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A Computational Study of Drag Type Vertical Axis Wind Turbine for Domestic Scale Power Generation by Utilizing Low Wind Speed

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Abstract - *Rapid increase in global energy requirements has resulted in considerable attention towards energy generation from the renewable energy sources. In order to meet renewable energy targets, harnessing energy from all available resources including those from domestic environment is required. Vertical Axis Wind Turbines (VAWT) are seen as a potential way of utilizing domestic wind energy sources such as low wind energy ranging from 2m/s to 6m/s free wind flow. This study is an attempt to use theoretical methods and Computational Fluid Dynamic techniques used to analyze the performance of a wind turbine under low wind speeds. The geometry of vane profile is selected on basis of lower tangential force is required to move the vane. 3-vane, 5-vane and 7-vane rotor is analyzed for turbulent kinetic energy (k) and concept of negative torque has been studied. Three different types of stationary guide vanes are introduced to rotor to reduce the effect of negative torque. Asymmetric guide vanes perform better by increasing the rotor speed by 13.98% rotor power by 35.86%. It has been shown that CFD analysis using k-ε model can be used as an effective tool to predict the performance outputs of a VAWT.*

***Key Words*: Vertical Axis Wind Turbine, Computational Fluid Dynamics, Vane Profile, Stationary Guide Vanes, Rotational Speed, Rotor Power.**

1. INTRODUCTION

Renewable energy plays a significant role in overcoming the increased energy demand. Considerable amount of research has been carried out in renewable energy sector, mainly in wind energy. Wind energy has a great potential to overcome excessive dependence on fossil fuels to meet energy demand. Along with the need for increased sustainability in the energy sector, wind energy systems are increasing their market share faster than any other renewable energy system. Horizontal axis wind turbines (HAWT) have emerged as the dominant technology in modern wind energy technologies. In comparison to a vertical axis wind turbine (VAWT); a HAWT can achieve higher energy efficiencies, thereby increasing the power production and reducing system expense per kW of power generated. But as the opportunity to expand wind capacity increases, it is important that all aspects of this sustainable and environmentally friendly technology are fully developed. VAWT have demonstrated an ability to fulfill certain energy generation requirements that cannot be fulfilled by HAWT. A HAWT can achieve higher efficiencies, but only if the energy quality of the wind is high. High wind turbulence, wind fluctuations, and high directional variability can cause significant problems for a HAWT, whereas VAWTs can operate well. The performance capabilities of the wind turbines depend greatly on the torque output which further depends upon the torque generating capability of the rotor. The domestic scale wind turbines have immense potential for wind power generation in built up areas. With current commercial domestic scale wind turbines, it is difficult to generate any appreciable power due to their poor performance [1], in domestic areas where wind is in-consistent and highly fluctuating, VAWT is more beneficial due to its low starting torque characteristics as well as other advantages like being in-expensive to build and of simple design. But the field of research for extracting low wind speeds is still open for research for developing standard and efficient drag based wind turbine designs which require lesser initial torque to rotate. With several advantages of drag based vertical axis wind turbine over lift based vertical and HAWT, it gives necessary potential for drag type vertical axis wind turbine for extracting low wind speed from domestic areas.

2. METHODOLOGY

The research objectives are to develop a drag type vertical axis wind turbine with stationary guide vanes so as to enhance performance of VAWT. The basic analysis in this study is restricted to analytical and computational methods. The foremost part of research is theoretical analysis by analytical equations. Then the theoretical analysis is compared with computational method using fluid flow computational tool to evaluate forces, tangential velocity, rotational velocity and torque and then to calculate power that can be generated.

2.1 Theoretical Analysis

Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air, like a sail or propeller can extract part of the energy and convert it into useful work. Three factors determine the output from wind energy converter.

1. Wind speed
2. The cross section of wind swept by rotor
3. Overall conversion efficiency of the rotor, transmission system and generator.

The wind mill works on the principle of converting kinetic energy of the wind into mechanical energy. As the free wind stream passes through a rotor, the wind transfer some of its energy to the rotor and its speed decreases to a minimum in the rotor.

2.1.1 Selection of Vane Profile

The objective is to develop better performing drag type VAWT and for an ideal drag machine, the study on VAWT has mainly concentrated on thrust principle; hence the vane profile should be developed without considering the lift force.

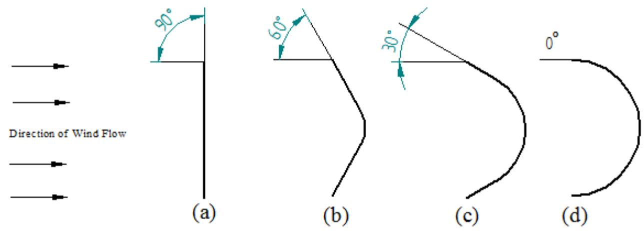


Fig -1: Different types of vane profiles

The vane profile varied from flat plate Fig -1 (a) which is perpendicular to the direction of free wind and vane having uniform section 60° Fig -1 (b), then 30° Fig -1 (c) and finally a semi-circular section Fig -1 (d). The width of vane 'b' that is exposed to free wind is constant 0.1m and height 'h' of vane that is perpendicular to the paper is 0.2m.

