

Experimental and Computational Investigations of Vertical Axis Wind Turbine Enclosed with Flanged Diffuser

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Abstract. Generation of wind energy is a must to meet out additional demand. To meet out the additional demand several long term plans were considered now being taken up for generation of energy for the fast developing industries. Detailed researches were since taken up to improve the efficiency of such vertical axis wind turbine (VAWT). In this work VAWT with diffuser and without diffuser arrangement are considered for experimental and analysis. Five diffusers were since provided around its blades of VAWT which will be placed inside a pentagon shaped fabricated structure. In this power output of the diffuser based VAWT arrangement were studied in both numerical and experimental methods and related with that of a bared VAWT. Finally, it was found that the output power of diffuser based VAWT generates approximately two times than that of bared VAWT.

1. Introduction

Wind energy is one type of renewable energy. For the application of an effective renewable energy resource inside the destiny and thinking about the dilemma of fossil fuels and with the safety of alternative energy and assets is an essential issue. Besides, due to limits on natural issues the improvement and the utility of renewable and new clean energies are predicted. The wind energy technology was developed swiftly and to play a huge role in a brand new energy subject. The essential aim of the wind turbine is to enhance the performance and efficiency. If the efficiency of a wind turbine is increased, the power of a wind turbine also increases according to Buyung Kosasih and Andrea Tondelli [5] were studied about power factor of the wind turbine which was increased to 2.0. Then the examine manner for the VAWT's execution could be conveyed out from various perspectives, such as analytical solutions, wind tunnel experiment, wind field experiment and numerical simulations.

In vertical-axis wind turbine (VAWT) the main rotor shaft is set to rotate in a vertical direction. From the type of VAWT, Savonius wind turbines are chosen for the purpose of reliability. Akinari Shigetomi et al., [1] investigated that multiple Savonius turbines are combined in the horizontal plane produces the extra amount of power in precise configurations. Much larger Savonius turbines have been used to produce electric power for profound water buoys, which require the little amount of power with low maintenance. The design of the wind turbine may be rearranged because unlike with horizontal axis wind turbines (HAWT), there will be no necessity from claiming pointing mechanism which may be needed for moving wind progression and the turbine is self-starting at diverse wind speed condition [16].

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In this paper, bared vertical axis wind turbine and diffuser based vertical axis wind turbines are compared. The diffuser-type wind turbine will be fit about gathering additionally accelerating those winds at high velocity[8]. Eventually by adding diffuser with a flange which is equipped to build the wind speed from forthcoming wind essentially by using different flow characteristics [15][17]. If a flange is added at the delivery end of the diffuser, power generation gets improved and the power directly proportional to cubic a velocity [9]. Hence the divergent diffuser of the wind turbine produces thrice the power of velocity than bared wind turbine. Many researchers were investigated in the first decade of the twentieth century [3][4] [20][21].

