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The effect of blade angles of the vertical axis wind turbine on the output performance.

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The Effect of Blade Angles of the Vertical Axis Wind Turbine on the Output Performance

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Abstract

There are many social, political and environmental issues associated with the use of fossil fuels. For this reason, there are numerous investigations currently being carried out to develop newer and renewable sources of energy to alleviate energy demand. Wind is one source of energy that can be harnessed using wind turbines. In this study, numerical investigations using CFD analysis have been carried out to determine the optimum dimensions of a wind turbine used in urban environments by varying the rotor and stator blade angles. The effect of these blade angles have been considered to be within the normal operating range (α from 1.689° to 21.689°, δ from 22.357° to 42.357° and γ from 18.2° to 38.2°) while β was kept constant to 90°. The results show that as α increase torque output and power output increases to a certain point after which both these quantities start decreasing. On the contrary to α, as δ increase torque output and power output decreases. From the results it can be concluded that the ideal blade angles, for optimal power output, are $\alpha=16.689^0$, $\gamma=18.2^0$ and $\delta=22.357^0$.

Keywords: VAWT; Power; Torque, Delta, Gamma,alpha

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Introduction

In recent years, the development of new energy sources has been increasing significantly due to continued depletion and consequent rise in fossil fuel prices. A solution to the energy crisis is to find sustainable energy sources that are clean and cost-effective. Wind is one of such energy source that can be harnessed using wind turbines.

Generally, wind turbines can be categorised into two types i.e. Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). From the late 1970s, a number of investigations have been carried out to improve the performance characteristics through design modifications in the Vertical Axis Wind Turbines (VAWT) using both experimental and numerical techniques. Baird et al. [1] conducted a series of wind tunnel experiments to measure the performance output of a small scale vertical axis wind turbine. Various blade shapes, with and without deflectors, have been analysed for their effectiveness in power generation from the VAWT. Pressure and power coefficients for 'S' shaped blades have been calculated and it is reported that the use of deflectors decreases the power output of the VAWT. Travis et al. [2] conducted numerical studies on the aerodynamic shape of conventional VAWT designs. Differential evolution algorithms have been used with available Computational Fluid Dynamic (CFD) tool in order to minimise an objective function based on constraints that are represented by floating point values rather than binary strings. It has been established that optimised VAWT design show a slight increase (1 - 2%) in the performance output of the VAWT. Colley et al. [3] conducted numerical studies to analyse the effects of rotor blade positions on the performance output of a VAWT. In this particular study, Multiple Reference Frame (MRF) approach has been used to rotate the rotor blades of the VAWT. The results stated that torque output of the turbine decreases with an increase in rotor tip speed ratio (TSR) for all rotor blade positions. Furthermore, the findings also concluded that the VAWT power curve characteristics vary with relative rotor blade position. Wirachai [4] conducted a series of laboratory and field tests on various blade designs of Darrieus type VAWT. It has been reported that CFD is unable to predict the performance output of a VAWT accurately and hence it was recommended to have performance field tests. However, the accuracy of the modeling techniques incorporated within the CFD domain was not accurate. Therefore, a highly simplified model with very basic boundary conditions (trying to capture the transient phenomena) was used, which resulted in a very crude agreement between the published and CFD results. Manabu et al. [5] conducted experimental studies to analyse the effects of directed guide vanes on the performance output of a VAWT. The power coefficient and starting characteristics have been investigated in detail to analyse the effects of the angle and gap between the rotor blade and guide vane. It has been shown that use of directed guide vanes increased the peak coefficient of the VAWT considerably. Furthermore, it was also found that by increasing the setting angle increases the performance output of the VAWT. Soraghan et al. [6] conducted numerical studies using double multiple stream tube method to optimise the aerodynamic performance of a VAWT with straight blades. The study introduced a method of calculating effective lift to drag ratio based on averaged torque per cycle. It was shown that solidity and conning angle of a VAWT had a significant impact on its optimal tip speed ratio and power generation. Furthermore, it has been demonstrated that an H-rotor with the same solidity as a V-rotor will operate optimally at a much lower rotational speed and attain a higher power coefficient.