The theoretical analyses of these vane profiles are carried out by calculating the tangential force 'Ft' experienced by the vane profile using velocity triangle method. Consider a free wind with density 'ρ' (kg/m^3) and velocity 'V_1' (m/s) is exerting drag force 'F_d' (N) and making vane to move with velocity 'U' (m/s) whose projected area is 'A_v'(m^2) and assuming coefficient of drag i.e. C_d = 1. From the theoretical analysis made by velocity triangle method; the tangential force exerted by the wind on 90°, 60°, 30° and 0° vane profiles as shown in Fig -1 is evaluated and we obtain,

$$\mathbf{F_{t\,60} < F_{t\,90} < F_{t\,30} < F_{t\,0}}$$

The tangential force experienced by the vane is lower for 60° vane profile and it is higher for 0° vane profile. Since, torque 'T' is proportional to tangential velocity exerted by the wind on vane profile. Therefore, the minimum torque required to move the vane is obtained by 60° vane profile; compared to 90°, 30° and 0° vane profile. Thus 60° vane profile i.e. Fig -1 (b) is selected for further work.

2.1.2 Development of Rotor

For selecting rotor parameters two factors play a vital role in the performance of VAWT, which are solidity and aspect ratio. The aspect ratio 'α' of a geometrical shape is the ratio between its sizes in different dimensions. So, as to maximize the power coefficient, the rotor's aspect ratio should be as small as possible [2]. And efficiency of turbine decreases with increase in aspect ratio. Hence aspect ratio of VAWT rotor is the ratio of height of rotor 'H' (m) to the outer radius of rotor 'r_1' (m).

Aspect Ratio, $$\alpha = \frac{H}{r_1} = \frac{0.2}{0.25} = 0.8$$

Solidity 'σ' is usually measures the percentage of the circumference of the rotor which contains material other than air and it is defined as ratio of vane area to the turbine rotor swept area [3]. Solidity of VAWT is directly proportional to number of vanes; keeping the vane area and rotor area constant. Hence increase in solidity explains more number of blades and increases the power output of the wind machine.

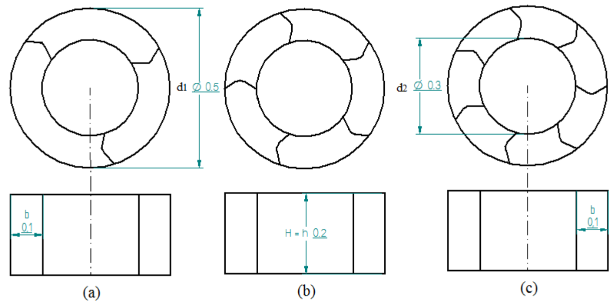


Fig -2: Types of rotor geometry (a) 3-vane (b) 5-vane and (c) 7-vane rotor

The outer diameter 'd_1' of rotor is 0.5m; inner diameter 'd_2' of rotor is 0.3m and height of rotor 'H' is 0.2m. The rotors with three different numbers of vanes are modeled in Solid Edge V19. The top view and front view of VAWT of (a)3-vane, (b)5-vane and (c)7-vane rotor is shown in Fig-2.

2.1.3 Concept of Negative Torque

Despite having some advantages such as fewer moving parts, quieter, lower cost & insensitive to wind direction VAWTs currently used in urban applications do not produce much more appreciable power. One of the major limitations of current VAWTs is the negative torque [4]. This restricts the rotor from accelerating to higher torque producing speeds. The first negative torque is produces on the returning blade (convex side). The second negative torque is produced on the rear blades when the swept airflow moves through the rotor and tries to exit at the rear. This exiting airflow impedes the returning blade. In addition, the exiting air stream is directed back into the path of the approaching wind, creating a turbulent zone which may introduce losses and minimize efficiency.

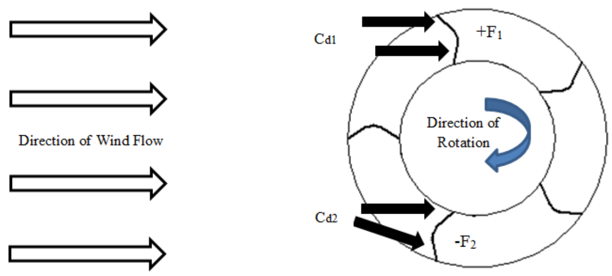


Fig -3: The concept of negative torque

The 5-vane drag type VAWT rotor as shown in Fig -3 experiences the drag force exerted by free wind with velocity 'V_1' m/s and rotates in clock-wise direction. From Fig -3 it is clear that concave side vane with drag coefficient, C_{d1}=2.2 aids necessary force (+F_1) to rotate the vanes meanwhile convex side vane with drag coefficient, C_{d2}=1.1 impede the rotation of vanes by producing negative force (-F_2) opposite to the direction of rotation. Torque 'T_n' generated by 5-vane rotor is calculated by using following equation

$$T_n = 3.5 \times \frac{1}{2} \times \rho \times A_r \times V_1^2 \times r_1 \quad \text{(Eq. 1)}$$

For a VAWT to operate at maximum possible capacity, it is important to eliminate and or to reduce the negative torque for ease of rotation of VAWT, to achieve so the stationary guide vanes are introduced around the rotating vane.

2.1.4 Analytical Study of Stationary Guide Vanes

This performance augmentation device called uni-directional stationary guide vanes (SGV) can help to address the problem of negative torque at low wind speed where the wind turbine can start producing energy at a lower wind [5]. SGV will create the venturi effect to increase the wind speed before the wind stream interacts with wind turbine blades. As a result, the VAWT power output can be improved since it is proportional to V_1^3. For simplicity, it is assumed that the flow is uniformly distributed and fulfills the continuity equation without flow separation [6].

