on VAWT and improve its efficiency. Moreover, horizontal axis wind turbine is not favorable in urban installation due to their operation at high TSR’s which might affect the surrounding by its noise. So, efforts are being done on wind turbines which will be favorable for urban installation such as vertical axis turbines.

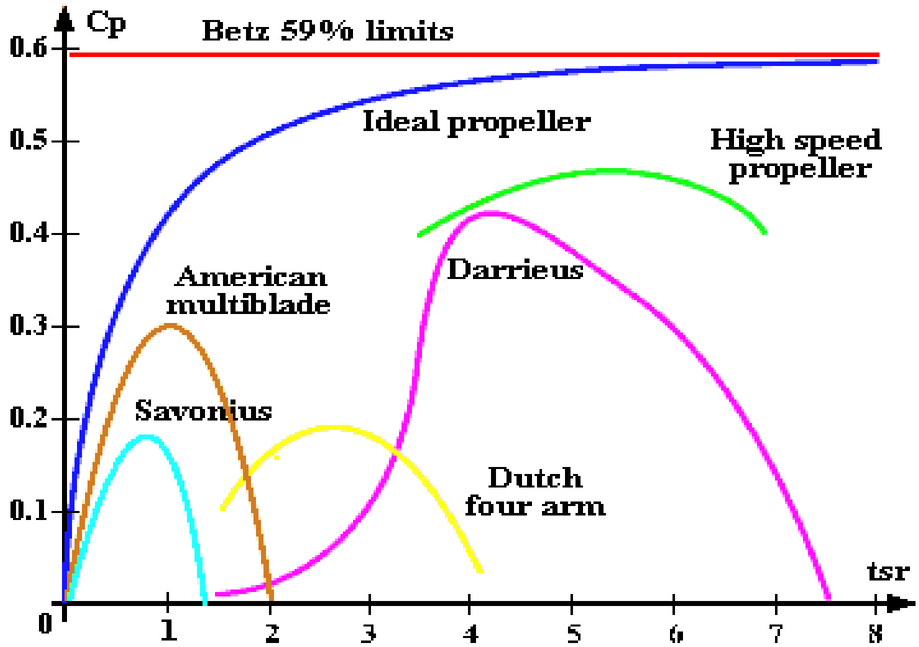

Figure 4 Power coefficient vs. TSR of different wind

1.5 Research Scheme:

The scheme of this research is shown in figure 5. The baseline geometry of VAWT which is being provided by the industrial collaborator is given as an input to Double Multiple Stream Tube Model code. The turbine data is further checked for sensitivity analysis, in order to analyze the factors

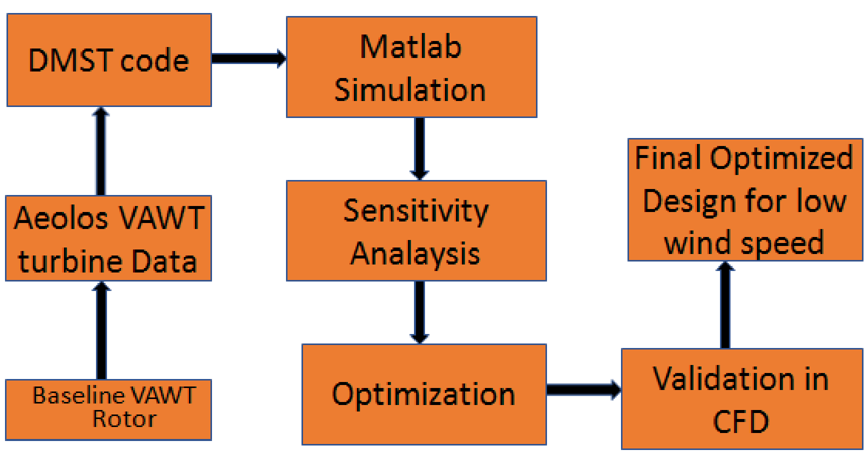

Figure 5 Research Scheme

that will influence the performance of the turbine (VAWT). The design is improved in MATLAB and then validated for low wind speeds using CFD.

1.6 Applications of wind Energy:

Currently the alarming rate of bi-products produced by fossil fuel and its impact on environment has made adverse changes to natural cycles. It's obvious to fetch alternative clean energy sources in an effort to reduce greenhouse gas emissions. Harnessing energy from the wind is not a farfetched idea. Wind turbines are suitable for producing energy at locations that are far from power grid, such as small cottages that need an alternative or back up energy sources. There are locations on Earth where extreme weather makes it unfeasible to transport fuel. Although a general perception is that wind energy can only be used for small scale applications however it is quite the opposite. Large wind farms are an alternative means of providing power to a large grid. There are a lot of unused land area that can be utilized for wind farm generation such as Canada, countries from Scandinavia, Pakistan. This can be seen currently in Atlantic Canada, with wind farms in both Prince Edward Island and Nova Scotia and in Pakistan where wind turbines are installed in Jhimpir. Wind energy can be used anywhere there is wind, and there are no harmful by products associated with this technology.

1.7 Summary:

This chapter gives an introduction to wind energy as well as types of wind turbines are discussed. The need of harnessing wind energy is necessity of the present time as the adverse environmental changes are threatening the existing of human beings. Pakistan wind potential is 130GW which is huge in terms of Pakistan total consumption of energy. Moreover, two main types of wind turbines are discussed and vertical axis wind turbine is selected for the research as it has less maintenance and operating cost along with other added advantages discussed. The amount of power extraction from wind turbine is not more than Betz limit of 59%. Research has been carried out by first validating the performance of baseline geometry provided by AEOLOS PVT. limited an industrial collaborator, then sensitivity analysis has been done followed by optimization of the baseline geometry and its validation in CFD (ANSYS 15). Wind energy can be utilized in those areas where transportation of fuel is problem in extreme weather such as hilly areas or unconventional sites.

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Chapter # 2
LITERATURE REVIEW

2.1 Background

Wind energy is one of the clean sources of energy. Two main types of turbine are used to translate wind energy into other form of energy most notably electrical energy, a) Horizontal Axis wind turbine and, b) vertical axis wind turbine. Much of the work is done on horizontal axis wind turbine but due to high maintenance cost and high manufacturing cost as well as complex design, vertical axis wind turbine has been the focus of research for the scientist.

Small-scale wind turbines are being developed (rated power outputs <50 kW) for decentralized power generation. For small-scale applications, VAWT offers a practical option due to its omni-directional operation and relatively easy installation and maintenance. A comprehensive review on the VAWT technology has been presented in ref. [1, 2]. The strong blade-wake interactions and the dynamic vortex shedding together with the vibrations caused by these aerodynamic factors increases the complexity of the VAWT design for aerodynamicists and structural designers. Nonetheless, the complexity of VAWT operation also provides an opportunity for advance research and development in order to exploit the energy yield from the available wind corridor. In this regard, different methods to enhance the VAWT rotor aerodynamic characteristics have been highlighted in ref. [3-6]. Studies have also shown that a number of VAWT when operated in close proximity can aerodynamically supplement each other resulting in a superior synergic performance and power density [5, 6]. Couples of co-rotating and counter-rotating VAWT has resulted in generating more power (between 50 and 100% of power augmentation) compared to a lonely VAWT by taking assistance of the beneficial induced velocity field [7]. Such an arrangement of multiple wind turbines would be advantageous for limited area urban population.

Momentum models have been useful when applied in the aerodynamic computation of Darrieus VAWTs since a longtime ago. Moreover, there are three momentum models used, although all are based on the same principle, i.e. to calculate flow velocities passing through a turbine by calculating the stream wise aerodynamic force on the blades, with the variation in rate of air momentum based on momentum models [8].

2.2 Energy Crisis in Pakistan

As the population is increasing at an alarming rate, the current situation of energy is worrisome as Pakistan is going through an energy crisis [9]. Moreover, the conventional sources of energy i.e. coal and petroleum are limited and not enough to encounter the growing energy need. In the past 20 years, Pakistan's energy demand has increased three folds and holds 0.5 % of world energy consumption [10]. Pakistan's energy demand is fulfilled by 64% of fossil fuel, 30% of hydroelectric and 6 % from nuclear energy source, which clearly means Pakistan rely on 94% of depleting source of energy which is hazardous for the environment. Furthermore, industrial and household sectors consumes about 74% of the total energy and 18 % is consumed by transportation, streetlight and agriculture.

The overall situation of Pakistan shows that renewable energy sources are not utilized keeping in mind that the country has a potential of 50 GW of energy from wind energy only. So, the need of the hour is to exploit that source of energy which will be clean, environmental friendly and are not depleted with the passage of time. Wind energy is the answer for this problem which is clean and environmental friendly. A lot of effort has been done on wind turbine especially horizontal axis wind turbine, but according to literature review vertical axis wind turbine is more advantageous when compared with HAWT. Hence VAWT is studied in this research keeping in view that Pakistan has areas where wind speeds are low.so the designs proposed in this study will focus on making Vertical Axis Wind Turbine suitable to be used in Pakistan.

2.3 Previous work done on Vertical Axis Wind Turbine (H- Darrieus)

In ref. [11] double multiple stream tube (DMST) model has been utilized at specific location for evaluating aerodynamic design and to predict the cost-effectiveness of VAWTs. A 1.5kWH NACA 4415 VAWT airfoil was analyzed to predict the yearly generation capacity and its economical assessment was carried out.

Similarly, in ref. [12], the researchers used double multiple stream tube model for the aerodynamic design and analysis of small VATWs. Further the results attained were used in the designing of small VAWTs that were mounted on the top of tall buildings for urban use.

In ref. [13-15] researchers optimized the span wise thickness and chord division of a Troposkien Darrieus VAWT. The double multiple stream tube model is used for the aerodynamic analysis and geometric shape was optimized using genetic algorithm.

In reference [16] the blade element momentum model was used to predict the performance map and it was combined with wind distribution to analyze the influence on turbine performance based on cut in speed. The analysis was done using dimensionless number and the aerodynamic configurations were highlighted to warrant the major annual energy yield for each wind distributions and a set of aerodynamic constraints.

Mahdi Torabi Asr et al. [17] studied the startup issues associated with vertical axis wind turbine in a region of low wind speeds. The startup behavior of VAWT was investigated using transient CFD modeling (ANSYS Fluent). The turbine was set free to accelerate based on the torque experienced over time, contrary to the conventional approach as by giving constant angular velocity. The result of above discussed simulation, as of an accelerating time series, established good agreement with the published experimental data, and this method gave a high level of accuracy. Thus, proving its usefulness for similar problems.

In [18] the researcher carried out similar research on a NACA 0018. The blade geometry constructed on fixed pitch three blade was studied using double multiple stream tube model and Afterwards it was validated with CFD. The results obtained in this research was very similar to previous studies. The result obtained at 0 TSR was negative while that of CFD was positive due to the fact that constant rotation was given to drive turbine in CFD.

2.4 Summary:

In this chapter different research carried out in past has been discussed. The complex operation of VAWT is studied to maximize the per annum conversion of energy by VAWT. Different approach to enhance the rotor aerodynamics of VAWT has been studied in order to utilize it in this research. The vertical axis wind turbine when operated in close proximity can aerodynamically assist the performance of each other which is not the case in horizontal axis wind turbine. Momentum models which are applied in the aerodynamic computation of VAWT long ago, has been modified and discussed in detail in next chapter. Further energy crisis of Pakistan has been discussed.as the conventional sources of energy such as coal, hydel petroleum is limited and not fulfilling the need of growing energy demand renewable energies such as wind which has huge potential too is one of the main sources to fulfil the energy demand in the country.

Double Multiple stream tube model has been used extensively as it is one the most reliable blade element momentum models for the calculation of the performance of vertical axis wind turbine. In one study DMST is used for the economic evaluation of 1.5KWH NACA 4415 VAWT airfoil and in another study the investigation of small vertical axis wind turbine has been done using DMST. Hence DMST can be used for economic as well as analysis of turbine performance and its less time consuming.