From the reviewed literature it is noticed that optimal designing of vertical axis wind turbines is very important as far as commercial viability of such machines is concerned. In this present study, numerical studies have been conducted to analyse the effect of the inlet and outlet angles of the rotor blades on the overall output performance of the vertical axis wind turbine.

1. Numerical modeling

In order to analyse the effect of rotor blade angles on the performance characteristics of a VAWT; a three dimensional vertical axis wind turbine model, similar to Colley [7], has been numerically created as shown in figure 1. The model has 12 rotor blades and 12 stator blades and the rotor blade angles have been varied in order to quantify effect of blade angles on performance characteristics and to obtain optimal VAWT design .The radius of the core region (r_c) is 0.5m whereas the radii of the stator and the rotor regions i.e. r_r and r_s are 0.7m and 1m respectively. The height of the VAWT, h is 1m.

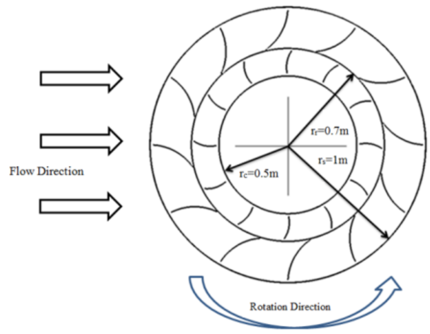

Figure 1: VAWT Dimensions

Figure 2 shows the flow domain used in the simulation of flow around the VAWT. The length, width and the height of the flow domain are 13m, 9m and 3m respectively.

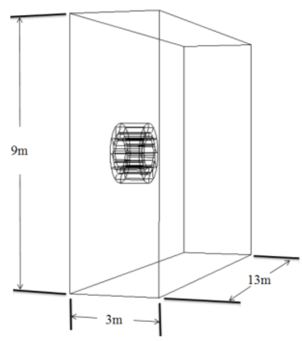

Figure 2: Flow domain dimensions

In order to analyse the effect of the blade angles only specific range of blade angles have been chosen in the present study (α from 1.689° to 21.689°, δ from 22.357° to 42.357° and γ from 18.2° to 38.2°) while β has been kept constant to 90° (see Figure 3 for the definitions of angles). β was kept constant due to design requirement of the incident flow and the inlet of the stator blade to be aligned with each other. The range of other blade angles (α, δ and γ) has been chosen to be within operation envelope, considering the difficulties in the manufacturing of such blades and integration of these blades with an in-house built VAWT.

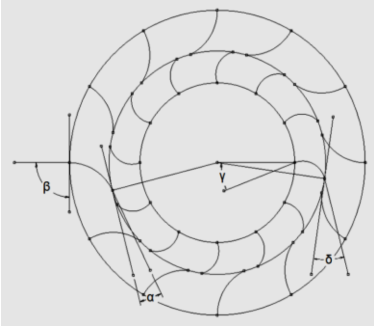

Figure 3: Blade angles of VAWT

1.1. Meshing the flow domain

The mesh has been created in five different steps illustrated in the table below. Domain mesh has been controlled by global sizing function i.e. maximum size of 100mm and minimum size of 0.1.

Table 1. Mesh

Zone	Maximum Size (mm)	Minimum Size (mm)	No. of Mesh Elements
Domain	100	0.1	24097
Stator	20	0.1	34075
Rotor	20	0.1	28167
Core	20	0.1	4061
Blade Edges	0.1	0.1	

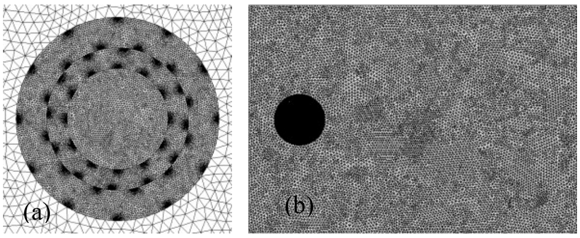

Figure 4: (a&b) show mesh in the VAWT and in the flow domain respectively

2.2. Boundary Conditions

The boundary types that have been specified are listed in the table 2. The incident flow is maintained at a constant velocity of 4m/s throughout this study since it is a practical wind speed value in urban environments. Tip Speed Ratio (λ) is also kept constant at 0.2 as it represents the most common operating condition in real world practice [7]. Atmospheric conditions at pressure outlet boundary means that zero gauge static pressure has been prescribed, which is expected in real world conditions. Furthermore, all the walls in the flow domain have been modelled as no-slip boundaries meaning that the flow does not slip on the surface of the walls.