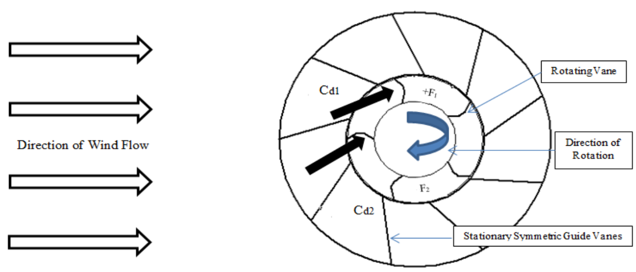


Fig -4: Method to reduce negative torque using SGV

The stationary guide vanes are fixed around the 5 vane rotor, when free wind velocity of V_1 m/s moves then stationary guide vanes deflect the wind flow in such a way that wind hits the rotating vane in tangential direction and exerts the necessary force (+F_1) with drag coefficient, C_{d1}=2.2 which makes the rotating vane to rotate in clock-wise direction irrespective of the direction of free wind flow as shown in Fig -4. This method reduces the influence of negative force by deflecting the wind in only one direction i.e. clock-wise direction.

$$T_p = 1.1 \times \frac{1}{2} \times \rho \times A_r \times V_1^2 \times r_1 \quad \text{(Eq. 2)}$$

Where 'Tp' is total torque generated by incorporating guide vanes (GV); a 5 vane VAWT rotor with stationary guide vanes (SGV) has to overcome to start rotating. From Eq.1 & Eq.2 it is clear that T_p is lower than T_n i.e. the torque required (T_p) for 5 vane VAWT is lower when the stationary guide vanes are incorporated than the torque required (T_n) when only 5 vane VAWT rotor allowed to extract wind energy. From the theoretical analysis it is very clear that, therefore introducing stationary guide vanes to rotating vane minimizes the negative torque.

The study of stationary guide vane is simple in design and it deflects the incoming wind from all direction to aid clock-wise rotation of 5 vane rotor and three different types of uni-directional stationary guide vanes studied are as follows, Wherein uni-directional means SGV deflects wind in such a way that rotor rotates in only one direction irrespective of direction of wind flow. In this case rotor rotates in clock-wise direction.

1. Asymmetric Stationary Guide Vanes (ASGV)

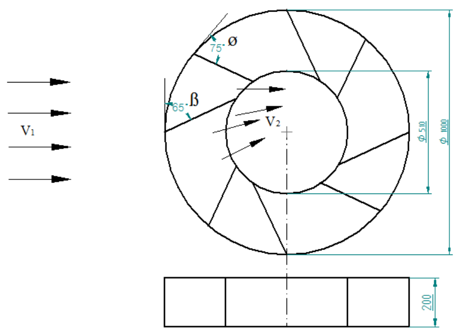


Fig -5: The geometry of asymmetric stationary guide vanes

This is one type of SGV wherein pair of two asymmetric straight guide vanes with angles β and ϕ is situated. Free wind with velocity V_1 hits the ASGV as shown in Fig -5 and there will be increase in wind speed V_2 inside the guide vanes as a result of venture effect created by ASGV.

2. Symmetric Stationary Guide Vanes (SSGV)

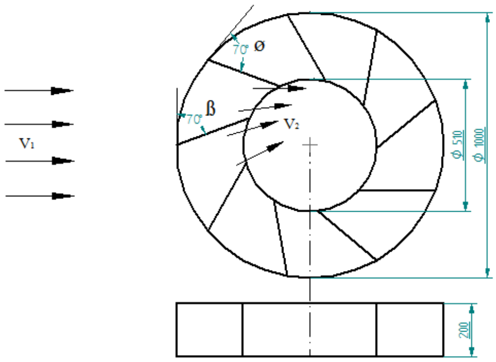


Fig -6: The geometry of symmetric stationary guide vanes

3. Curved Stationary Guide Vanes (CSGV)

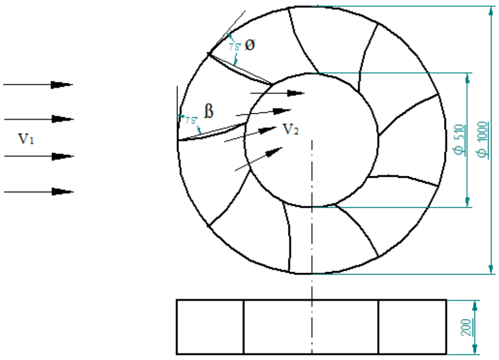


Fig -7: The geometry of curved stationary guide vanes

In SSGV and CSGV with angles β = ϕ are situated. Free wind with velocity V_1 hits the both SGV as shown in Fig -6 and Fig -7 and there will be increase in wind speed V_2 inside the guide vanes as a result of venture effect.

2.2 Computational Analysis

2.2.1 Domain Generation

In practical application the fluid flow across VAWT is always turbulent with higher Reynolds number for that standard turbulent kinetic energy (k) and turbulence dissipation rate (ε) model (k-ε) is used. The k-ε model is very popular for industrial applications due to its good convergence rate and relatively low memory requirements. It does not very accurately compute flow fields that exhibit adverse pressure gradients, strong curvature to the flow, or jet flow. It does perform well for external flow problems around complex geometries. For example, the k-epsilon model can be used to solve for the airflow around a bluff body.

The very first step to get going with CFD analysis is preprocessing. The entire CFD results depend upon the preprocessing parameters such as domain preparation, mesh selection, initial conditions. Since the drag type VAWT is an example of external flow device; that it is kept in environment filled with fluid i.e. air. Generally external flow devices are examined in wind tunnel experiment. In the same way the domain preparation plays very significant role in analyzing, as this domain behaves as the wind tunnel. While generating domain the longest dimension of the model should be taken as reference.