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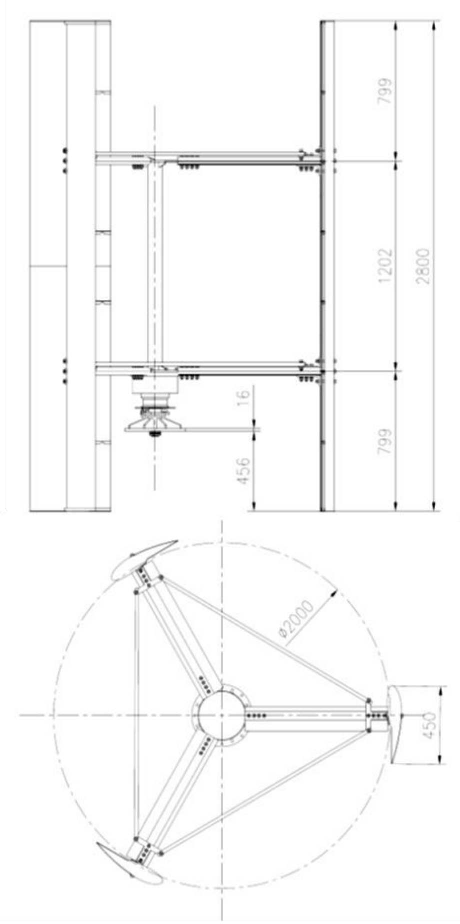
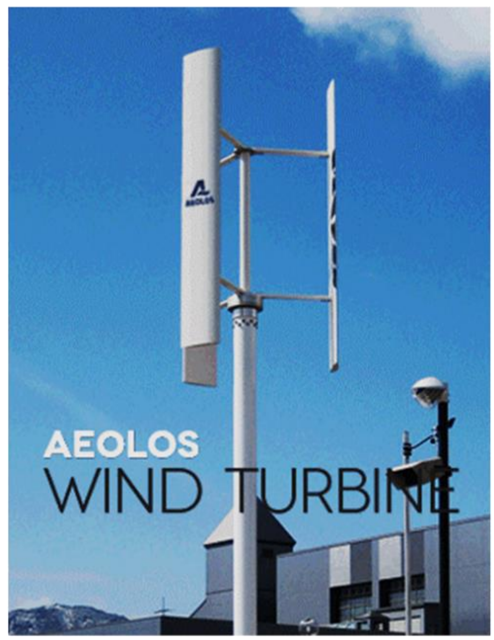
CHAPTER # 3

VALIDATION OF BASELINE GEOMETRY

3.1 Baseline Geometry:

The geometrical data along with its performance at optimum and designed condition has been provided by the industrial collaborator, AELOS Wind Energy Ltd. As shown figure 11, the turbine rotor is comprised of three-blade configuration. The output of the turbine is 1kW at rated wind speed of 10m/s. The 3-phase permanent magnet generator (PMG) has an efficiency of 96% as claimed by the manufacturer. Moreover, the airfoil coordinates and data indicating lift and drag





Rated Power	1000 W
Cut-in Wind Speed	2.5 m/s
Rated Wind Speed	10 m/s
Rated RPM	200
Generator	3-Phase PMG

Figure 6 AEOLOS 1kW

coefficient were also supplied by AELOS. The data including C_l and C_d values are the input to the Blade Element Momentum Model (BEMT) used in this research. The data for C_l and C_d is experimentally calculated by AEOLOS.

3.2 Methodologies

The past studies show that there are three basic research methods for Darrieus vertical axis wind turbines which mainly include (a) computational aerodynamic, (b) computational fluid dynamics (CFD) and (c) experimental methods.

3.2.1 Computational Aerodynamics

There are three main aerodynamics theories studied for Darrieus VAWT. These are broadly classified into (i) vortex model, (ii) cascade model and (iii) momentum model. The most appropriate pick according to literature survey is momentum model. Based on this, our main focus will be momentum model in this work.

3.2.1.1 Vortex model

Vortex model is a method to calculate the aerodynamic performance of VAWTs. The Vortex models are fundamentally potential flow models based on calculating the velocity field about the turbine through the effect of vorticity in the wake of the blades. Vortex model was used in forecasting the performance of a VAWT calculating with small angle of attack therefore, stall effect was ignored in the work presented by Larsen [1].

Vortex model has high precision in the prediction, however it takes a lot of computation time. Moreover, the computational accuracy of vortex model is greatly dependent on the potential flow model used in the computation [2].

3.2.1.2 Cascade model

The Cascade model was suggested by Hirschand Mandal [3] to utilize the cascade principles for the investigation of VAWTs for the first time. In order to advance the analytical capability of this model, Mandal and Burton [4] later on, involved the dynamic stall and stream line curvature in the model.

3.2.1.3 Momentum models

The stream tube model which is used as a performance indicator for VAWT will be explained in this section. The stream tube model is based on Blade element method (BEM) and momentum theory. The combination of these give rise to blade element momentum theory (BEMT). There are three BEMT models, which are based computing the velocities flowing through a turbine by comparing the stream wise aerodynamic force on the blade with change in rate of air momentum based on the momentum model.

The first and basic of all stream model is called a Single stream model, which is used for the analysis and prediction of Darrieus VAWT performance. The rotor is supposed to be enclosed with in single stream tube and has combined actuator disc theory into the analysis for prediction of Darrieus VAWT. This model can forecast the overall performance of light wind turbines, and predict higher power than experimental results. More-over, in single stream tube model the velocity distribution across the rotor cannot be predicted [2].

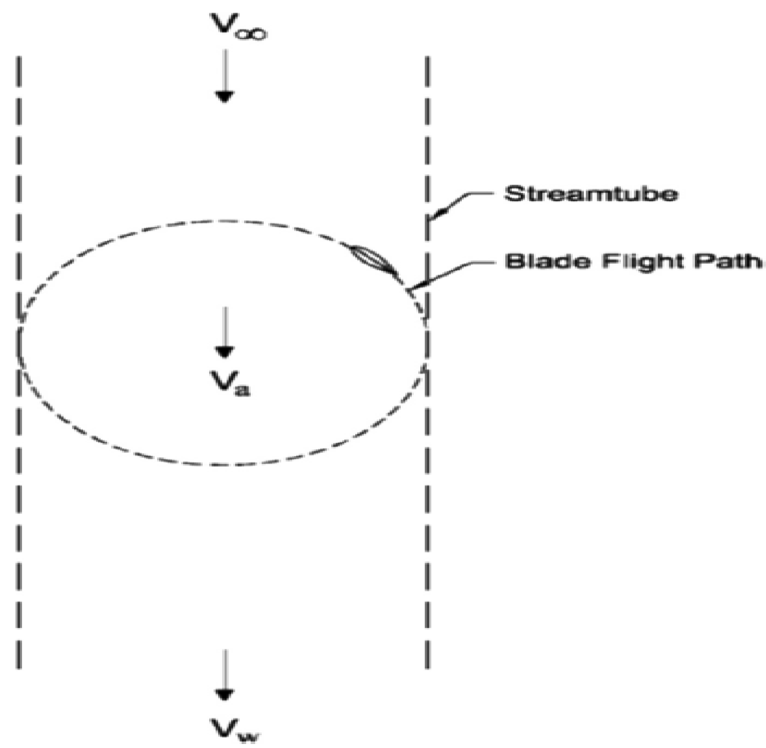


Figure 7 Single Stream Tube Model

Multiple stream tube model was presented by Wilson and lissaman in 1974 [5] due to the drawbacks of single stream tube model. The main difference in the multiple stream models is that the rotor volume is divided into multiple stream tube, which are aerodynamically independent as shown in figure 7. The blade element and momentum theory are applied to each stream tube. The flow is considered as inviscid and incompressible for the calculation of induced velocity. As only lift force is considered in calculation, Strickland in 1975 suggested another model in which drag force was introduced in calculation. The drag force reasonably predicts the performance of the rotor [6].

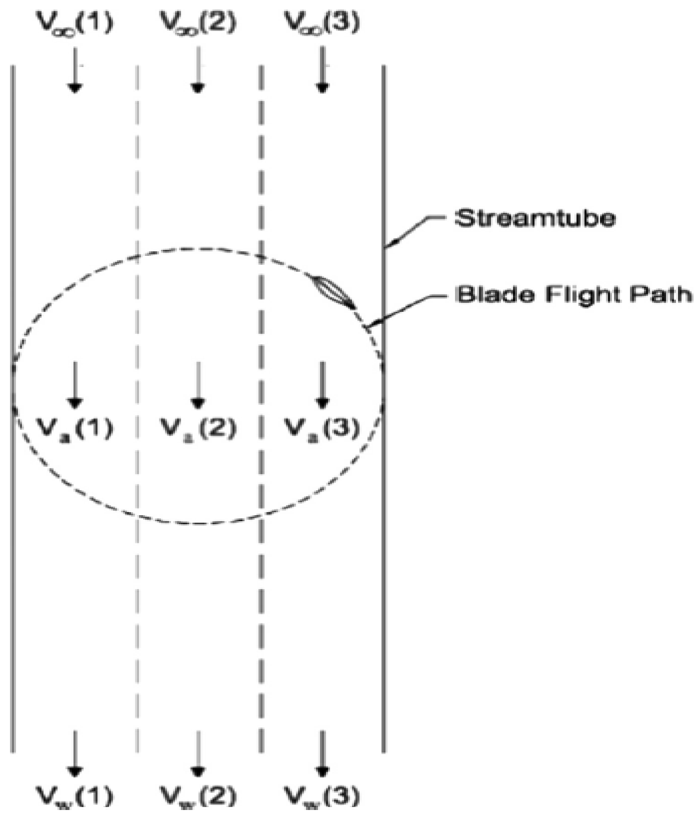


Figure 8 Multiple stream tubes model

Double multiple stream tube method is more advanced and reliable in terms of accuracy, from the previous momentum model. In DMST the rotor swept volume is divided in to two hemispheres the upper and lower stream tube and their induced velocities are calculated based on two actuator discs in tandem Figure 8.

When related with the previous two momentum models, the DMST model yields improved results between the calculated and experimental results. Especially, it has greatly enhanced the simulation of dynamic stall effect. However, the model may have its precision further improved at higher solidity and tip speed ratio.

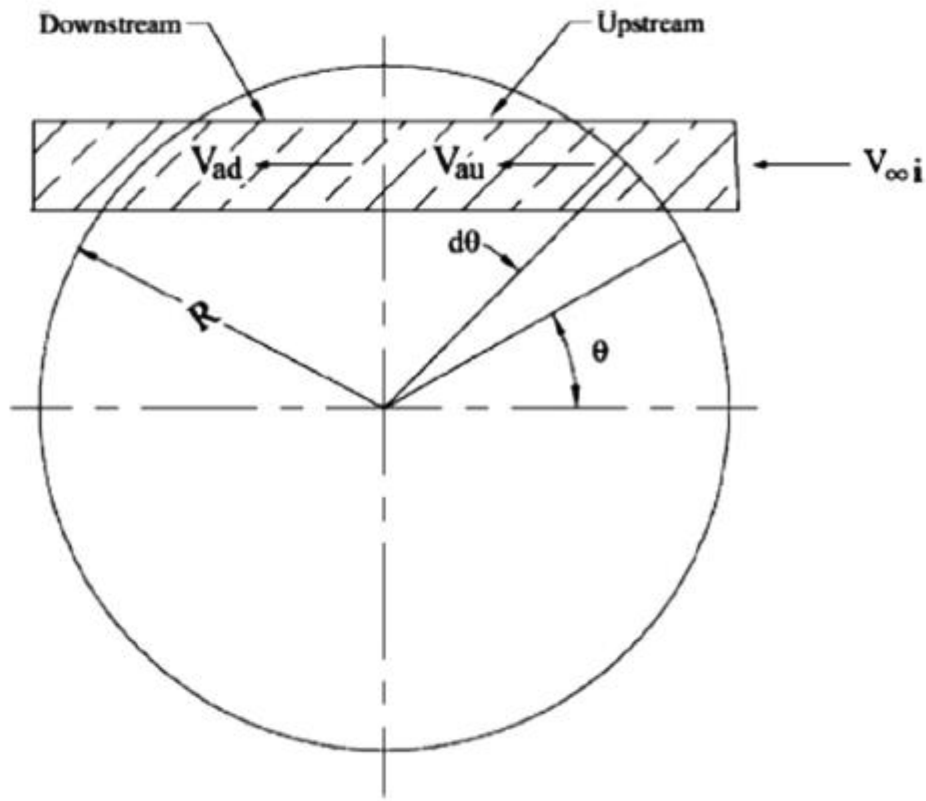


Figure 9 Double Multiple stream tube model

Due to the survey in literature and the precision of DMST near to experimental result, double multiple stream tube model has been used in this work. The results from DMST has been validated against those of CFD ANSYS.

Double multiple stream model uses governing equation to calculate the thrust force on each stream tube i.e. forces parallel to it and then the same forces is calculated from load analysis which are dependent on flow velocity. Hence, they are related to obtain a system of equations, that are shown below.

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_{€} \varrho \mathrm{dV} + \oint_{\partial €} \varrho\, \mathrm{u}.\boldsymbol{n}\, dS = 0 \tag{1}$$

$$\frac{d}{dt}\int_{€} \varrho\, \mathrm{u}\, dV + \oint_{\partial €} \varrho\, \mathrm{u}\, (\mathrm{u}.\boldsymbol{n})\, dS = \sum Fext \tag{2}$$

$$\frac{d}{dt}\int_{€} \varrho\, \mathrm{u}^{\mathbf{2}}\, dV + \oint_{\partial €} \varrho\, \mathrm{u}^{\mathbf{2}}(\mathrm{u}.\boldsymbol{n})\, dS \;=\; -P \tag{3}$$

Where € is the domain where those equation will be applied and $\boldsymbol{n}$ is the unit vector normal to $\partial €$ and point outwards. $\sum Fext$ is the sum of forces that flow receives and P is the power output of the portion of the turbine inside the domain.