A numerical method is one type of method which is used for simulation purpose and it is based on Finite Volume Method (FVM). According to Wong. K.H. et al., [18] they were carried out that the wind flow of power augmented shrouded wind turbine with a single blade NACA 0015 aerofoil of VAWT using the solver of ANSYS FLUENT 14.0 with shear stress transport (SST) $k-\omega$ model with sliding mesh technology the coefficient of power of the respected wind turbine was predicated. With the help of computational fluid dynamics is used to predict the wake regions and all other parameters such as pressure and velocity, whereas RANS can confirm wake measurement by Reynolds stress model over a flat terrain [2]. Elkhoury. M et al., [7] were studied about that CFD is capable of solving a lot of 3D problems and simulated a micro VAWT. This micro VAWT had three blades with struts. By using the approach of Large Eddy Simulation (LES) with dynamic Smagorinsky Subgrid Scale (SGS) model understand the associate go along with the flow structure via the use of wind speed, turbulence intensity, airfoil shape, and performance have been calculated. According to Basu. D et al., [6] DES technique and hybrid RANS/LES models which are mainly used to predict the unsteady the separated flows. The Omni-flow wind turbine is solved numerically by Finite Volume Method (FVM) and the turbulence model has studied with the help of several RANS models such as Standard $k-\epsilon$, Realizable $k-\epsilon$, Standard $k-\omega$ and SST $k-\omega$ models, further, the torque and performance of the wind turbine are found [20]. Huming Wang et al.,[9] studied about the 2D unsteady flow condition, by varying velocities of input and its respected torque and performance of the wind turbine and are founded by Realizable $k-\epsilon$ model. Then Ji Yao et al., [11] were investigated that by influencing the turbulence model of VAWT the technology of sliding grid and Semi-Implicit Method for Pressure-linked Equation (SIMPLEC) algorithm under unsteady flow fields, find the variations of the velocity field, pressure field and torque of the wind turbine. The micro-wind turbine rotor having semi-circular blades are compared with Savonius rotor to find the average of torque and coefficient of performance using unsteady continuity RANS equation. Additionally, Realizable $k-\epsilon$ turbulence model using SIMPLE algorithms as well as Sliding Mesh Model are used to solve the rotational motion of the wind turbine by Yan-Fei Wang and Mao-Sheng Zhan [19]. Rolland. S et al., [15] state CFD tool were mainly developed for analyzing purpose which saves more time and gave more accuracy while comparing experimental method. Along with that, it can be used for evaluation purposes, such as wind speed, yaw angle, rotor speed and blade pitch angle of VAWT. According to Matin S. Aube et al., [14] were carried out highly complicated problems in wind engineering can be solved and simulations were computed with Navier-Stokes solver FENSAP at steady-state condition using an ensemble averaged Navier-Stokes equation. It was found that diffuser can be used to increase the velocity flow hence the power can be increased. From the survey, the objective of the work is fixed that flow of a VAWT with diffuser and without a diffuser to be analyzed by CFD simulations and compared the simulation work with experimental work.

2. Experimental Setup

The wind turbine is a device used for the purpose of wind energy conversion. The wind turbine follows a basic principle of converting the kinetic energy of the wind's motion into mechanical energy that energy is transmitted to the shaft and connected with generator further it converts to electrical energy. With the help of a compressor, the input velocities are varied on different levels.

2.1 VAWT without diffuser

Savonius type VAWT with four blades are selected to conduct experimental work to predict power is shown in Figure 1, while conducting experiments various parameters are taken into consideration for the calculation which is given as follows

Pressure of the surrounding, $P_1 = 1.013$ bar

Temperature in the surrounding, $T_1 = 298 \text{ K}$
 Swept Area of the turbine, $A_1 = 0.07\text{m}^2$



Figure 1. Bared VAWT

2.2 Coefficient of performance and Power

The power in the wind can be computed by using the concepts of kinetics.

$$K.E = \frac{1}{2} \rho AV^3 \tag{1}$$

This equation (1) tells us that the power available is proportional to air density (ρ) and intercept area where A is the Area of the turbine and V is the Velocity of air.

Coefficient of performance is important parameter to calculate the power of VAWT. Coefficient of power is calculated by equation (2)

$$P = 0.5\rho A V^3 C_p \text{ Watts} \tag{2}$$

2.3 Power of the Bared VAWT

The entry velocity is varied with the help of compressor and the corresponding exit velocity and speed of turbines are measured by using Anemometer and Tachometer. The power produced by the bared type VAWT for various wind velocity and speeds are calculated and listed in Table 1.

Table 1. Power calculation of bared based VAWT

| Entry Velocity (m/s) | Exit velocity (m/s) | Speed (rpm) | Coefficient of performance (no unit) | Power (W) |
|----------------------|---------------------|-------------|--------------------------------------|-----------|
| 6.1 | 9.8 | 109 | 3.13 | 27.08 |
| 8.0 | 12.1 | 128 | 2.70 | 52.73 |
| 9.4 | 15.7 | 140 | 2.45 | 108.42 |
| 10.5 | 19.8 | 154 | 2.31 | 175.28 |

2.4 Diffuser based VAWT

A Pentagon shaped diffuser setup is arranged around the bared VAWT to carrying out experiment shown in Figure 2. To improve the power with the help of compressor the input velocities ear varied and the correspondent exit velocities and speed are measured and listed in Table 2. The corresponding power also calculated is listed in the same table.