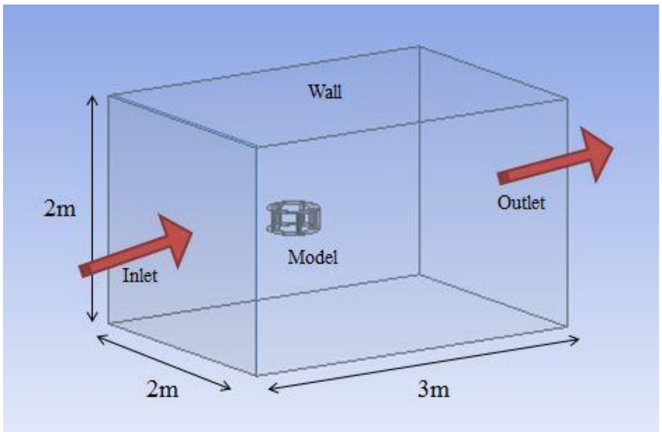


Fig -8: Domain generation over 5-vane single rotor.

Now this domain as shown in Fig-8 acts as duct through which air is made to pass. Mesh generation is adopted by ICEM-CFD method as shown in Fig-9. Now the initial conditions as shown in Table -1 are incorporated during preprocessing.

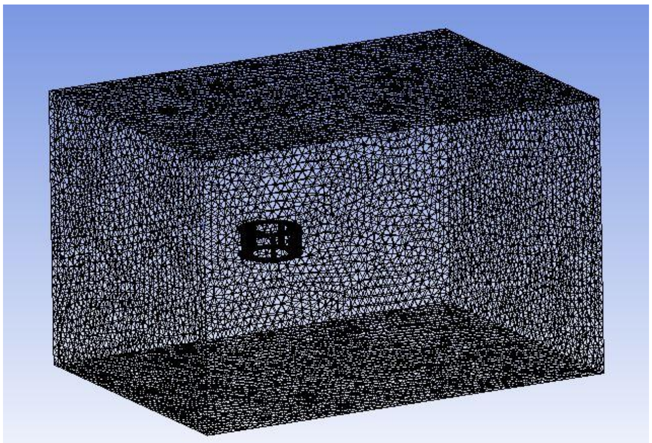


Fig -9: Mesh generation on 5-vane single rotor domain.

Table -1: Initial conditions incorporated into preprocessing

Properties	Values
Fluid Type	Air
Density of fluid (ρ)	1.225 kg/m^3
Fluid Viscosity (μ)	1.789 x 10^{-5} Ns/m^2
Specific Heat (γ)	1.4
Reynolds Number (Re)	273896
Analysis Model	k-ε

And next step is solver where the boundary conditions are applied to the domain as shown in Table -2 which decides the physical condition of fluid flowing through the domain.

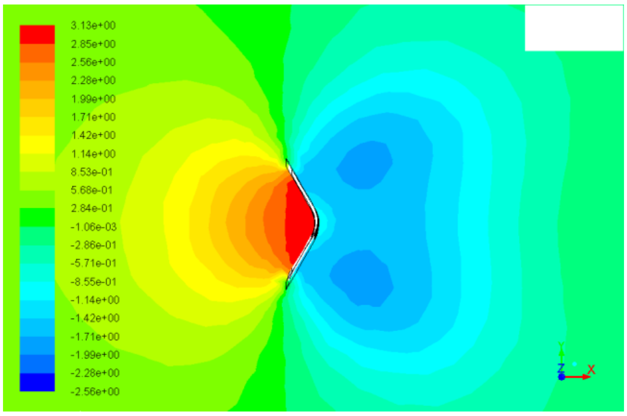
Table -2: Boundary conditions assigned for preprocessing

Inlet	Type - Velocity-inlet	2m/s
	Hydraulic Diameter (Dh)	2m
	Turbulent Intensity (TI)	3.34%
	Gauge Pressure	0 Pa
Outlet	Type - Pressure-outlet	
	Gauge Pressure	0 Pa
Wall	Type - Wall	
	Wall motion	Stationary
	Shear Condition	No slip

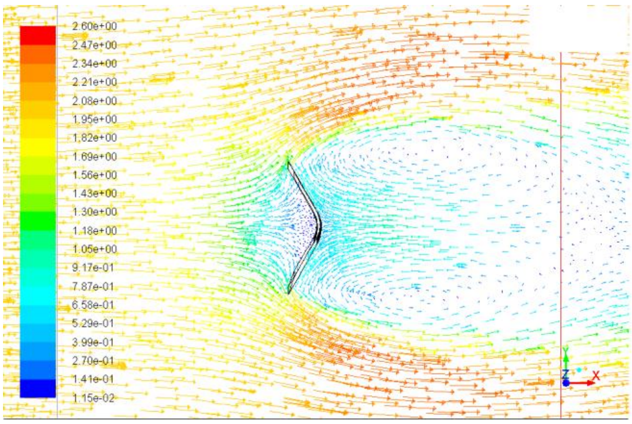
The same computational procedure is adopted for analysis of vanes and analysis of rotor with SGV.

3. RESULTS AND DISCUSSIONS

3.1 CFD results of Vane Profile



(a)



(b)

Fig -10: (a) Pressure contour and (b) velocity distribution of 60º vane profile

It is quite significant that the pressure across vane profile is lower for 60º vane and highest for 0º vane profile. The pressure on incoming side of vane profile is directly related to tangential force required to push the vane. Therefore, higher the pressure then higher the tangential force required to push the vane.