3.2.1.4 Physical Definition:

The double multiple stream tube model is considered to be the most precise due to the fact that it allows to consider the energy losses of the flow separately for both the half of the rotor i.e. front and rare half. The mass of air is considered to flow through two consecutive actuator disks, which in turn extract energy from it. The difference in velocity of the flow can be calculated at any position of the blade as the turbine domain is discretized in multiple stream tube parallel to the flow. Then the different velocities from rare and front half stream tubes are added together. The five different states of flow can be distinguished from schematic illustration of DMST in fig. 9.

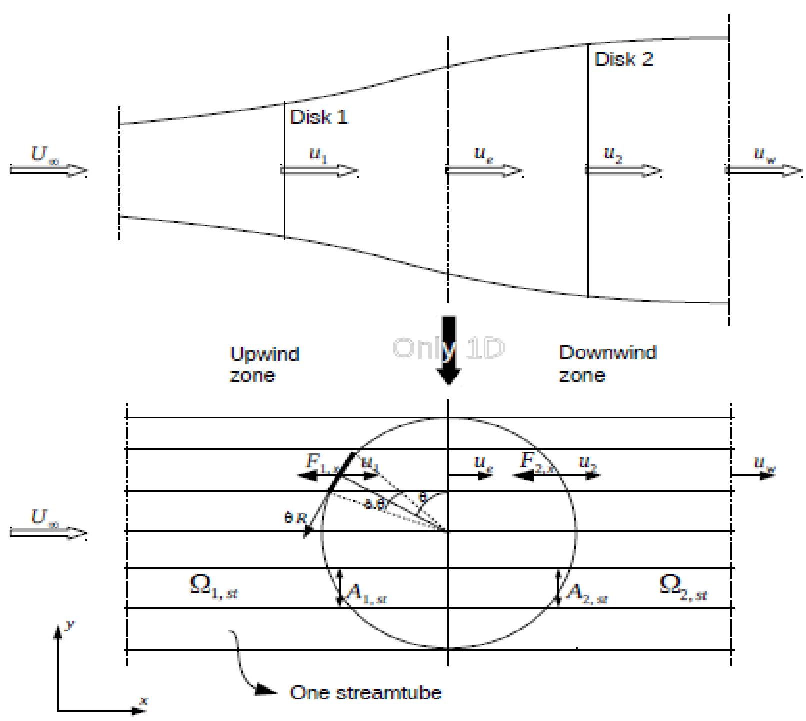


Figure 10 Scheme of DMST in a VAWT Domain

a) The input state where the free stream velocity U_∞ acts as input to disk 1.

b) In second state the flow interacts with front half cycle of the turbine or upwind actuator disk.

c) State ***e*** is considered as output state of disk 1 and input state for disk 2. An assumption which is used to seek very fast convergence through simple modeling. This is steady state and flow is considered far enough for both disks hence equilibrium.

d) When flow interacts with downward actuator disk or rear half cycle of the turbine it indicated the state.

State **ω** is the wake state and act as output state for disk 2.

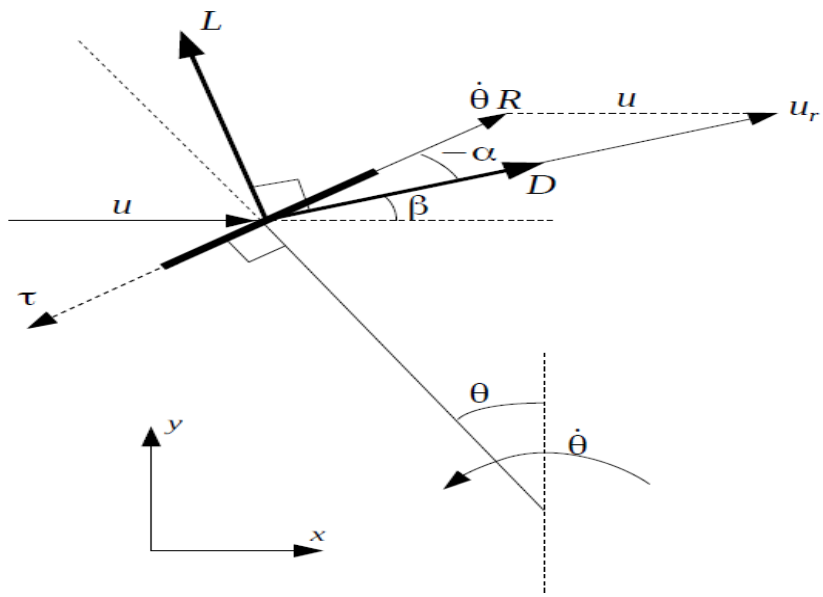


Figure 11 Flow Velocities and Forces with respect to Blade

In order to define geometry of vertical axis wind turbine in terms of parameters, Figure 10 used. The relative velocity (u_r) of the wind from blade reference point of view is,

$$\frac{u_r}{U_\infty} = \sqrt{\left(\frac{u}{U_\infty}\right)^2 + TSR^2 + 2\frac{u}{U_\infty} TSR\ cos\theta} \tag{4}$$

Also, the flight path angle is

$$\beta = arctan\left(\frac{TSR\ sin\theta}{{}^{u}/_{U_\infty} + TSR\ cos\theta}\right) \tag{5}$$

Where U_∞ is the free stream velocity, TSR is the tips speed ratio which is turbine rotational speed divided by free stream velocity. Once the flight angle is known from which angle of incident can be obtained to calculate the lift and drag coefficients by taking data of C*l* and C*d* from empirical tables. The values which are not present in the tables will be interpolated or extrapolated. The lift and drag will determine the value of Cp which is the performance indicator for the turbine.
And angle of attack,

$$\alpha = modulus\left(\frac{\pi+\beta-\theta}{2\pi}\right) - \pi \tag{6}$$

Once the blade angle of attack is known, the lift coefficient C_L and Drag coefficient C_D, of the vertical axis wind turbine blade profile can be obtained by the experimental data

$$L = {}^{1}\!/_{2}\, \rho\ \ C_L c\, u_r^2 \tag{7}$$

And

$$D = {}^{1}\!/_{2}\, \rho\ \ C_D c\, u_r^2 \tag{8}$$

The load that the blade receives from the wind expressed as a function of lifts and drag components,

$$F = [D\ cos\beta - L\ sin\beta]i\ + [D\ sin\beta + L\ cos\beta]j\ , \tag{9}$$

is used to calculate the torque that turbine receives from each blade,

$$T = R\ F.t = R(Ll + Dd).\tau \tag{10}$$

Where $l = -sin\beta\ i + cos\beta\ j$, $d = cos\beta\ i + sin\beta\ j$ and $\tau = cos\theta\ i - sin\theta\ j$. Therefore, the power coefficient obtained from one blade

$$P = \frac{1}{2\pi}\int_0^{2\pi} \dot{\theta}\ T\ d\theta \qquad (11)$$

The result of averaging the instantaneous torque times the angular velocity along a period of azimuthal angle is determined from equation 11.

The coefficient of performance Cp can be calculated using double multiple stream tube model by obtaining Cp front and Cp back is given by.

$$C_{p,1} \equiv C_{p,front} = \frac{\sigma\, TSR}{2\pi}\int_0^{2\pi} C_{T_b}\, \mathrm{d}\theta \qquad (12)$$

Where as Cp back is given by,

$$C_{p,2} \equiv C_{p,back} = \frac{\sigma\, TSR}{2\pi}\int_0^{2\pi} C_{T_b}\, \mathrm{d}\theta \qquad (13)$$

Finally Cp total will be the summation of Cp_1 and Cp_2.

3.3 Validation of Baseline geometry:

The baseline geometry provided by AEOLOS is first validated with the help of blade element momentum theory (BEMT) using Double Multiple Stream Tube model. The Cl and Cd values provided by AEOLOS are given input to the Double Multiple Stream Tube model.

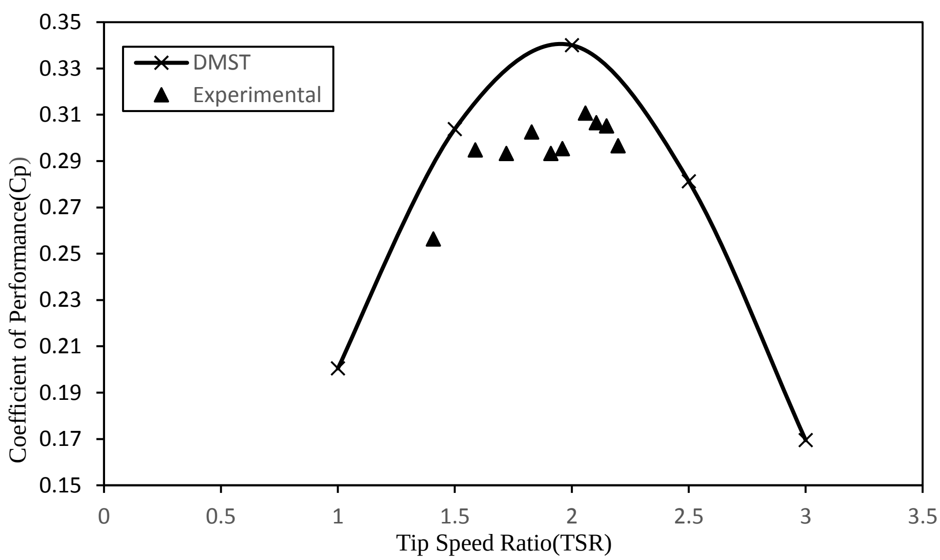


Figure 12 DMST vs Experimental result

The turbine is run for number of TSR's. further the result obtained from DMST is compared with CFD as shown in the figure 12. The result obtain from DMST was in good approximation with those of experimental data. As DMST predicts higher value than CFD so this result of DMST is further validated with CFD later on in chapter 5.

3.4 Summary:

In this chapter the baseline geometry provided by AELOS for 1kW is simulated in MATLAB 2013. The aerodynamic performance can be done with the number of methods. Vortex model and cascade model are also discussed along with basic types of blade element momentum models (BEM). Double Multiple Stream Tube model (DMST) has been used for this analysis due to the precision of output performance by DMST. The input values of DMST are Cl and Cd of the baseline profile. As DMST is one of the most reliable and fast to predict the performance of the Vertical axis wind turbine (VAWT), so the result obtained are in good approximation with those of experimental results provided by AEOLOS.

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CHAPTER # 4

Optimization of Baseline Geometry

4 SENSITIVITY ANALAYSIS:

Sensitivity analysis is carried out to analyze the parameters that affects the performance of the turbine using Double Multiple Stream Tube Model in MATLAB. First number of blades are varied to know the effects of the turbine over number of TSR's. Further cord length was increased and decreased to know the outcome on the performance of the turbine. The effect of cord length is that the initial performance has been improved however the turbine didn't performed well at higher TSR's as shown in figure.

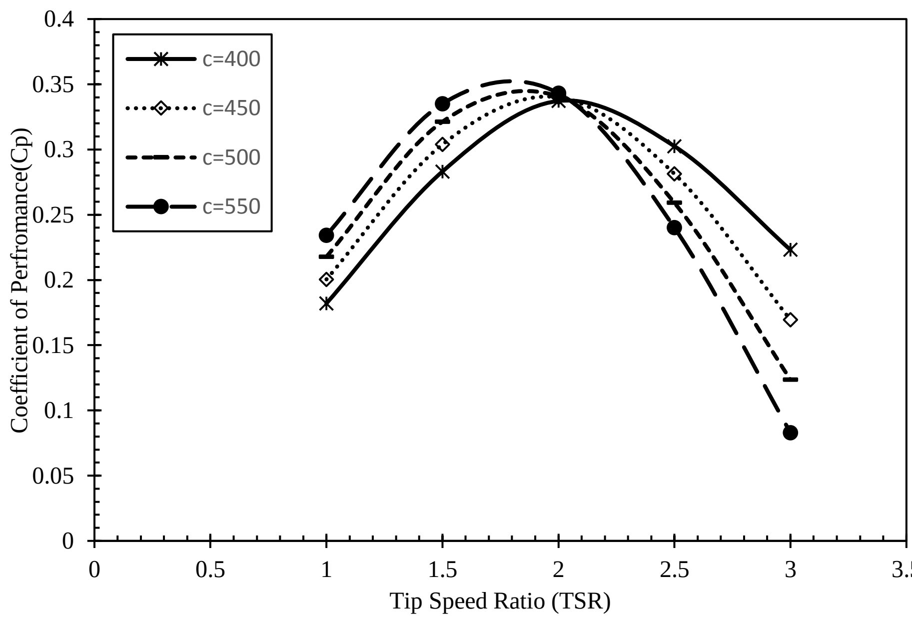

Figure 13 Effect of Cord Length on Performance of VAWT

Secondly the number of blades were changed to know the effect on the efficiency of the turbine. As the number of blades increases the blades tend to perform at higher efficiency initially however at higher TSR's the turbine's performance shows sudden decrease. The main reason of turbines failure at higher TSR is due to blockage effects as the rotor tends to act as a wall when the turbine runs at higher speed.