Figure 2. Diffuser based VAWT

Table 2. Power calculation of diffuser based VAWT

| Entry Velocity (m/s) | Entry velocity of diffuser1 (m/s) | Exit velocity of diffuser2 (m/s) | Speed (rpm) | Coefficient of performance (no unit) | Power (W) |
|----------------------|-----------------------------------|----------------------------------|-------------|--------------------------------------|-----------|
| 6.6 | 8.6 | 3.4 | 201 | 4.60 | 50.40 |
| 8.8 | 10.8 | 4.8 | 241 | 4.00 | 104.00 |
| 10.2 | 12.3 | 5.0 | 285 | 4.06 | 164.27 |
| 12.5 | 14.3 | 6.8 | 324 | 2.99 | 213.00 |

2.5 Coefficient of performance and power

The graph clearly explained that the wind velocity increases the power of the turbine is increased. At the meanwhile, the power of the diffuser based VAWT increases to a greater extends which is represented in Figure 4. The relationship between input velocity and coefficients of performance are plotted in Figure 3. From the graph it was observed that coefficient of performance is more in diffuser based VAWT compared to bared VAWT because diffuser collects more amount of velocity than bared VAWT, so the rotation of the blade is increased and its performance of the VAWT also increased. Figure 3 shows that for 12.5m/s input velocity the coefficient of performance is 0.2 and 0.4 for bared and diffuser based VAWT respectively. Similarly for 4.1m/s input velocity coefficient of performance is 0.6 and 1.6 for bared and diffuser based VAWT respectively. The difference between the bared and diffuser based VAWT is higher at starting due to higher torque at initial.

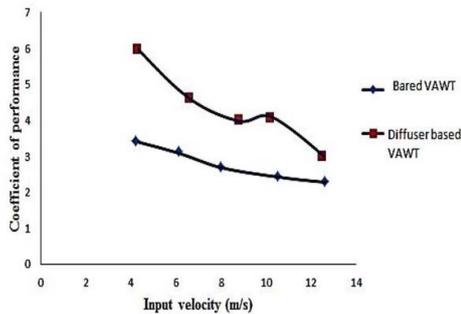


Figure 3. The coefficient of performance Cp of bared and diffuser based VAWT as a function of input velocity (m/s)

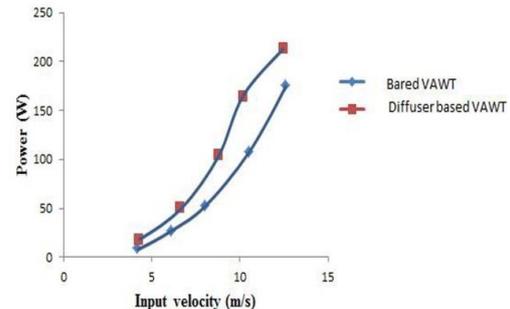


Figure 4. Performance curve of bared and diffuser based VAWT as a function of input velocity (m/s)

The performance curve is plotted between power and wind velocity is shown in Figure 4. The length of the diffuser is made. Along with this the brim height also made. Then diffuser setup which surrounded the blade of the wind turbine. By using this setup flow velocity through the turbine area is accelerated up to approximately more than twice times than the main flow velocity. This increases the power output from the turbine. The conventional wind turbines do not produce the same amount of electricity all the time. But also the same amount of electricity is produced at all conditions.

3. Computational Modeling

Computational fluid dynamics (CFD) modeling is a common technique which used for the persistence of understands the compartment of airflow at interior and exterior conditions. In this computational modeling, diffuser based vertical axis wind turbine and a bared vertical axis wind turbine have been undertaken to determine outlet velocity and visualize the velocity profiles at different conditions. To simulate the velocity profile the airflow over the model had been tested for diverse wind velocities and the turbine is specified to be spinning at constant Rotation per Minute (RPM) towards its adjacent velocities.

3.1 Modeling Details

The 3D model of VAWT was created using Solidworks 12.0. The geometrical details of four blades

with vertical shaft are shown in Figure 5. The height of the blade is 300mm. From the literature review, it was observed that diameter of the blade is equal to a height of the blade Ken-ichi Abe and Yuji Ohya [12].