Table -3: Analytical and CFD values of tangential force exerted on vane profile.

Vane Profile	Tangential Force 'Ft' (N)		
	Analytical	CFD	%Error
0º	0.121	0.109	9.917
30º	0.113	0.103	8.850
60º	0.093	0.084	9.677
90º	0.098	0.089	9.184

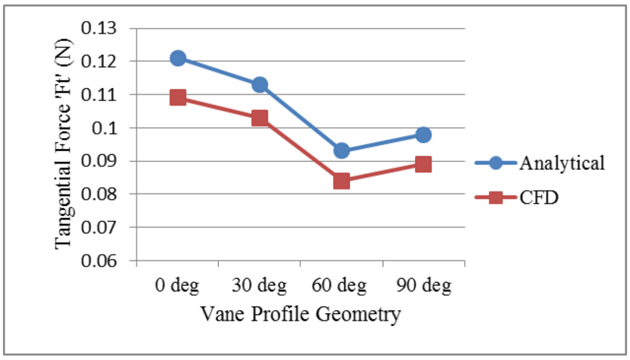
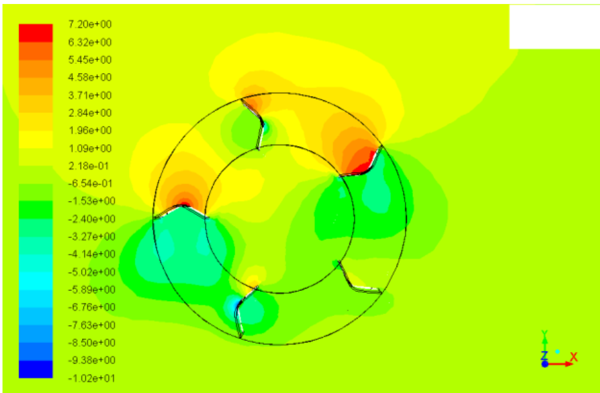


Chart -1: Variation in analytical and CFD values of tangential velocity.

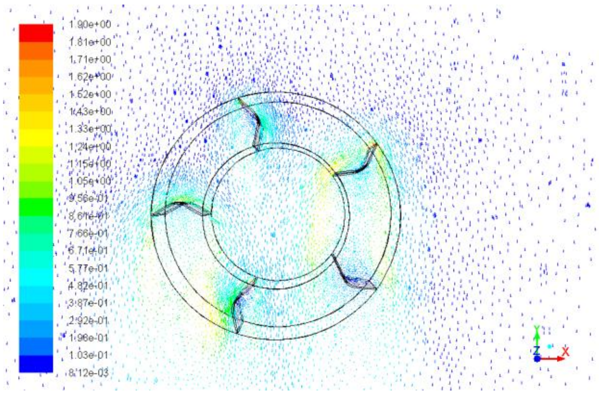
Hence a 60º vane profile experiences lower pressure and require lower tangential force to move and 0º vane profile experiences more pressure and hence require more tangential force to move. Table -3 shows the percentage error incurred between analytical results and computational results. The 60º vane profile is better suited for the development of VAWT rotor so as to extract low wind kinetic energy and convert it into useful electricity; as it requires less tangential force to rotate.

3.2 CFD results of rotor

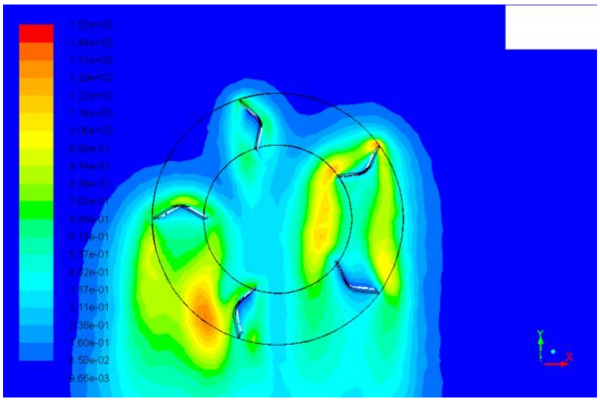
Three different VAWT rotors 3-vane, 5-vane and 7-vane rotors are analyzed for pressure, velocity and turbulent kinetic energy at three different wind speeds such as 3m/s, 4m/s and 5m/s.



(a)



(b)



(c)

Fig -11: (a) Pressure contour, (b) velocity vector distribution and (c) turbulent kinetic energy of 5-vane rotor at 3m/s

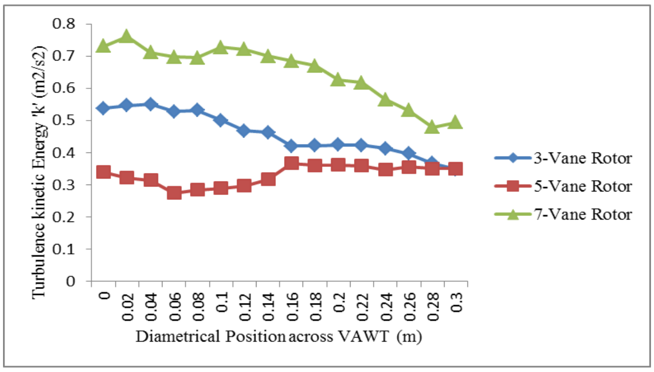


Chart -2: Variation of turbulence kinetic energy at 3m/s along different rotors

The turbulence kinetic energy (k) is a measure of the intensity of turbulence. If 'k' is more; then more dissipation of energy takes place, rather than conservation of energy. The concept is analyzed for three different rotors and observation is concentrated in the core of VAWT, where energy has to be transferred i.e. lower the turbulence kinetic energy then better the conservation of energy. From Chart -2, 3 and 4 it is clear that turbulence created across VAWT is less in 5-vane rotor compared to 3-vane and 7-vane rotor. Hence conservation of energy in terms of kinetic energy is better in 5-vane rotor.