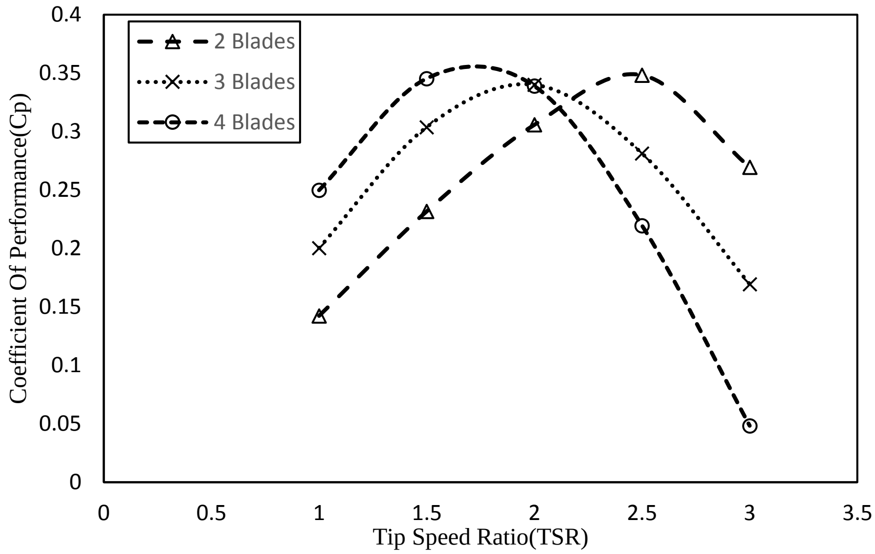

Figure 14 Effect of Blade Number on Cp

Lastly the radius was varied and efficiency of the turbine decreases but gets uniform over number of TSR's. the trend obtained from changing radius yield different result as compared to the change in chord length and number of blades. As the radius is increased the turbine tend to have less efficiency at lower TSR's however, as the turbine speed is increased the efficiency tends to improve and provide optimum result at higher TSR's as clear shown is figure 15.

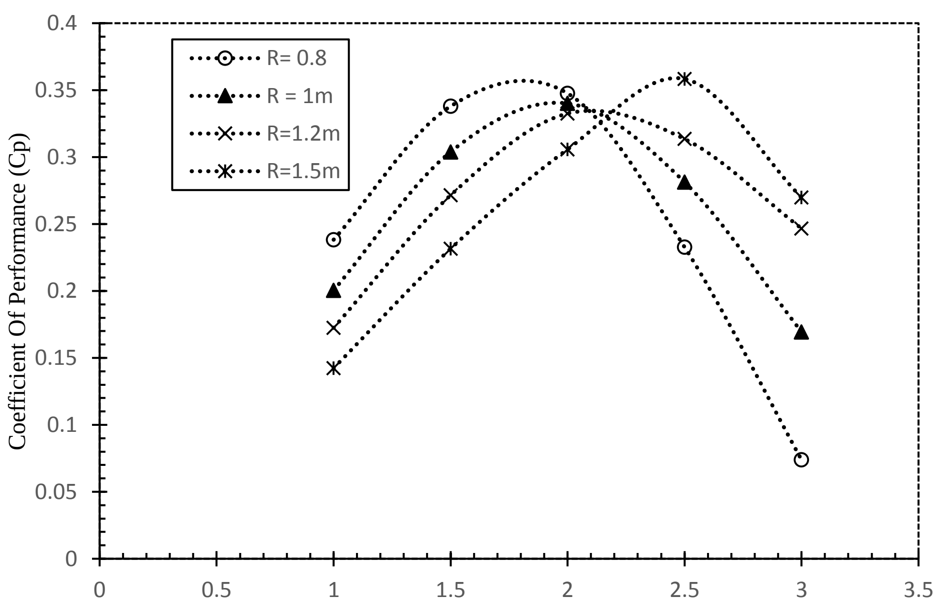

Figure 15 Effect of Radius on Performance of the Turbine

4.1 Optimization:

A number of simulation was done by using MATLAB , utilizing double multiple stream tube mdoel to predict the performance of the turbine .These results are compared with those of CFD ANSYS fluent. Solidity of the turbine which defines the performance of the turbine is given by,

$$\sigma = \frac{N_b \ c}{2R} \qquad (14)$$

Where N_b is the number of blades used, c is the chord length and R is the radius of the rotor. The solidity is a representation of the blockage effect of the VAWT against the wind [1]. High solidity shows high Cp but drastically fail at high tip speed ratios (TSR). A reference design of AEOLOS 1kW is used in this study along with optimized designed for low wind speeds. Different parameters were varied in range to change the solidity of the turbine. High solidity is due to one of the reasons:

(a) higher number of blades,

(b) longer chord length blades is used or

(c) the radius of turbine is small as compared to blade chord.

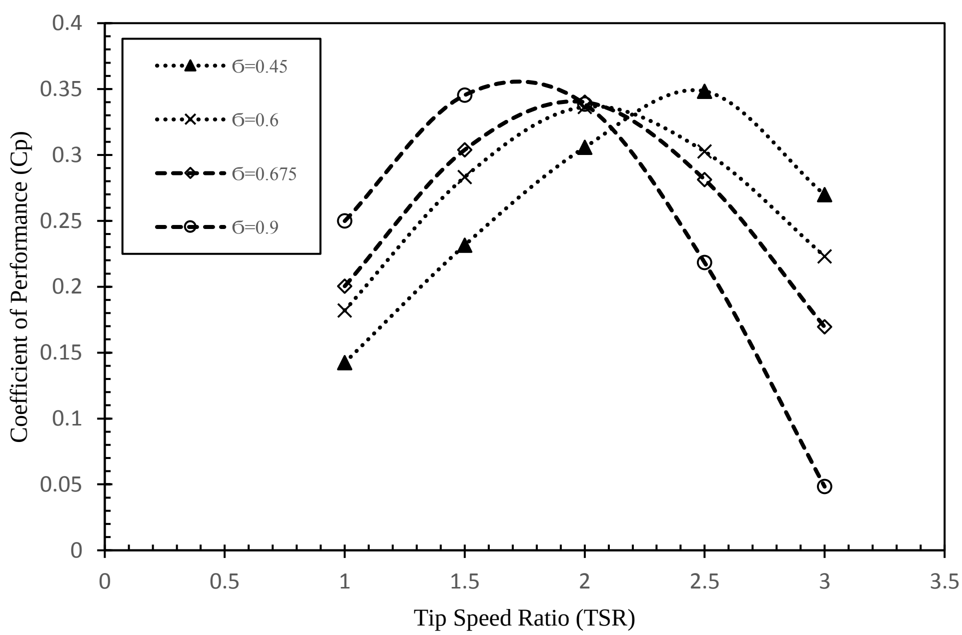

Figure 16 solidity change vs Cp of AEOLOS 1kW

All of the above cases will make the turbine such that at higher tip speed ratios the rotating baled of turbine will act as a wall and will not let the air to pass through it, which will make the design very poor. On the other hand, if the solidity is low the turbine will operate along number of tip speed ratio but will have decreased optimum efficiency compare to low solidity. In figure 4 solidity 0.45 means turbine has diameter of 3 meters, with three blades cord length of 450mm, solidity 0.6 has three number of blades as well as same chord length whereas the diameter of the rotor is taken 2 meters instead of 3 meters. The third case with 0.675 solidity has 3 blades with diameter of the rotor being 2 meters whereas cord length is kept same. The fourth case has utilized four blades with diameter of 2 meters and the resulting solidity for this case 0.9. All these solidities were run for different TSR's to know the performance of the turbine. As the figure clearly shows that the case with least value of solidity has shown consistent performance over number of TSR's, however compromising for the low efficiency at lower TSR's. as the solidity is increased till 0.9 the performance of the turbine shows a drastic decrease at higher TSR's this is due to the blockage effect due to higher number of blades of the rotor or increased cord length. The increase in number of blades or cord length will act as a wall at higher TSR's and turbine will act as a wall that will not let more air to pass through the turbine.

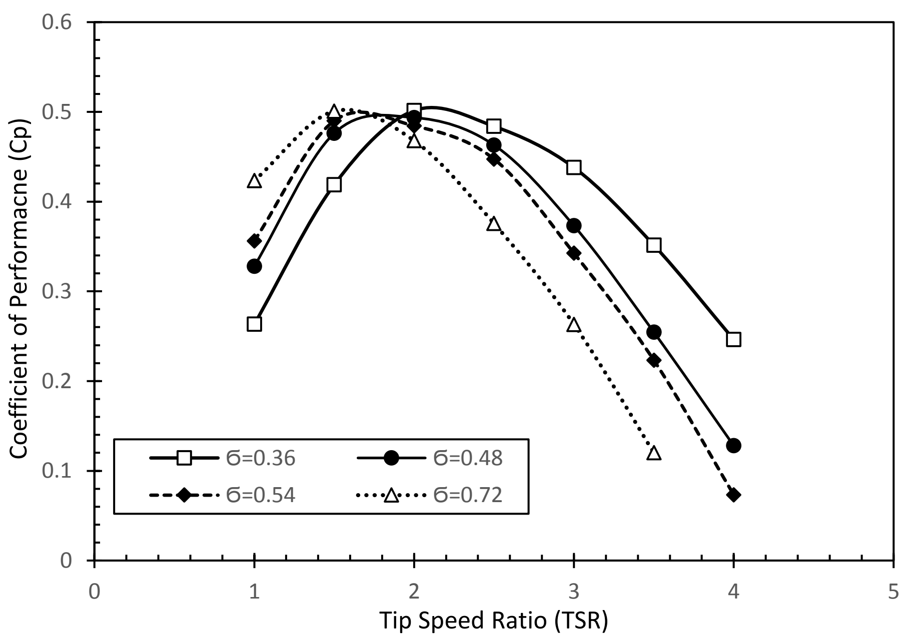

Figure 17 Effects of solidity NACA 0021

Furthermore, another airfoil with the name NACA 0021 was used to examine the effects of solidity and the following results were obtained showed in figure 15. The result obtained shows similar trend but higher Cp as compared to AEOLOS 1kW, which is obvious for symmetrical blades. The reason symmetrical blades are not used in vertical axis wind turbines is their low startling torque which will make them unable to rotate in the beginning of operation. Contrary to symmetrical airfoil chambered airfoil has less C_p but will resolve startling torque issue.

AEOLOS 1kW and NACA 0021 airfoil were compared with CFD results. When compared AEOLOS with NACA 0021 the results show high Cp of NACA 0021 airfoil, but negative Cp at low tip speed ratios. This result shows that cambered airfoil will have reduced Cp but it will improve startling issues, which is one of the main problems in vertical axis wind turbine.

The difference in the CFD and DMST result is same which is validating the work done in this research.

4.2 Power Output:

The power output of the turbine is given by,

$$P_T = \frac{1}{2} C_P \, \rho \, A \, v^3 \tag{15}$$

The above equation shows that the power of turbine will reduce three folds, when the wind is reduced from the optimum design condition. Now reducing the velocity of wind by just 2 m/s from the designed speed of 10 m/s will reduce the output by nearly half. In order to compensate this loss, there are two options either by increase the size of the turbine or increase the output efficiency i.e. C_p of the turbine. As increasing the turbine size might have adverse effect on the turbine output so sensitivity analysis shows the effect of different parameters on turbine with increase and decrease in efficiency. The other option is increasing the efficiency of the turbine by accurately increasing those parameters, which will optimize this turbine. Both area and increase in efficiency of the turbine will compensate the effect of decreasing wind speed, giving the output design for low wind speed with much higher efficiency. Increasing the area in terms of radius will add the area of the turbine, however the solidity of the turbine will be lowered. As it is discussed above that lower solidity has adverse effect on the initial performance of the turbine so the number of blades or increasing the cord length might neutralize the effects of increasing radius, thus opting solidity for optimum condition.