Table 2. Boundary Conditions

Boundary Name	Boundary Type	Boundary Condition
Inlet	Velocity Inlet	4m/s
Outlet	Pressure Outlet	Atmospheric conditions
Surrounding sides	Stationary Walls	No-Slip
Rotor Blades	Rotating walls	No-Slip
Stator Blades	Stationary Walls	No-Slip
Core & Passages	Interior	Interior

2.3. Sliding Mesh

When a time-accurate solution for rotor-stator interaction (rather than a time-averaged solution) is desired, sliding mesh model should be used to compute the unsteady flow field. The sliding mesh model is a very accurate method for simulating flows in multiple moving reference frames, but is also very computationally demanding. In the sliding mesh technique two or more cell zones are used. Each cell zone is bounded by at least one interface zone where it meets the opposing cell zone, as shown in figure 5. The interface zones of adjacent cell zones are associated with one another to form a mesh interface. During the calculation, the cell zones slide (i.e. rotate) relative to one another along the mesh interface in discrete steps. As the rotation takes place, node alignment along the mesh interface is not required. Since the flow is inherently unsteady, a time-dependent solution procedure is required. This situation requires a means of computing the flux across the two non-conformal interface zones of each mesh interface.

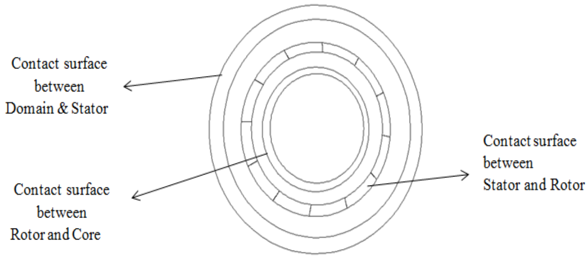

Figure 5: Interfaces between different zones

The flow domain is divided into sub-domains, each of which may be rotating and/or translating with respect to the inertial frame. The governing equations in each sub-domain are written with respect to that sub-domain's reference frame. At the boundary between two sub-domains, the diffusion and other terms in the governing equations in one sub-domain require values for the velocities in the adjacent sub-domain. The simulations have been started from a predefined stator rotor positions identified as 0^o angular position.

2. Results / Discussion

2.1. Effect of blade angle α on the performance output of the VAWT

A numerical analysis has been carried out on a VAWT for α=1.689°; and the results show that there is a high pressure region going up to 39.5 Pa on the windward side of the VAWT whereas the pressure is lower on the leeward side of the VAWT. Furthermore, the pressure is comparatively low on the upper section as compared to the lower section due to the orientation of the blades (figure 6).

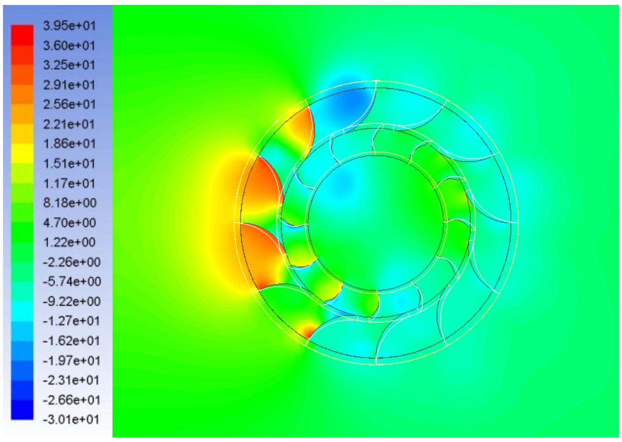

Figure 6: Pressure variations at 0^0 angular position of the VAWT having α=1.689^0, γ=18.2^0 and δ=32.357^0

Additionally, analysing the flow structure in the vicinity of the VAWT, figure 7 depicts that the flow velocity is considerably high within the passages formed on the windward side due to the orientation of the blades. The velocity increases as high as 8.12m/s where the incident flow velocity is 4m/s. The reduction in the effective flow area, as these passages are formed, increases the flow velocity.