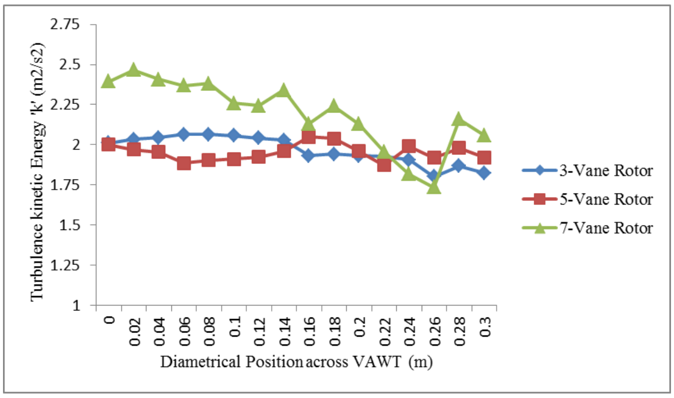


Chart -3: Variation of turbulence kinetic energy at 4m/s along different rotors

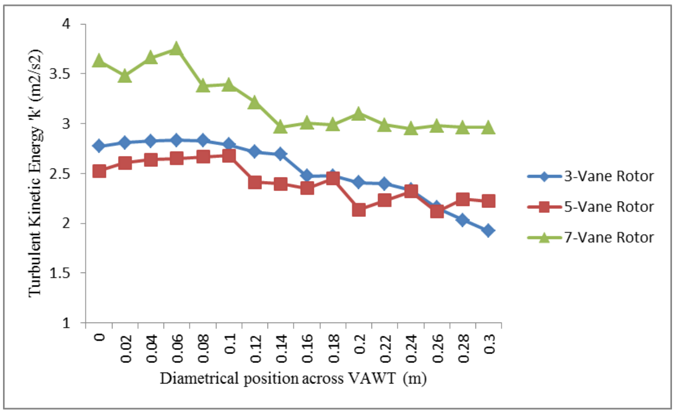
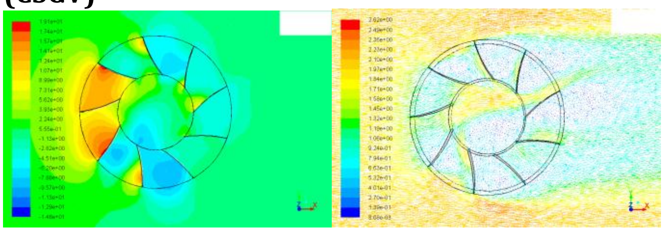


Chart -4: Variation of turbulence kinetic energy at 5m/s along different rotors

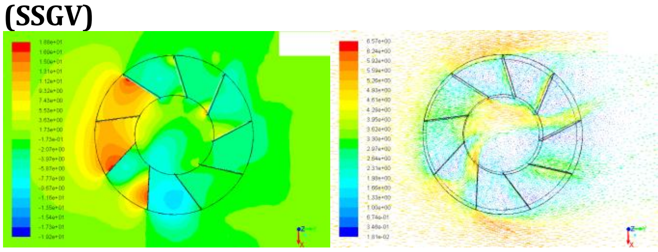
3.3 CFD results of curved stationary guide vanes (CSGV)



(a) (b)

Fig -12: (a) Pressure contour and (b) velocity vector of CSGV at 5m/s free wind velocity

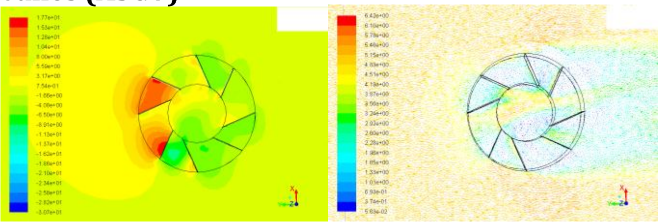
3.4 CFD results of symmetric stationary guide vanes (SSGV)



(a) (b)

Fig -13: (a) Pressure contour and (b) velocity vector of SSGV at 5m/s free wind velocity

3.5 CFD results of asymmetric stationary guide vanes (ASGV)



(a) (b)

Fig -14: (a) Pressure contour and (b) velocity vector of ASGV at 5m/s free wind velocity

After understanding the concept of negative torque it is important to choose the better possible design or geometry of stationary guide vanes. Hence CSGV, SSGV and ASGV is analyzed for pressure and velocity variation at 5m/s as shown in Fig -12, 13 and 14 respectively. Further the pressure and velocity variations are analyzed for various wind velocities from 2m/s to 6m/s and increase in wind velocity is obtained.

The CFD analyses show that using a guide vane not only suppress the effect of negative torque but also enhances the wind speed through it before hitting to rotor. From Table -4 it is clear that, the increase in wind speed is greater in ASGV and lower in CSGV.