4.3 MATLAB Optimization:

The optimization of the baseline turbine of 1kW is carried out in MATLAB and then validated with the help of ANSYS 15. A number of sensitivity analysis were done to know the effect of different parameters on the turbine. Then an optimizer was introduced in MATLAB to know the optimized rotor. The sensitivity analysis shows that three inputs of the rotor defines the output of the rotor i.e. solidity, TSR and number of Blades. These three are also interconnected one way or another while performing the analysis. The analysis shows the output is not dependent on merely increasing any of three parameters mentioned before; rather it is varied with constraints.

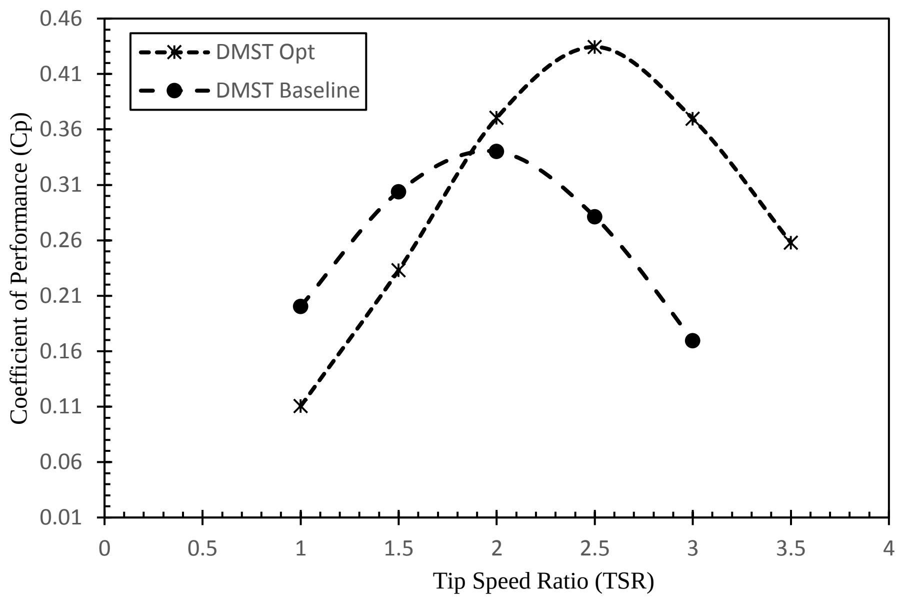

Figure 18 DMST Optimized VS DMST Baseline

Three inputs which were solidity, TSR and Number of blades were defined in MATLAB. The ranges were given to each and every parameter has constraints which were according to literature survey. The solidity for each simulation ranges from 0.2 to 0.9, the TSR ranges from 1 to 7 with increase of 0.5, and the number of blades varied from 2 to 5. The MATLAB simulated each and every combination of the above three inputs, keeping the last optimum value while simulating for the next value until all the combination are simulated and solidity for highest value of Cp is attained. The output of the optimization through this technique is a rotor with 4 blades at TSR 3.0 with increased efficiency. However further analysis shows that the turbine has near to optimum value at TSR 2.5 also, which is additional gain as the turbine will perform better with variation in speed of the turbine. The optimized design is validated with the help of ANSYS and the result was according to the trend obtained by MATLAB.

Parameters	Baseline	Optimized	Difference
Chord	450mm	500mm	+50mm
Radius	1m	1.5m	+500mm
Number of blades	3	4	1
Coefficient of Performance (C_p)	0.34	0.43	26% Increased in efficiency

Table 1 Difference between baseline and optimized designs

The above table shows 26% increase in efficiency of the optimized turbine by changing the chord length by 50mm, number of blades from 3 blade to 4 blade and radius is increase to 1.5m from the baseline geometry which was 1m.

4.4 Summary:

In this chapter sensitivity analysis has been done, by changing different parameter of turbine geometry. First number of blades were varied and the turbine shows that the more the number of blades the higher will be efficiency while turbine is starting the operation, however the efficiency tend to drop drastically at higher TSR's due to blockage effects. The same happen while increasing the chord length as well. However increasing radius shows opposite trend then that of chord length and number of blades. The turbine has lower efficiency while starting but at the speed increases the turbine get better and shows better performance coma

CHAPTER # 5

CFD VALIDATION OF OPTIMZIED TURBINE

5.1 CFD Analysis:

ANSYS 15 is used for the validation of baseline and optimized four blades rotor. The movement of fluid can be numerically defined by the equations for conservation of mass, momentum and energy. These partial differential equations (PDEs) are based on the hypothesis that the fluid can be described as a continuous medium. The PDEs are replaced by a set of algebraic equation dividing the physical domain into large discrete control volume in these techniques, called elements or cells. Algebraic relationships with in these cells describe how the flow variables, such as velocity, temperature or pressure, vary locally with the space coordinates. The general idea behind Computational Fluid Dynamics, also known as CFD. The analysis performed in this research is unsteady. The results obtained from CFD for baseline geometry were near to that experimental data provided by the designer and manufacturer of the baseline geometry (AELOS). Following section details the steps involved in achieving the objective.

The geometrical data along with its performance at optimum and designed condition has been provided by the industrial collaborator, AELOS Wind Energy Ltd. As shown figure 6 (chapter 3), the turbine rotor is comprised of three-blade configuration. The output of the turbine is 1kW at rated wind speed of 10m/s. The 3-phase permanent magnet generator (PMG) has an efficiency of 96% as claimed by the manufacturer.

Moreover, the airfoil coordinates and data indicating lift and drag coefficient were also supplied by AELOS. The data is used to prepare the 2D CAD geometry of the rotor and which is then transferred to CFD (ANSYS) for modeling and simulations.

5.1.1 CFD Test Case:

A 2D model of VAWT with circular domain is created to study the flow of fluid around the rotor blades for three blades and four blades optimized rotor. It predicts the output of the turbine by investigating the effect of fluid passing through the rotor. The result obtained were in good approximation however a 3D analysis can improve the accuracy of results, but due to lack of computational resources, it was not possible to simulate a 3D rotor.

5.1.2 CFD domains:

Two types of turbine geometry were generated first for baseline design and second for optimized four bladed design. In order to generate baseline geometry a file containing the coordinates of the airfoil from leading to trailing edge is obtained from AELOS, however optimized designed has same coordinates with increase in cord length keeping the same ratio. Thus, this will form rotor blades of the turbine. The three blades will be at 120^{o} azimuthal angle relative to each other, however in case of optimized design the four blades will be at 90^{o} azimuthal angle to each other. In order to include the influence of shaft's wake shedding on the rotor blades, the central shaft is also considered in the generation of geometry. The supporting structure of the turbine rotor is not modeled for the sake of simplification of the problem. Two circular domains were created. The inner domain contains the 2D rotor and shaft, and is defined as the rotating zone. The effect of size of the inner and outer domains on the efficiency analysis of VAWT has been inspected in [1]. The inner domain size is kept at a diameter of 1.35D. The outer circular domain is kept stationary at a radius of 9 m with an interface separating the two zones. The outer domain has been kept large enough to avoid blockage effects and to capture the wake formation of operating VAWT.

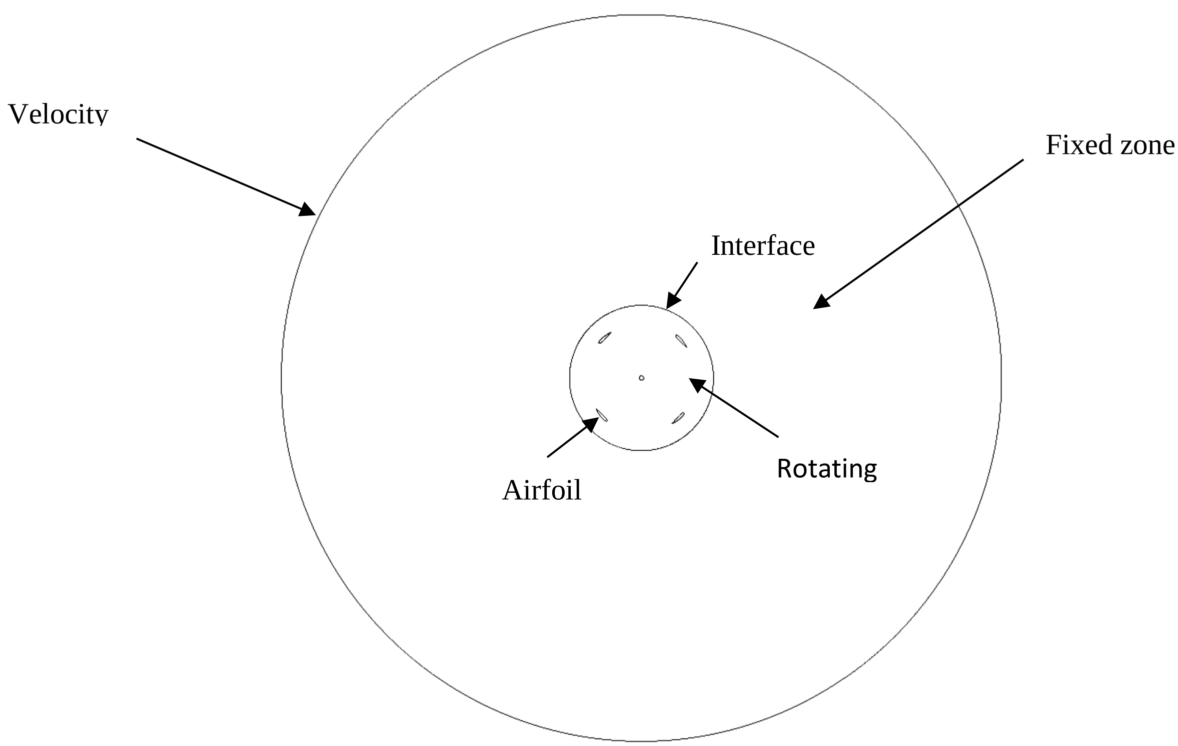

Figure 19 2D VAWT rotor and circular Domain Optimized

In [2], 2D simulations of VAWT were compared with that of wind tunnel experiments and it was discovered that due to blockage effects, flow velocities increase near the blades when compare to inlet velocities to much higher values. Therefore, to avoid this over prediction of the velocity, the domain has to be kept large enough. Interface between the two zones, allows the rotation of the rotating zone against the stationery zone.

5.1.3 Grid generation:

The breaking down of geometry into smaller parts in a distinct scheme, such as nodes, elements, volumes or any particular geometry. The subsequent discretized geometry, that comprises of group of several smaller computational sections, is named as a mesh or a grid. The estimated formulations of the governing equations, like NS, attained through a discretization pattern are solved on the discretized geometry or grid or mesh [3, 4]. The accurateness of the simulation generally rises with increasing number of cells or elements, subsequently reducing the cell size or volume. However, as the computer storage have certain limits as well as the limited by processing some trade-off in mesh size is unavoidable.

5.1.4 ICEM

ANSYS ICEM CFD software was utilized to create structured grid. The discretization process translates the differential equation into a set of algebraic equations, such that it uses the continuous Navier Strokes and change the equations into distinct problems, both in space and time. The breaking down of geometry into smaller parts in a distinct scheme, such as nodes, elements, volumes or any particular geometry. The subsequent distinct geometry, that is now a cluster of several smaller computational sections, is called a mesh or a grid.

Some of the features of grid generation in ICEM are (a) a structured grid has regular connectivity between its elements and the neighborhood relationships are defined by a function making it easy for software to evaluate different parameters, (b) In terms of computer memory usage, structured grid has faster convergence rate, (c) ICEM CFD provides a controlled and structured meshing on the surface of airfoil as well as on far-field region. The far-field region has to be large enough to capture the wake formation behind the turbine.