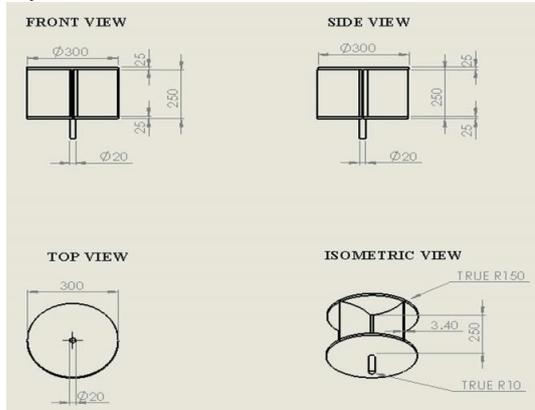


Figure 5. 2D Model of bared VAWT

The thickness of the blade is 3.70mm with an angle of the single blade is 45° and angle between blades are 90° which its following diagram is shown in Figure 5. The structure of the blade was designed based on aerofoil structure and a variable pitch. The purpose behind picking four blade wind turbine model is hosting those ability to process higher torque over that two alternately three blade wind turbine. Normally, four blade wind turbine model has more drag force in at whatever position. Also at low tip speed, the turbine rotates slowly, so it produces less noise Toshiaki Setoguchi et al., [17]. In VAWT the power is proportional to V^3 and diffuser based VAWT increases the velocity hence the power increases according to Bernard Francois and Ivan Vrslovic [3]. Five diffusers surrounded by the blade of VAWT forms the Pentagon structure. In the front end of the VAWT, three inlet diffusers act as convergent type its dimension is 80mm x 100mm. Then at the other end, two outlet diffusers act as divergent type its dimensions are 140mm x 180mm. The length of the diffuser model is 140mm. The width of the brim is 25mm respectively Ken-ichi Abe et al., [12]. Although it adopts a diffuser-shaped structure which surrounds a wind turbine and the reputable brim is hooked up at the exit of diffuser shroud. According to Laila ledo gomis [13], the wind turbine is located within the diffuser shroud attached with a brim and evaluated the power output get generated. The shrouded wind turbine is properly-gear up with a flanged diffuser established and its power augmentation for a respected wind turbine diameter and wind speeds which are compared to a standard micro wind turbine Yuji Ohya and Takashi Karasudani [22]. The combination of a diffuser shroud and a brim is based on its length, which its following diagram is shown in Figure 6.

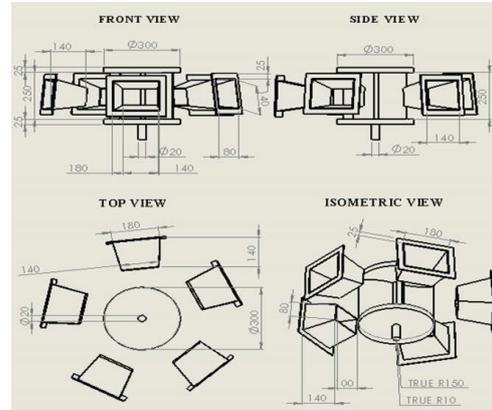


Figure 6. 2D model of diffuser based VAWT

3.2 Meshing Strategy

The model of bared VAWT is imported to flow analysis and the surface area of the blade geometry meshes with triangular elements shown in Figure 7. To simulate the flow actions of the fluid volume mesh are generated using tetrahedral elements is shown in Figure 9.

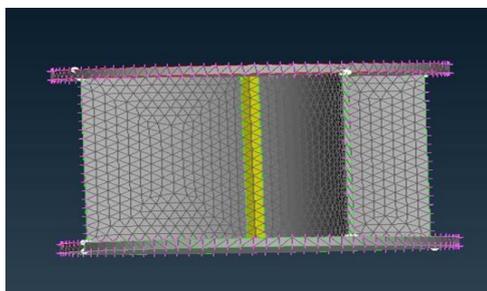


Figure 7. Surface mesh of Bared VAWT

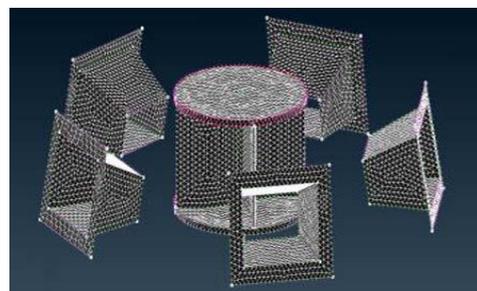


Figure 8. Surface mesh of Diffuser based VAWT

Similarly, for diffuser based VAWT, the surface area of the whole setup meshes with triangular elements using the software of ANSA and volume mesh are generated using tetrahedral elements in ANSYS FLUENT shown in Figure 8 and Figure 10. The total numbers of elements used in a surface mesh are 24618 and 108458 for bared VAWT and diffuser based VAWT respectively. Similarly, the total numbers of elements used in volume mesh are 80656 and 113000 for bared VAWT and diffuser based VAWT respectively.