Table -4: Variation of wind speed past three different guide vanes

Free wind velocity 'V_1' (m/s)	Wind speed past guide vane 'V_2' (m/s)			
	Without GV	CSGV	SSGV	ASGV
2	2	2.21	2.23	2.27
3	3	3.3	3.35	3.45
4	4	4.39	4.48	4.55
5	5	5.58	5.72	5.73
6	6	6.7	6.87	6.89

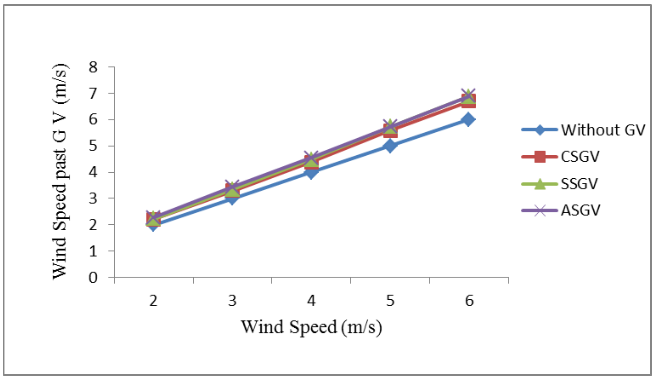
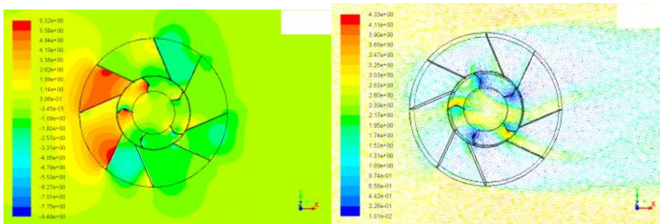


Chart-5: Variation of wind speed past different guide vanes

The main reason behind lower wind speed from CSGV is formation of re-circulation zones within subsequent guide vanes. This makes increase in pressure in the core of CSGV and hence smaller the speed of wind. While ASGV helps wind to speed up not only by creating higher pressure difference across guide vanes but also by increase in pressure difference by reaction effect between two adjacent pair of guide vanes. And finally, without having re-circulation zones in SSGV, it increases the wind speed higher than CSGV. Since SSGV has symmetric profile and it cannot have reaction effect between adjacent vanes, therefore increase in wind speed is lower than ASGV. Chart -5 shows the graphical representation of variation of wind speed past guide vanes.

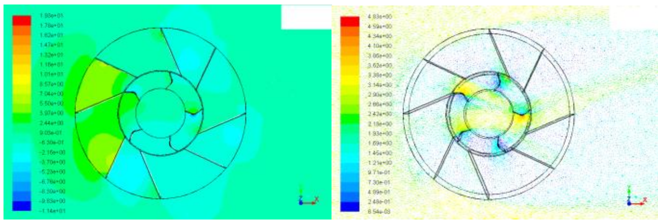
3.6 CFD analysis of ASGV with 5-vane rotor

The research has reached a final segment of the study, where an assembly of 5-vane rotor and asymmetric stationary guide vane (ASGV) is analyzed statically by keeping 5-vane rotor which is making different angles such as 0°, 30° and 60° to the incoming free wind velocity of 3m/s is shown in Fig -15, 16 and 17 respectively. Further the same analysis is carried out for different positions of rotor i.e. 0°, 30° and 60° for 2m/s to 6m/s.



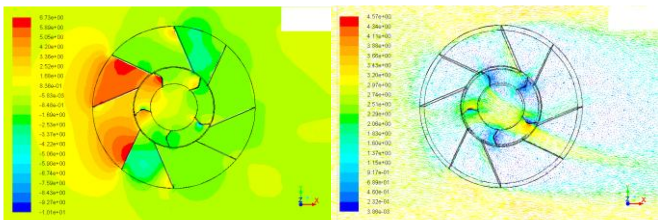
(a) (b)

Fig -15: (a) Pressure Contour and (b) velocity vector at 3m/s of 0° orientation of rotor



(a) (b)

Fig -16: (a) Pressure contour and (b) velocity vector at 3m/s of 30° orientation of rotor



(a) (b)

Fig -17: (a) Pressure contour and (b) velocity vector at 3m/s of 60° orientation of rotor

And the variation of torque over one complete rotation i.e. 360° of 5-vane rotor at wind speed of 3m/s is analyzed as shown in Chart -6. The variation of torque makes the sinusoidal wave in one complete rotation of rotor. When 5-

vane rotor is maintained at 60° to incoming wind flowing through ASGV creates maximum torque, because two vanes experience maximum pressure at this orientation of rotor. Since pressure is proportional to drag force created and intern drag force is proportional to torque. When 5-vane rotor is rotated further to 72° which again resembles 0° rotor orientation to free wind flowing through ASGV, the pressure experienced by two vanes exposed to wind directly is lesser compared to 60° orientation of rotor; and hence the torque reduces at 0°. And later when 5-vane rotor makes 30° orientation, only single vane is exposed to free wind flowing through ASGV and torque experience by the rotor at 30° is still lower than 0° orientation.