In addition, sufficient mesh density has to be provided. Consequently, the overall grid contains approximately 0.3 million elements. In order to determine the boundary layer over the rotor blades

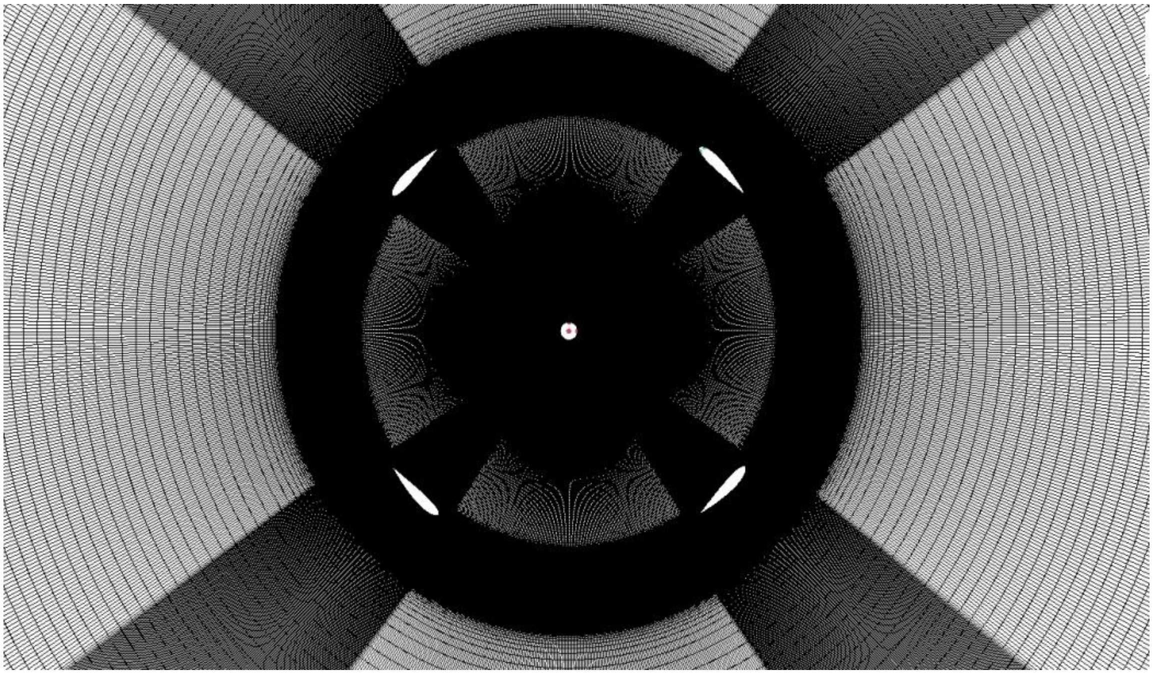

Figure 20 Four Blade rotor (Optimized Design)

and capture the separation of flow adequately, near-wall distance between the mesh elements and the rotor blade surface has been defined to obtain a y+ lower than 1.0. Wall y+ is a dimensionless number used to define the distance between the surface/wall and the first layer of the mesh. Figure 10 displays the structured grid of the four-blade optimized rotor.

5.1.5 Simulation Setup*:*

All the simulations are performed in ANSYS FLUENT 15.0. Appropriate boundary conditions and turbulence model are required to run the unsteady Reynolds-averaged Navier-Stokes (URANS) solution. A constant design air velocity of 10 m/s has been defined along a particular axis at the domain inlet for all computational evaluations, where as a speed of 8 m/s is defined for the optimized design for low wind speed. The sliding mesh procedure has been utilized to rotate the mesh against a stationery domain mesh. In order to establish the characteristic performance curve, the inner rotating domain is defined with varying rotational speeds in the range of 100-250 RPM, for both baseline and optimized geometry. The VAWT operates in an incompressible flow regime. A pressure-based solver is, therefore, utilized instead of the density-based solver.

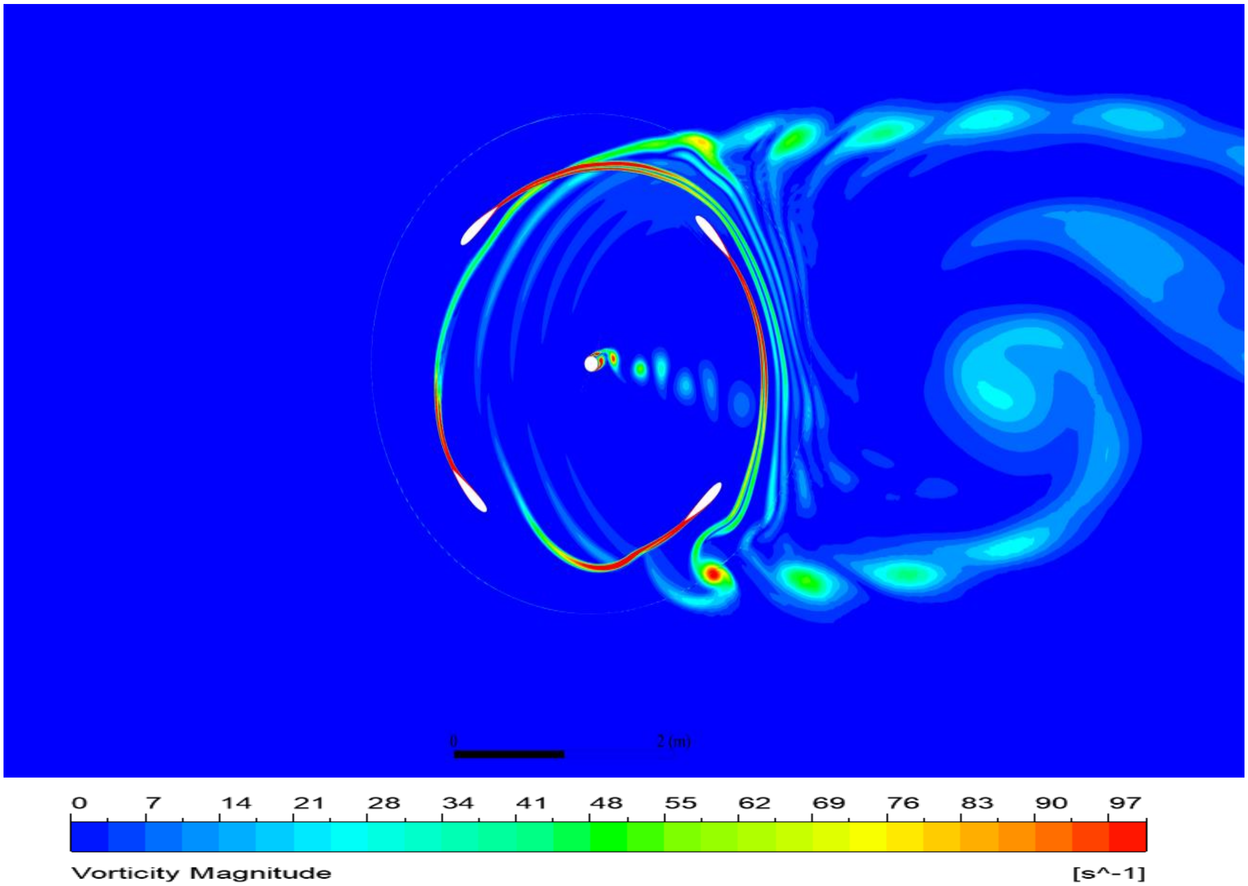

Figure 21 vorticity contours for optimized turbine at design point TSR 2

5.1.6 SST k-ω model

The K-ω shear stress transport (SST) mode, a amalgamation of both K-ε and K-ω turbulence models, was applied. The SST turbulence model uses a special blending function to switch between K-ε and K-ω turbulence models depending on free-stream and near-wall flow conditions, respectively.

The transient SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) scheme has been used. Second order upwind discretization scheme were used to solve all the solution variables, since most of the flow in VAWT can be supposed to be not in line with the mesh [1]. The second order upwind scheme is a good compromise between stability and accuracy [2]. A time-step is required to simulate the given transient case. The time-step size and precision of results are inversely proportional to each other with an influence on the computational time. For transient simulation of the turbine rotor, time-step size has been equated with the degree of rotation by finding the time required by the rotor to move 1° in azimuth. The smaller time step increases the accuracy of the solution but computational cost also increases. In [2] the time step size of 1° was found to be a good choice between accuracy and computational time

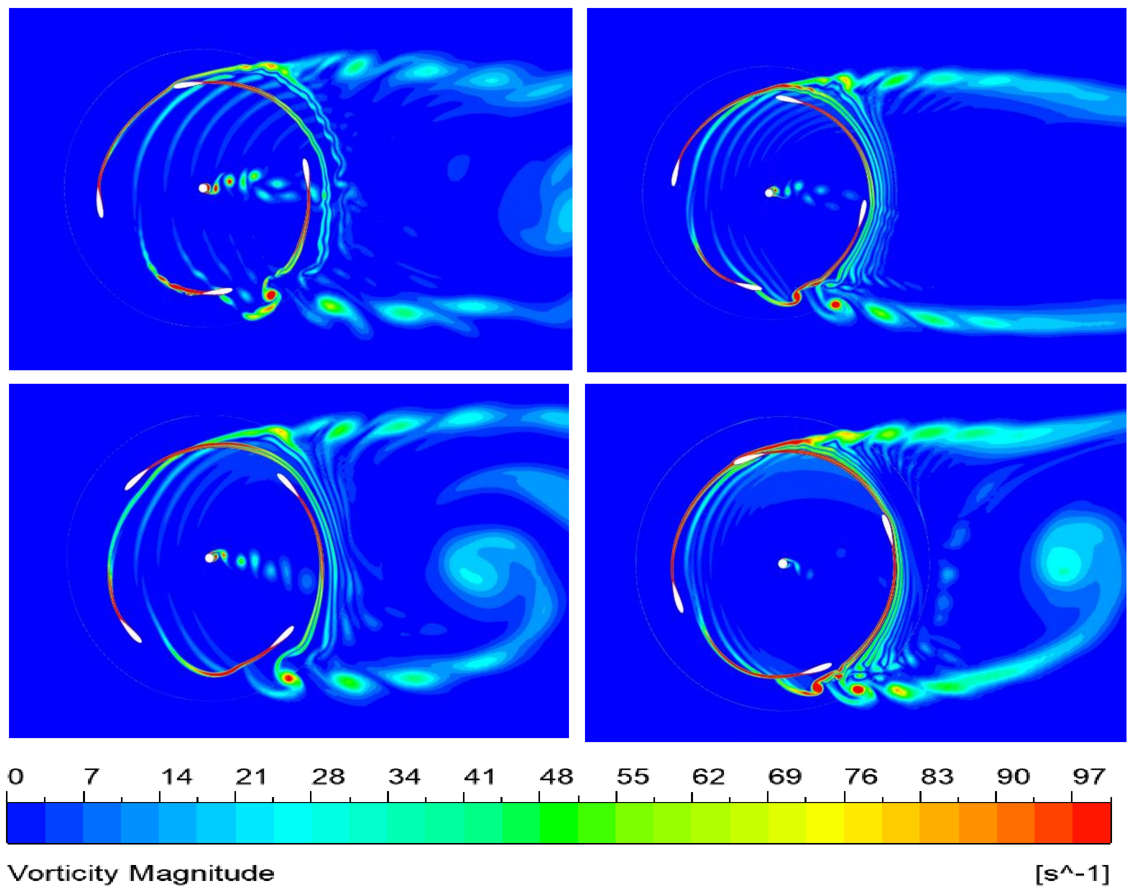

Figure 22 Vorticity contours for optimized turbine at different TSRs (design point TSR 2.75)

5.2 Result comparison/Validation:

Both results from Double Multiple Stream Tube Model and CFD (ANSYS) were compared to validate the result of DMST after optimization. The result shows similar scheme as that of baseline geometry as shown in figure 18. The result from the CFD shows maximum value of Cp at TSR 2.75. This is in between TSR 2.5 and TSR 3.0, where DMST has also shown maximum value of Cp. The detail of CFD has been given in last chapter where information of mesh and CFD setup is discussed in detail. The CFD shows better performance at low TSR's, as turbine is given constant velocity when simulating in ANSYS fluent. Whereas, the torque drives the turbine in simulation of DMST.

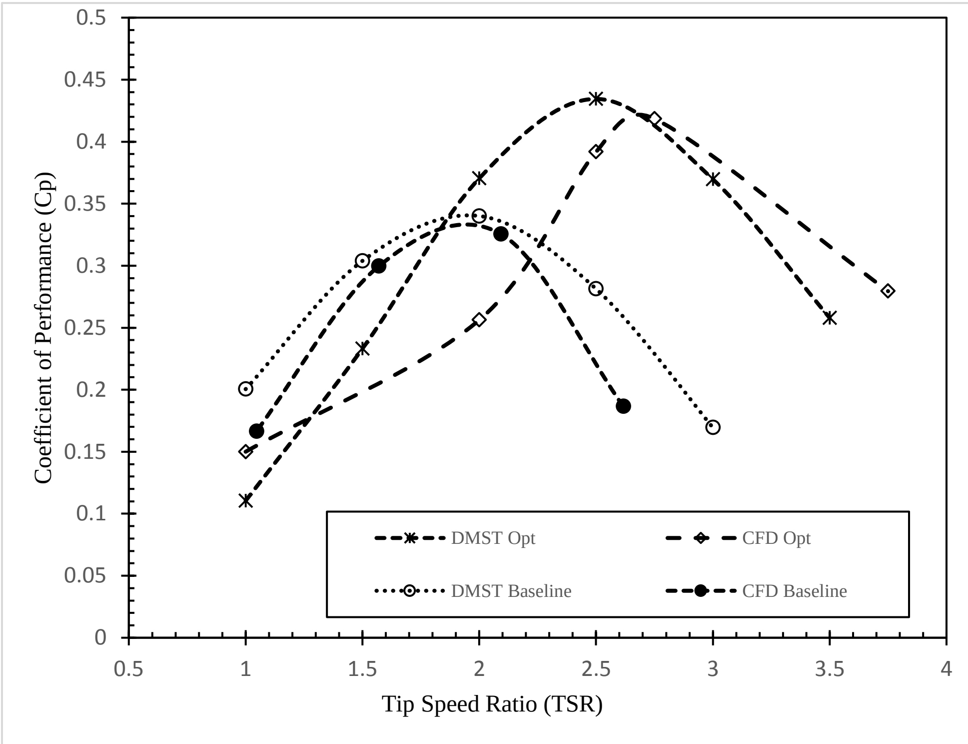

Figure 23 Comparison of DMST VS CFD results

Lastly in figure 23, all the results were compared and it can be seen that the optimized result shows approximately 26% of increase in the result from DMST. While, approximately 28% increase in performance is predicted from the result of CFD ANSYS. As the optimized turbine has radius of 1500mm compared to baseline geometry which is 1000mm, this increase in radius will directly reflect the increase in final result as the power of turbine is equal to product of area, velocity and density of the medium flowing through the turbine i.e. air. So, increasing the radius will increase the area of the turbine as well as power of the turbine.