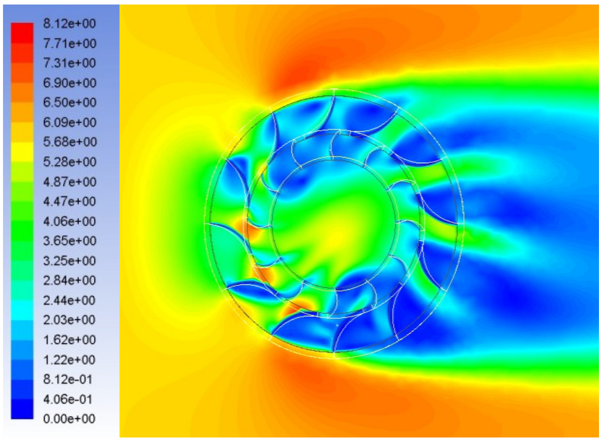

Figure 7: Velocity variations at 0^0 angular position of the VAWT having α=1.689^0, γ=18.2^0 and δ=32.357^0

In order to quantify the performance output of the VAWT considered here, the instantaneous torque output for one revolution of the VAWT has been plotted in figure 8. It can be seen that the torque output of the VAWT is cyclic with the number of peaks/valleys equal to the number of rotor and stator blades. This is due to the orientation of the blades within the VAWT.

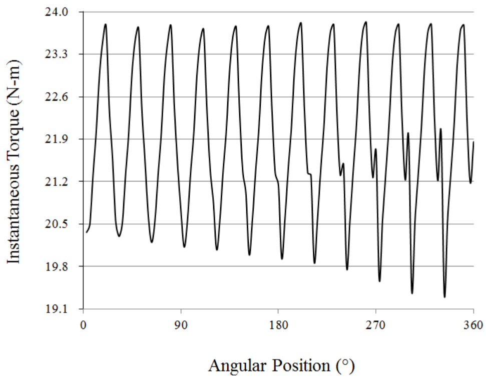

Figure 8: Instantaneous torque output of the VAWT having α=1.689^0, γ=18.2^0 and δ=32.357^0

Table 3 and Figure 9 show that as α increase the average torque (Tavg) output increases, and the average power (Pavg) increases to a certain point after which both these quantities start decreasing. Therefore, there is an optimum value of α that corresponds to the maximum performance output of the VAWT, which in the present study is 16.689^0. It is essential to mention here that the power of a VAWT can be represented by:

$$P = \omega * T$$

Where P is the power output, ω is the angular speed of the rotor blades and T is the torque output of the VAWT.

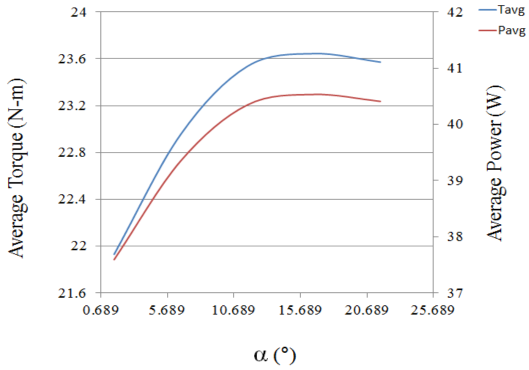

Figure 9: Effect of α on the performance output of VAWT

Table 3. Alpha angle variations

Rotor Angles			Torque Output(N-m)		
α	**γ**	**δ**	**Max.**	**Min.**	**Avg.**
1.689^0	18.2^0	32.357^0	23.81	19.33	21.93
11.689^0	18.2^0	32.357^0	25.71	21.41	23.53
21.689^0	18.2^0	32.357^0	25.69	21.99	23.57