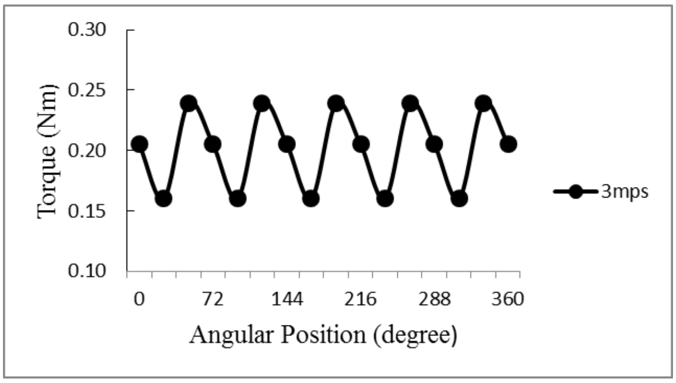


Chart -6: Variation of torque for 360° rotation of 5-vane rotor in a rotor-ASGV assembly at 3m/s

Table -5: The average torque generated at different wind speeds

Orientation of 5-vane Rotor (degree)	Torque 'T' (Nm)				
	2m/s	3m/s	4m/s	5m/s	6m/s
0°	0.094	0.205	0.36	0.565	0.802
30°	0.081	0.160	0.311	0.534	0.779
60°	0.099	0.239	0.389	0.583	0.829
Average Torque	**0.092**	**0.201**	**0.353**	**0.561**	**0.803**

The average torque is calculated for varying torque values from 0°, 30° and 60° rotor orientation at particular speed. In a same way average torque values at different wind speed is calculated as shown in Table -5. The development of guide vane was given importance in reducing the negative torque on rotor. But CFD analysis shows that ASGV geometry not only helps in reducing negative torque but also enhances the performance by increase in rotational speed of rotor as shown in Chart -7.

Table -6: Variation of rotational speed without G V and ASGV at different wind velocity.

Wind Velocity 'V_1' (m/s)	Rotational Speed 'N' (rpm)		
	Without G V	ASGV	% Increase in 'N'
2	20.58	24.02	14.324
3	30.86	35.80	13.793
4	41.15	47.53	13.421
5	51.43	59.67	13.806
6	61.73	71.50	13.669

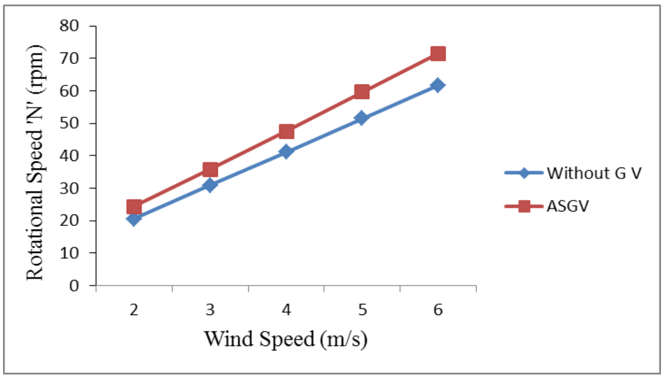


Chart-7: Variation of rotational speed at different wind velocity

The variations of rotor power that can be generate by 5-vane rotor with asymmetric stationary guide vanes and without guide vanes at different wind velocity is as shown in Chart -8. In general power varies in cubical fashion with incoming wind velocity.

Table -7: Variation of rotor power at different wind velocity.

Wind Velocity 'V1' (m/s)	Rotor Power 'P_{rotor}' (W)		
	Without G V	ASGV	% Increase in 'Protor'
2	0.145	0.229	36.684
3	0.490	0.765	35.948
4	1.161	1.790	35.140
5	2.269	3.541	35.922
6	3.920	6.092	35.653

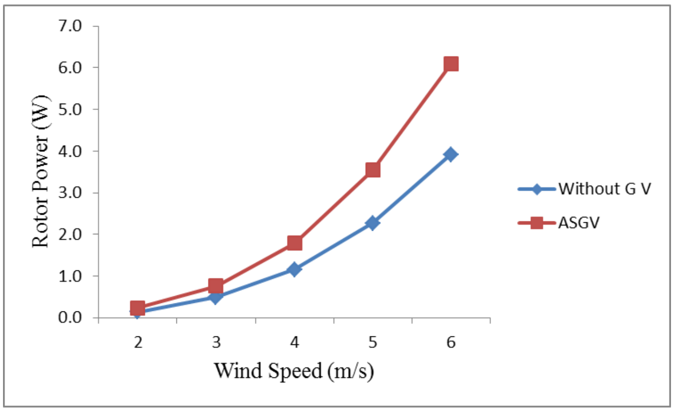


Chart -8: Variation of rotor power at different wind speed with ASGV and without guide vanes (GV)

4. CONCLUSIONS

The major concern to developing nations is to meet energy demand. As conventional energy sources are going to deplete in near century, hence it is important to find an alternative, eco-friendly way to eliminate energy crises. With nearly centuries of research in the field of wind energy, work is majorly concentrated on extracting wind flowing more than 6.5m/s. The present work shows domestic scale vertical axis wind turbine have immense potential in extracting low wind speed ranging from 2m/s to 6m/s. The results obtained so far are very encouraging and reinforce the conviction that vertical axis wind turbine is an emerging technology in the field of wind energy conversion shows that the systems are practical and potentially very contributive to the production of clean energy. In this report importance is given to reduce the effect of negative torque and enhance the performance of VAWT using stationary guide vanes. The CFD analysis is carried out using ANSYS-Fluent 14.5 using steady state, k-ε model and it is compared with analytical results. Following are some useful outcomes of this work.

- VAWT has immense potential in extracting low wind energy from domestic areas and convert it into useful energy.
- One of the drawbacks of VAWT is mainly due to negative torque and development of stationary guide vanes are used to reduce the effect of negative torque.
- Asymmetric stationary guide vane (ASGV) exhibits better result in overcoming negative torque compared to symmetric stationary guide vane (SSGV) and curved guide vanes (CSGV).

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