Figure 9. Volume mesh of bared VAWT

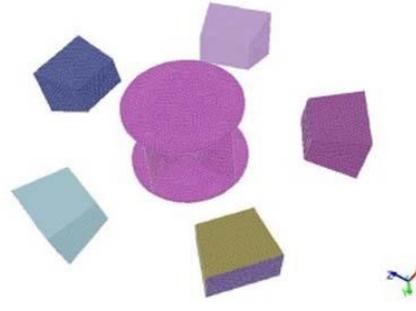


Figure 10. Volume mesh of Diffuser based VAWT

3.3 Boundary Conditions and CFD solver approach

To simulate the flow velocity, for both bared and diffuser based VAWT, the inlet conditions of velocity are implemented on the inlet boundary. The fully developed turbulence conditions are carried out on the outlet boundary. Output pressure is indicated as atmospheric pressure for both bared and diffuser based VAWT. Under steady state condition, the rotor is considered as fixed condition and moving reference frame (MRF) solving technique has been adapted to carry out the process. For finding the outlet velocity initially two separated fluid ring has been created.

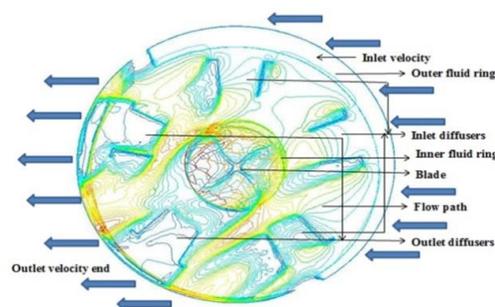


Figure 11. Boundaries and flow path of wind turbine

One fluid ring is created at 150mm radius from the axis of the blade of the wind turbine and another layer is created at the radius 500mm. This fluid ring is an imaginary layer in which fluid can pass through without having any disturbance. The important function of MRF technique is used to compute the force acting on the rotor and the reaction is given to the fluid. Similarly, for diffuser based VAWT, MRF technique is used. In diffuser based VAWT also two fluid ring is created. One fluid ring is created to a blade of the wind turbine and another layer is created in front of the diffuser at a radius of 500mm which covers the whole setup and it is also used for visualizing outlet velocity at different regions is shown in Figure 11. The direction of fluid passes through the setup is mentioned as the clockwise direction.

Most of the computation techniques are performed using Navier-Stokes equation with continuity and momentum equation and the equations solved together additional with the equation of turbulence model. The details of spatial discretization and solver used are listed in Table 3.

Table 3 Spatial discretization and solver used

| SOLVER | |
|-----------------------------|-------------------------|
| Pressure-Velocity Coupling | |
| SPATIAL DISCRETIZATION | |
| Gradient | Least square cell based |
| Pressure | Second order |
| Momentum | Second order upwind |
| Turbulence Kinetic Energy | First order upwind |
| Turbulence dissipation rate | First order upwind |

The turbulence model depends on considerations regarding the physics of the flow, a specific class of problem, a level of accuracy and availability of time for analysis and simulations. Based on the transport equation for turbulence kinetic energy and its dissipation rate, the standard k- ω model is used. This model will give good accuracy for a wide range of turbulent flows.

4. Results and Discussion

The distribution of the velocity of bared VAWT and diffuser based VAWT for different input velocities are simulated.

4.1 Velocity Analysis of Bared VAWT

After the iteration process is stable, for different input velocities are listed in Table1 and the different rotational speeds at the different working condition, the velocity contour of standard k- ω turbulence model are shown in Figure 12, 13, 14 and15. The wind velocity is authorized to inlet and blade area of the wind turbine turned into studied for velocity and it is absorbed that the output velocity is increased gradually for increasing input velocity. There could be a narrow region of the velocity wake created in the blade area of wind turbines. The velocity of a few regions is greater than the velocity of free flow. The velocity gradient is enormous around the wind turbine blade; the leeward of the blade has a much larger velocity than the front blade of the wind turbine. For the different input velocity, the magnitude of the velocity distribution around the blade is different.