2.2. Effect of blade angle (γ on the performance output of the VAWT

In order to analyse the effect of γ on the performance output of the VAWT, three different γ values of 18.2^0, 28.2^0 and 38.2^0 have been chosen for the analysis purpose, keeping α=11.689^0 and δ=32.357^0 constant. Figure 10 depicts the pressure variation in the vicinity of the VAWT for γ=18.2^0. It can be seen that there is a high pressure region similar to as discussed earlier (increasing to 38.9Pa) on the windward side of the VAWT whereas, the pressure is lower on the leeward side of the VAWT. Moreover, the pressure is comparatively low on the upper section as compared to the lower section due to the orientation of the blades as observed earlier.

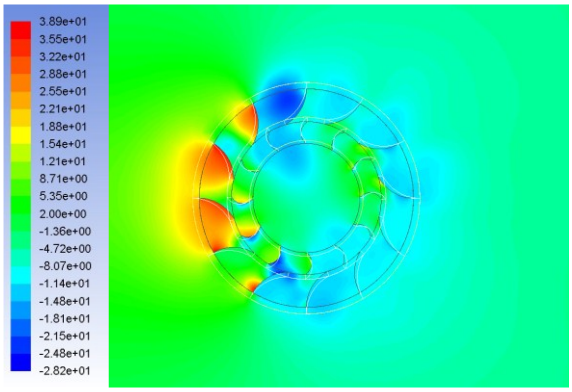

Figure 10: Pressure variations at 0^0 angular position of the VAWT having α=11.689^0, γ=18.2^0 and δ=32.357^0

Figure 11 analyses the flow structure in the vicinity of the VAWT at 0^0 angular position having α=11.689^0, γ=18.2^0 and δ=32.357^0; it can be seen that the velocity variation increases to a maximum value of 8.28 m/s in the passages formed by the windward. This is due to the blade orientation and reduction in the effective flow area that increases the flow velocity as the passages are formed.

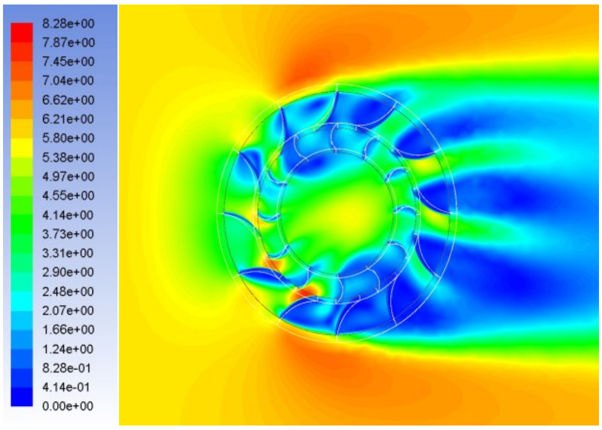

Figure 11: Velocity variations at 0^0 angular position of the VAWT having α=11.689^0, γ=18.2^0 and δ=32.357^0

Figure 12 shows the instantaneous torque output of the VAWT with α=11.689^0, γ=18.2^0 and δ=32.357^0 for one revolution. It depicts that the torque output of the VAWT is cyclic. Additionally, it can be seen that the maximum torque output is 26.3N-m whereas the minimum is 22.5N-m.

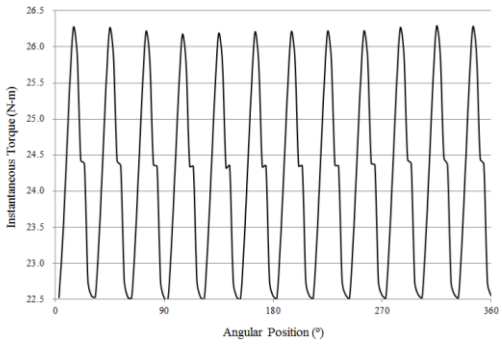

Figure 12: Instantaneous torque output of the VAWT having α=11.689^0, γ=18.2^0 and δ=32.357^0

Furthermore, Table 4 shows the performance output of the VAWT for the three different values of the blade angle γ considered in this particular study.