5.3 SUMMARY:

This chapter explains the different steps involved in carrying out CFD simulation in ANSYS. Two types of turbine geometry were generated first for baseline design and second for optimized four bladed design. ICEM is used to create mesh with 'O' topology round the blade. SST k-ω model has been used as it yields better result near wall and far field calculation. The k- ω provided good accuracy in calculating near wall calculations whereas, k-ε gives reliable results in far field calculations. The simulation is run for number of TSR's in order to get the desired Cp vs TSR curve. lastly all the Cp vs TSR curves are compared and optimized geometry shows better performance as compared to baseline geometry.

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CHAPTER # 6

CONCLUSIONS AND FUTURE WORK

Different airfoils along with baseline geometry were investigated using Double Multiple Stream Tube Model (DMST) and validated with CFD (ANSYS 15). The main focus is to have a design which will be best suitable for low wind speed conditions, or where variation in wind speeds frequently happens. So, the design is to have optimal efficiency at number of TSR's. The Cp's are calculated from both methods i.e. DMST and CFD which are very much in agreement with literature done.

6.1 Conclusions (VAWT)

After studying Aeolos (1kW), NACA 0021, NACA 0018 the conclusions are:

- Symmetrical airfoil provides better performance when compared to cambered airfoil however, cambered airfoil performs better at low TSR which clearly shows that they will have better performance at the start of operation. This is due to better lift at the beginning of operation of cambered airfoil.
- Solidity provides better understanding of wind turbine, the higher the solidity the higher will be peak performance however, this peak performance will be for a specific TSR. On the other hand, lower solidity means comprising the peak performance however, the turbine will perform better at number of TSR's by just compromising a little on optimum value of Coefficient of Performance.
- Increasing the number of blades will improve performance at low TSR's however, increasing blades without increasing radius of the rotor will fail drastically at higher TSR's. this is the result of wall effect as at higher TSR's the blade will form a wall and will not allow air to flow from the turbine.
- Increasing the radius of the turbine will show better result till it is not bound by mechanical constraints, it will also increase the power of the turbine. However, this increase might not help the startling issues which is one of the main concerns in VAWT operation. Therefore, chord length or number of blades has to be increased also to counter the effects.

6.2 Future Work:

VAWT can be improved by changing the geometry of the turbine and airfoil. The following recommendations will surely improve the performance of VAWT,

- Variable pitch phenomenon/Active pitch control will make much improvements in operation of Vertical Axis Wind Turbine (VAWT). It will improve the performance at higher TSR's.
- Modified hybrid design must be studied for VAWT utilizing Savonius and Darrieus turbine. The initial startling torque issue can be resolved with drag type Savonius while, Darrieus will perform better at higher TSR's.
- The VAWT can be install in farm which will assist the performance other turbines install around. If the turbines are varied in size it may assist in terms of starting torque issues also.

Appendix A

1st International Conference on High Performance Energy Efficient Buildings and Homes (HPEEBH 2018)
August 1-2, 2018, Lahore, Pakistan

Vertical Axis Wind Turbine for Low Wind Speed Corridors

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Abstract

Wind is the cheapest and most environmental friendly resource of renewable energy. Wind power generation has so far favored the multi-megawatt horizontal axis wind turbine (HAWT) over the vertical axis wind turbine (VAWT) technology. Principal advantages of the VAWT technology are: (a) Omni-directional operation independent of the directional changes in the wind, (b) heavy components such as the electric generator installed close to the ground, (c) simple design, less manufacturing and maintenance costs, (d) small operating space requirement (high farm power density), and (e) low environmental impact and noise signature. These properties support the application of VAWT in urban environments. However, the VAWT characterizes lower power coefficient Cp compared to the HAWT due to the presence of dynamic stall and associated blade-wake interaction induced vibrations. Generally, wind turbines are designed at rated wind speeds of 10-12 m/s. However, for low wind speed corridors such as Pakistan, maximum wind speed of 8 m/s is available. At such low wind speeds, a turbine can be significantly large compared to higher wind speed designs. In addition, a small-scale application will also incur low Reynolds number effects. The current study is therefore focused on designing a VAWT rotor for low wind speeds of 5-8 m/s by considering a number of design variables and parameters. The double multiple stream tube (DMST) model, an advance type of the blade element momentum theory (BEMT) is being used to design the VAWT rotor. The DMST model is coupled to an optimizer in order to obtain optimum rotor geometry for low wind speeds. An optimal selection of different design variables can lead to a smaller yet effective VAWT rotor design in terms of performance.

Key words

Vertical Axis wind Turbine, Double Multiple Stream Tube Method, Blade Element Momentum Theory, Low Wind Speed Corridor.

Introduction

The need of the present time is to utilize those resources of harnessing Energy which has minimum or no effects on climate of Earth. Currently from vehicles to domestic use and from industrial to product manufacturing everything relies on oil as a main source, which is itself depleting exponentially. Moreover, oil is extremely harmful for natural habitat. Therefore, we need to develop a lifestyle that will rely on clean and renewable energies.

Wind energy is one the clean source of energy. Two main types of turbine are used to convert wind energy into other form of energy most notably electrical energy, a) Horizontal Axis wind turbine and, b) vertical axis wind turbine. Much of the work is done on horizontal axis wind turbine but due to high maintenance cost and high manufacturing cost as well as complex design, vertical axis wind turbine has been the subject of research for the scientist.

Small-scale wind turbines are being developed (rated power outputs <50 kW) for decentralized power generation. For small-scale applications, VAWT offers a practical option due to its omni-directional operation and relatively easy installation and maintenance. A comprehensive review on the VAWT technology has been presented in ref. [1, 2]. The strong blade-wake interactions and the dynamic vortex shedding together with the vibrations caused by these aerodynamic factors increases the complexity of the VAWT design for aerodynamicists and structural designers. Nonetheless, the complexity of VAWT operation also provides an opportunity for advance research and development in order to maximize the energy yield from the available wind corridor. In this regard, different methods to enhance the VAWT rotor aerodynamic characteristics have been highlighted in ref. [3-6]. Studies have also shown that a number of VAWT when operated in close proximity can aerodynamically supplement each other resulting in a superior synergic performance and power density [5, 6]. Pairs of co-rotating and counter-rotating VAWT were seen to generate more power (between 50 and 100% of power augmentation) compared to an isolated VAWT by taking advantage of the beneficial induced velocity field [7]. Such an arrangement of multiple wind turbines would be advantageous for limited area urban population.

Momentum models have been applied in the aerodynamic computation of Darrieus VAWTs since a longtime ago. Currently, there are three momentum models used, but all are based on the same thought, i.e. to compute flow velocities through a turbine by equating the stream wise aerodynamic force on the blades with the change rate of air momentum based on momentum models [8].

In ref. [9] the aerodynamic design and economical evaluation of VAWTs at specific location based on the double- stream tube model was performed. He worked on and optimized a 1.5kWH-type VAWT (NACA4415 airfoil sections), predicted the annual generation capacity and carried out economical evaluation of the design.

Similarly, in ref. [10] the researchers conducted the aerodynamic design and analysis of small VATWs based on the double- multiple stream tube model, the results were used in the design of small VAWTs mounted on the top of tall buildings in urban areas.

In ref. [11-13] researchers optimized the span wise chord and thickness distribution of a Troposkien Darrieus VAWT. The aerodynamic analysis was performed based on the double-multiple stream tube model, and the genetic algorithm was used to optimize the geometrical shape.

Objective

The performance of Vertical axis wind turbine can be predicated using different method such as Computational fluid Dynamics CFD, Momentum model or vortex model. The reliable, computationally inexpensive and less time consuming of all is momentum model [14]. The main objective of the research is to increase the efficiency of a reference turbine i.e. AEOLOS 1kW to make it efficient for low wind speed. Double Multiple Stream Tube Model is used to predict the performance of Vertical axis wind turbine.

The result is a very fast computational method with significant error in the final result. The amount of error is very dependent on the nature of the problem studied and, therefore, the governing equations. BEMT applications for VAWT cases give a fair approximation of the VAWT power output, especially for lower tip-speed ratios [14].

Double multiple stream tube model was first proposed in ref. [15,16], which was output of improved Multiple stream tube method by considering the turbine as two actuator disks—one for upwind and other for downwind cycle as shown in Fig. 1.

Double Multiple Stream Tube Model

Double multiple stream model using governing equation to calculate the thrust force on each stream tube i.e. forces parallel to it and then the same forces is calculated from load analysis which are dependent on flow velocity. Hence, they are related to get system of equation.

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_{€} \varrho \mathrm{dV} + \oint_{\partial €} \varrho\, \mathrm{u}.\boldsymbol{n}\, dS = 0 \quad (1)$$

$$\frac{d}{dt}\int_{€} \varrho\, \mathrm{u}\, dV + \oint_{\partial €} \varrho\, \mathrm{u}\, (\mathrm{u}.\boldsymbol{n})\, dS = \sum Fext$$

(2)

$$\frac{d}{dt}\int_{€} \varrho\, \mathrm{u}^{\mathbf{2}}\, dV + \oint_{\partial €} \varrho\, \mathrm{u}^{\mathbf{2}}(\mathrm{u}.\boldsymbol{n})\, dS = -P$$

(3)

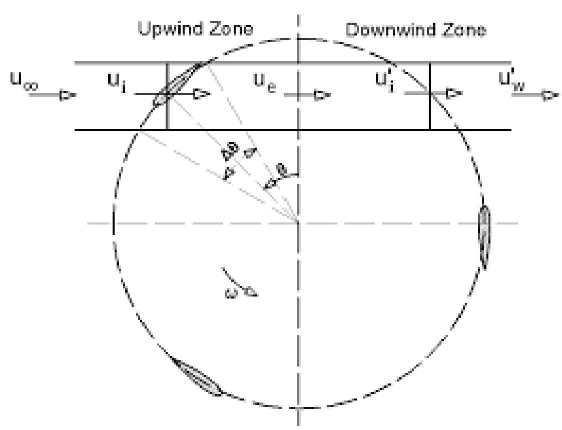

Figure 1: Schematic illustration of DMST [18]

Where € is the domain where those equation will be applied and $\boldsymbol{n}$ is the unit vector normal to $\partial €$ and point outwards. $\sum Fext$ is the sum of forces that flow receives and P is the power output of the portion of the turbine inside the domain.

Physical Definition

In order to define geometry of vertical axis wind turbine in terms of parameters, a Figure 2 is used for this purpose. The relative velocity (u_r) of the wind from blade reference point of view is,

$$\frac{u_r}{U_\infty} = \sqrt{\left(\frac{u}{U_\infty}\right)^2 + TSR^2 + 2\frac{u}{U_\infty}TSR\cos\theta} \tag{4}$$

Also the flight path angle is

$$\beta = \arctan\left(\frac{TSR\sin\theta}{u/_{U_\infty} + TSR\cos\theta}\right) \tag{5}$$

Where U_∞ is the free stream velocity, TSR is the tips speed ratio which is turbine rotational speed divided by free stream velocity. Once the flight angle is known from which angle of incident can be obtained to calculate the lift and drag coefficients by taking data of Cl and Cd from empirical tables. The values which are not present in the tables will be interpolated or extrapolated. The lift and drag will determine the value of Cp which is the performance indicator for the turbine.