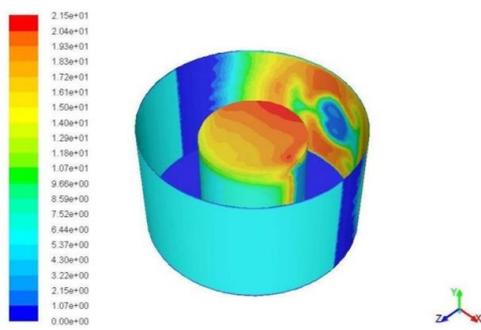


Figure 12. Input velocity as 6.1m/s

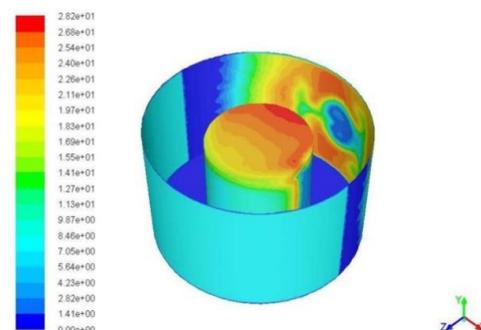


Figure 13. Input velocity as 8.0 m/s

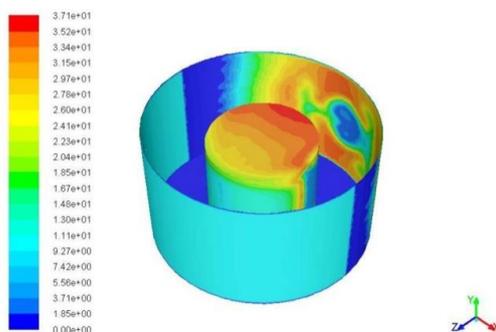


Figure 14. Input velocity as 10.5 m/s

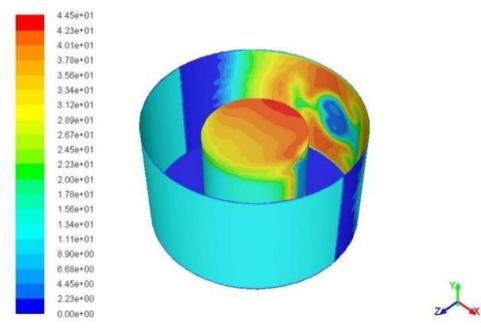


Figure 15. Input velocity as 12.6m/s

In Figure 16, the graph represents about input velocity and output velocity of bared VAWT. For every input velocity, there is a gradual rise in output velocity at a certain point there is sudden pressure drop occurred at the delivery end of the VAWT so the output velocity is increased after 8m/s. The graph shows, up to 8m/s of wind speed there is a gradual rise in the output velocity. Above 8m/s the output velocity is increased due to the pressure drop at the delivery end of the VAWT.

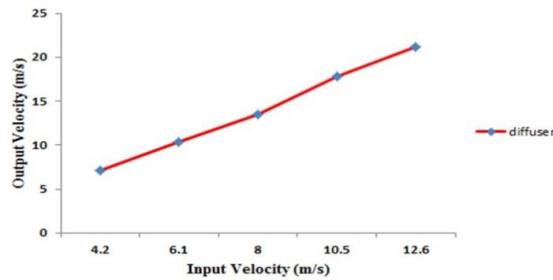


Figure 16. Input and Output Velocity of bared VAWT

4.2 Velocity Analysis of Diffuser Based VAWT

Similarly, the flow fields at different wind velocities for diffuser based VAWT are simulated and it is plotted in Figure 21. Among five diffusers three diffusers act as an input convergent diffuser and input velocities are assigned to those three convergent diffusers. Due to the pressure drop developed at the area of outlet diffusers, the velocity increases abruptly around the diffuser setup. There might be a narrow region of the velocity wake developed within the certain region among the outlet diffuser and blade region of the wind turbine. The flow velocity through the turbine is accelerated at the high amount due to brim structure in the diffuser. This increases the power output of the wind turbine.