Table4. γ Angle variations

Rotor Angles			Torque Output(N-m)		
α	**γ**	**δ**	**Max.**	**Min.**	**Avg.**
11.689^0	18.2^0	32.357^0	26.29	22.50	24.17
11.689^0	28.2^0	32.357^0	25.71	21.41	23.53
11.689^0	38.2^0	32.357^0	25.30	21.00	22.98

Figure 13 shows the effect of γ on the performance output. It can be seen that for a given α and δ, as γ increases, the average torque output and the average power output of the VAWT decreases. Hence, indicating that lower γ angle generates more torque and power outputs from the VAWT. Moreover, it can also be seen that there are non-linearities in the curves that arises due to complex and transient interactions between the blades.

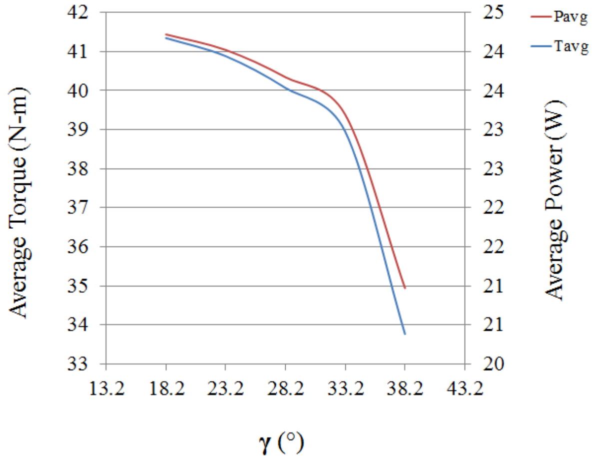

Figure 13: Effect of γ on the performance output of VAWT

2.3. Effect of angle (δ on the performance output of the VAWT

In order to analyse the effect of δ on the performance output of the VAWT, three δ values of 22.357^0, 32.357^0 and 42.357^0 have been chosen for the analysis, keeping α=11.689^0 and γ=28.2^0 constant. Figure 14 represents the pressure variations in the vicinity of the VAWT for δ=22.357^0. It can be seen that the presence of non-uniformly distributed pressure with high pressure (increasing to 39.1Pa) on the windward side of the VAWT and low pressure on the leeward side of the VAWT. Additionally, the pressure is comparatively low on the upper section as compared to the lower section due to the orientation of the blades as observed earlier.

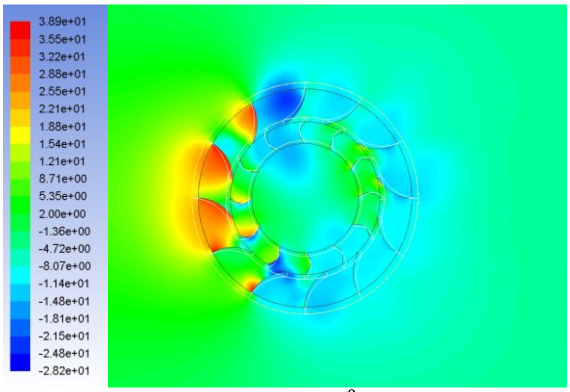

Figure 14: Pressure variations at 0^0 angular position of the VAWT having α=11.689^0, γ=28.2^0 and δ=22.357^0

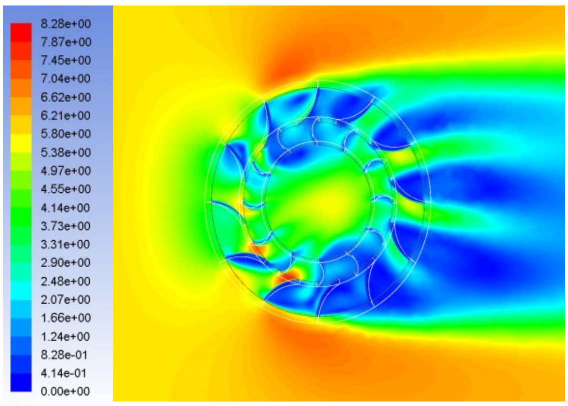

Figure 15: Velocity variations at 0^0 angular position of the VAWT having α=11.689^0, γ=28.2^0 and δ=22.357^0