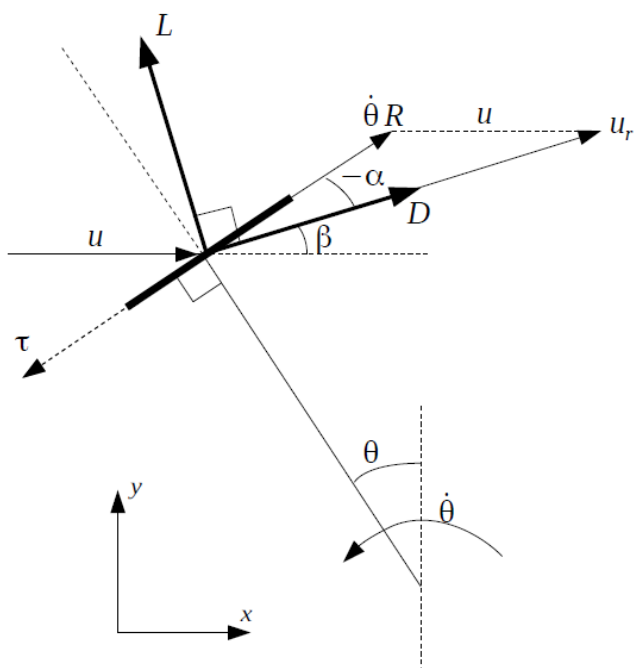

Figure 2: Scheme of the flow velocities and forces from the blade point of view. [14]

And angle of attack,

$$\alpha = modulus\left(\frac{\pi+\beta-\theta}{2\pi}\right) - \pi \quad (6)$$

Once the blade angle of attack is known, the lift coefficient C_L and Drag coefficient C_D, of the vertical axis wind turbine blade profile can be obtained by the experimental data

$$L = {}^{1}/_{2}\, \rho\ \ C_L c\, u_r^2 \quad (7)$$

And

$$D = {}^{1}/_{2}\, \rho\ \ C_D c\, u_r^2 \quad (8)$$

The load that the blade receives from the wind expressed as a function of lifts and drag components,

$$F = [D\ cos\beta - L\ sin\beta]i\ + [D\ sin\beta + L\ cos\beta]j\ , \quad (9)$$

is used to calculate the torque that turbine receives from each blade,

$$T = R\ F.t = R(Ll + Dd).\tau \quad (10)$$

Where $l = -sin\beta\ i + cos\beta\ j$, $d = cos\beta\ i + sin\beta\ j$ and $\tau = cos\theta\ i - sin\theta\ j$. Therefore, the power coefficient obtained from one blade

$$P = \frac{1}{2\pi}\int_0^{2\pi} \dot{\theta}\ T\ d\theta \quad (11)$$

The result of averaging the instantaneous torque times the angular velocity along a period of azimuthal angle is

The coefficient of performance Cp can be calculated using double multiple stream tube model by obtaining Cp front and Cp back.

$$C_{p,1} \equiv C_{p,front} = \frac{\sigma\, TSR}{2\pi} \int_0^{2\pi} C_{T_b}\, \mathrm{d}\theta \qquad (12)$$

Where as Cp back,

$$C_{p,2} \equiv C_{p,back} = \frac{\sigma\, TSR}{2\pi} \int_0^{2\pi} C_{T_b}\, \mathrm{d}\theta \qquad (13)$$

Finally Cp total will be the summation of Cp_1 and Cp_2.

Result and disscussion

A number of simulation has been carried out using matlab 2013 utilizing double multiple stream tube mdoel to predict the performance of the turbine . solidity of the turbine which define the performance of the turbine is

$$\sigma = \frac{\mathrm{N_b\ c}}{2R} \qquad (14)$$

Where N_b is the number of blades used, c is the chord length and R is the radius of the rotor. The solidity is a representation of the blockage effect of the VAWT against the wind [14]. High solidity shows high Cp but drastically fail at high tip speed ratios (TSR). A reference design of Aeolos 1kW is used in this study. Different parameters were wary to change the solidity of the turbine. High solidity shows one of the reasons (a) higher number of blades, (b) longer chord length blades is used or (c) the radius of turbine is small as compared to blade chord. All of the above cases will make the turbine such that at higher tip speed ratios the rotating turbine blades will act as a wall and will not let the mass of the air to pass through it, which will make the design very poor. On the other hand, if the solidity is low the turbine will operate along number of tip speed ratio but will have less maximum efficiency. In figure 4 solidity 0.54 means turbine has diameter of 2 meter, and chord length of 360 mm with three blades, solidity 0.36 shows same number of blades as well as same chord length whereas the diameter of the rotor is taken 3 meters instead of 2 meters. The third case with 0.76 solidity has 4 blades and 360 chord length but with 2-meter diameter of the rotor. The fourth case has utilized the same data as the last case, with only changing diameter from two to three meters. Lastly the data obtained by the CFD (ANSYS) for the same turbine was compared with DMST results.

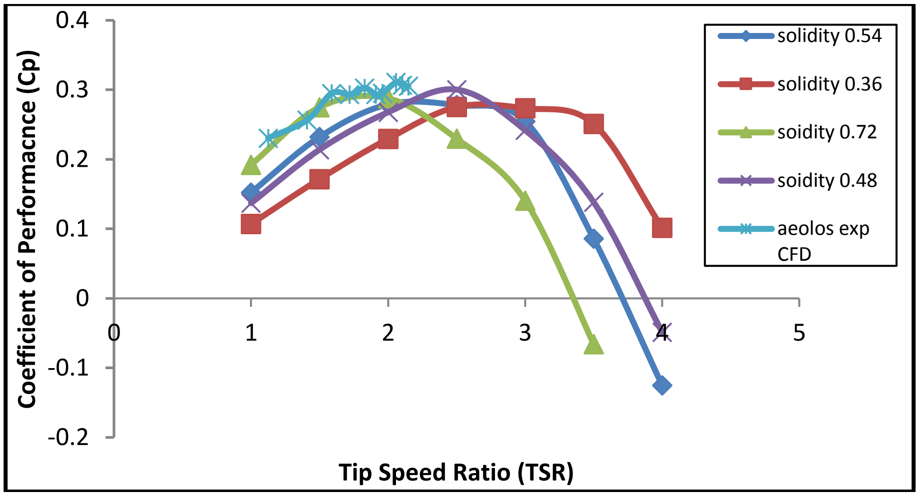

Figure 3: Effect of solidity due to blade and Radius of rotor change. (AEOLOS 1kW)

Furthermore, another airfoil with the name NACA 0021was used to know the effects of solidity and the following results were obtained showed in figure 5.

The result obtained shows similar trend but higher Cps as compared to AEOLOS 1kW, which is obvious for symmetrical blades. The reason symmetrical blades are not used in vertical axis wind turbines is their low startling torque which will make them unable to rotate in the beginning of operation. Contrary to symmetrical airfoil chambered airfoil has less Cp but will resolve startling torque issue.

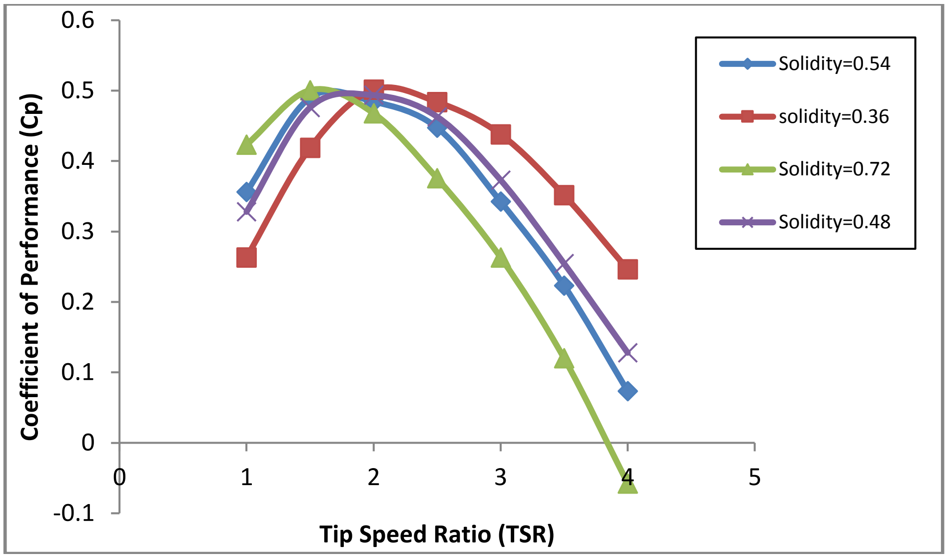

Figure 4: Effects of solidity NACA 0021

Aeolos 1kW and NACA 0021 airfoil were compared with CFD results and the result are validated by another research done using same model as shown in figure 6. When compared Aeolos with NACA 0021 their results shows high Cp of NACA 0021 airfoil, but negative Cp at low tip speed ratios. This result shows that chambered airfoil will reduce Cp but it will improve startling issues, which is one of the main problems in vertical axis wind turbine.

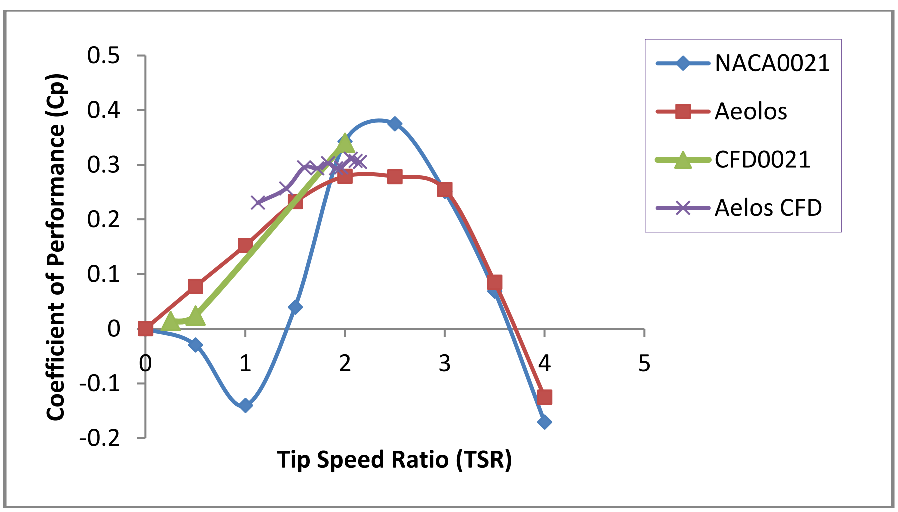

Figure 5: Comparison between NACA0021 and Aeolos 1kW

The comparison between CFD and DMST model results were validated with another work. The difference in the CFD and DMST result is same which validates the work done in my research.

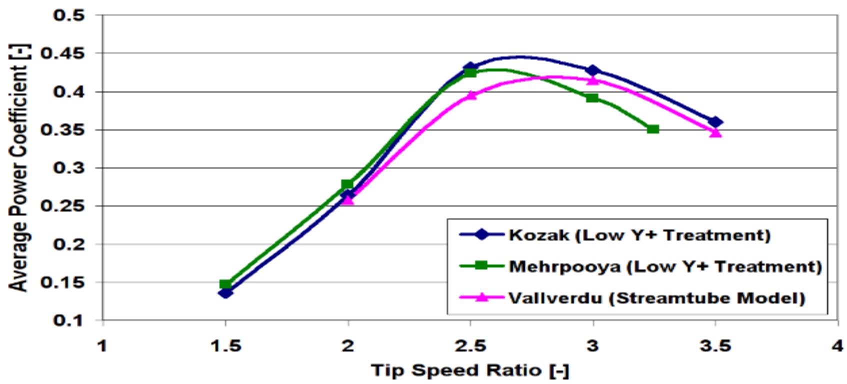

Figure 6: Improvement of VAWT via turbine coupling [17]

Conclusions

In this work, a DMST model has been used to predict the power coefficient of two different turbines designed, AEOLOS 1kW and NACA 0021, employing three and four blades. Number of blades and radius were varied and results were obtained by varying solidity. The following conclusions can be drawn from the present study.

(i) Increasing the number of blades while keeping the same solidity gives similar power curves.
(ii) With a constant solidity, increasing the number of blades from three to four significantly reduces the torque; therefore, radius should also be increased to counter the effect.
(iii) Low solidity shows reduction in Cp but will operate at optimum Cp for number of TSRs, while high solidity shows higher Cp but will operate at optimum efficiency at only one TSR.
Opting for an additional blade reduces the maximum loads generated by the turbine but it also increases the frequency of these loads. However, the reduction of maximum thrust and lateral force obtained by the use of a third or even a fourth blade seems to be significant enough to improve the design life of the turbine. Moreover, higher number of blades might not be favorable to operate at high TSRs. The same is for increasing the chord length will increase the load but will drastically fail at higher TSRs because the turbine will have less area for wind to pass through is when it will operate at high TSRs. Hence, we can rightly select between high Cp and to operate a turbine over number of TSRs, to make it efficient for low wind speed.