Figure 15 depicts velocity variations at 0^0 angular position of the VAWT having α=11.689^0, γ=28.2^0 and δ=22.357^0. It can be seen that velocity magnitudes are considerably higher over a large flow area in front of the wind turbine. The velocity increases as high as 9.21m/s whereas the incident flow velocity is 4m/s. The reduction in the effective flow area as these passages are formed increases the flow velocity.

Figure 16 shows the variation in instantaneous torque output of the VAWT with $\alpha=11.689^0$, $\gamma=28.2^0$ and $\delta=22.357^0$. Figure depicts that the torque output of the VAWT is cyclic as earlier.

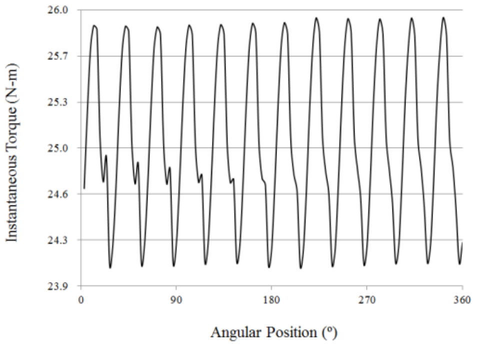

Figure 16: Instantaneous torque output of the VAWT having $\alpha=11.689^0$, $\gamma=28.2^0$ and $\delta=22.357^0$

Table 5 provides the torque output of VAWT. It is clearly shown that the average torque output for $\delta=42.357^0$ is considerably lower than for $\delta=32.357^0$ (by 8.5%). An important point to mention at this stage is that as δ increases, the amplitude of the torque output also increases (125% from $\delta=22.357^0$ to 32.57^0 and 26% from $\delta=32.357^0$ to $\delta=42.357^0$).

Table 5. Delta angle variations

Rotor Angles			Torque Output(N-m)		
α	**γ**	**δ**	**Max.**	**Min.**	**Avg.**
11.689^0	28.2^0	22.357^0	25.94	24.05	25.01
11.689^0	28.2^0	32.357^0	25.71	21.41	23.53
11.689^0	28.2^0	42.357^0	24.42	19.00	21.51

Figure 17 shows that the average torque output and power output from the VAWT decreases almost linearly. It is evident that for $\delta=22.357^0$, the torque output is considerably higher than for the other two models. Therefore it can be concluded that as δ increases, the torque output of the VAWT decreases. This trend is contrary to the one observed for α, where the torque output increases as α increases (up to a certain point).

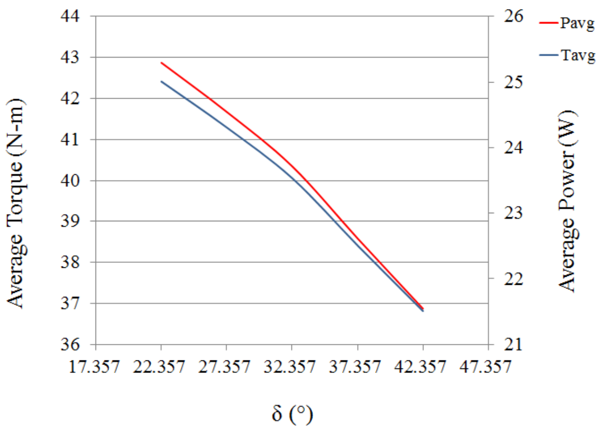

Figure 17: Effect of δ on the performance output of VAWT

3. Optimal VAWT Design

After carrying out detailed analysis on the performance output of various VAWT configurations, the optimal VAWT design based on blade angles considered in the present study, is the one with $\alpha=16.689^o$, $\gamma=18.2^o$ and $\delta=22.357^o$. Figure 18 and 19 represent the pressure and velocity variations in the vicinity of the optimal VAWT.

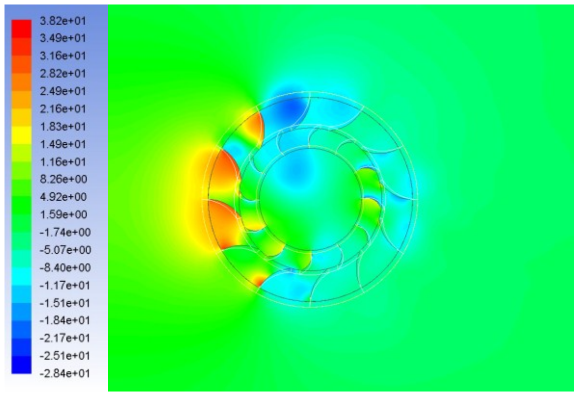

Figure 18: Pressure variations at 0^0 angular position of the VAWT having $\alpha=16.689^0$, $\gamma=18.2^0$ and $\delta=22.357^0$

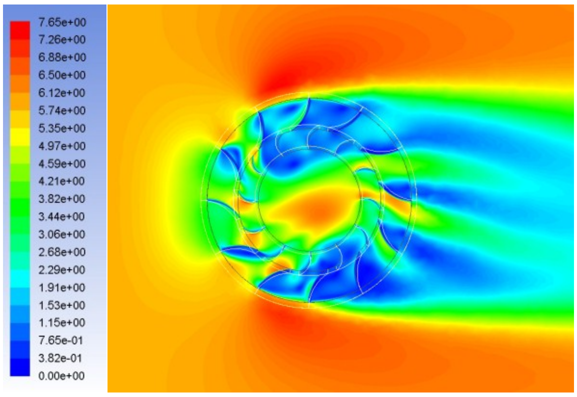

Figure 19: Velocity variations at 0^0 angular position of the VAWT having $\alpha=16.689^0$, $\gamma=18.2^0$ and $\delta=22.357^0$

Figure 20 depicts the instantaneous torque output from the optimised VAWT design. The torque output is cyclic but average value over one revolution is higher than previous combinations (Table 6).

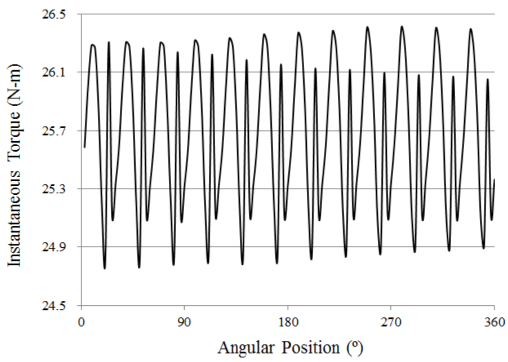

Figure 20: Instantaneous torque output of the VAWT having $\alpha=16.689^0$, $\gamma=18.2^0$ and $\delta=22.357^0$

Table 6. Torque output from optimal design

Rotor Angles			Torque Output(N-m)		
α	**γ**	**δ**	**Max.**	**Min.**	**Avg.**
16.689^0	18.2^0	22.357^0	26.41	24.8	25.67

4. Conclusion

In this study, the effect of various blade angles on the vertical axis wind turbine performance output has been numerically examined and analysed. It has shown that the pressure and the velocity fields in the vicinity of the VAWT are highly unsymmetrical and non-uniform. The instantaneous torque output of the VAWT consists of peaks and valleys equal to the number of blades of the VAWT. The results suggest that increase in α increases the performance output of the VAWT up to a certain value after which the torque starts decreasing with increasing α However, increase in δ decreases the performance output of the VAWT.

It has been concluded that the ideal blade angle, for optimal power output from VAWT, are $\alpha=16.689^0$, $\gamma=18.2^0$ and $\delta=22.357^0$.

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