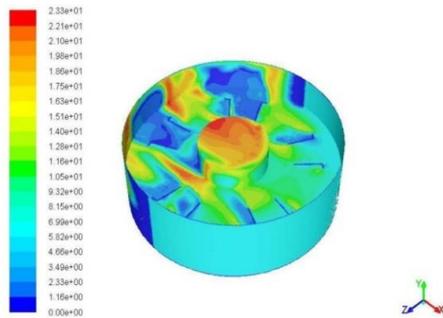


Figure 17. input velocity as 6.6m/s

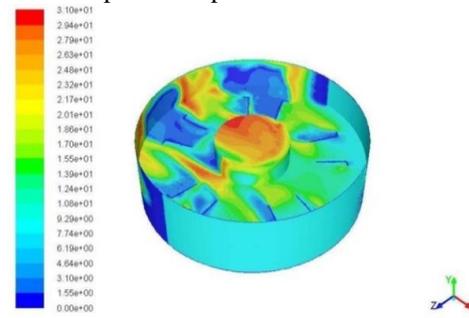


Figure 18. input velocity as 8.8m/s

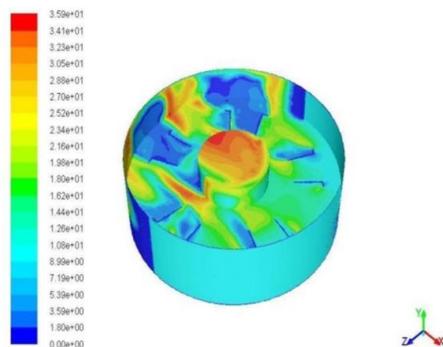


Figure 19. input velocity as 10.2m/s

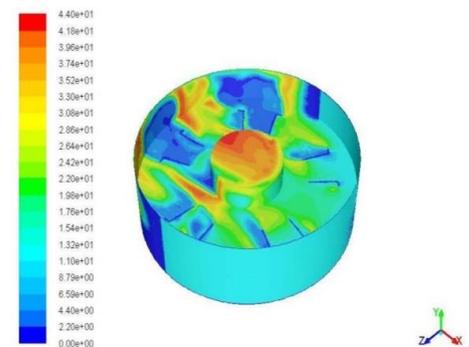


Figure 20. input velocity as 12.5 m/s

The output velocity of diffuser based VAWT for various input are plotted in Figure 17, 18, 19 and 20. This graph shows diffuser1 generate more velocity than diffuser2 for each and every input velocity because rotor of the blade rotates in the direction of clockwise. Following to the direction of the wind at certain position outlet diffuser1 is placed, so outlet diffuser1 collects more amount of wind velocity than diffuser2. This graph represents that for 6.6m/s input velocity the output velocity of diffuser1 is 8.6m/s for same input velocity, the output velocity of diffuser 2 is 3.4m/s. Similarly, for each input velocity, output velocity of diffuser1 is abruptly increased and output velocity of diffuser 2 is gradually increased.

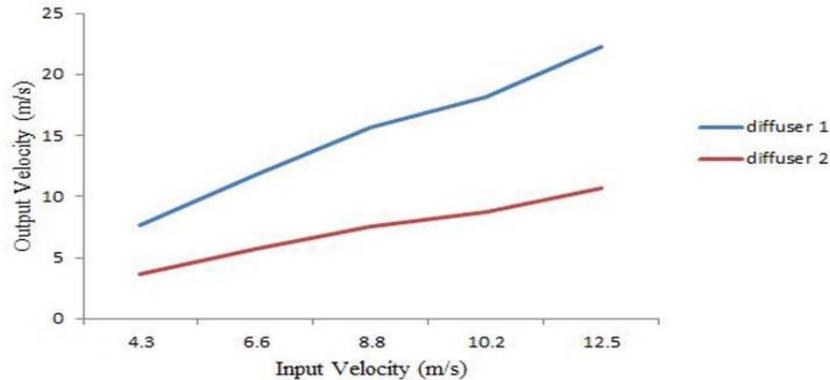


Figure 21. Comparison between input and output velocity of diffuser based VAWT

5. Validation

The velocity field simulated using CFD is validated with the experimental values. And these comparisons graphs for bared VAWT are presented in Fig 22. The simulated velocities are almost similar to experimental results

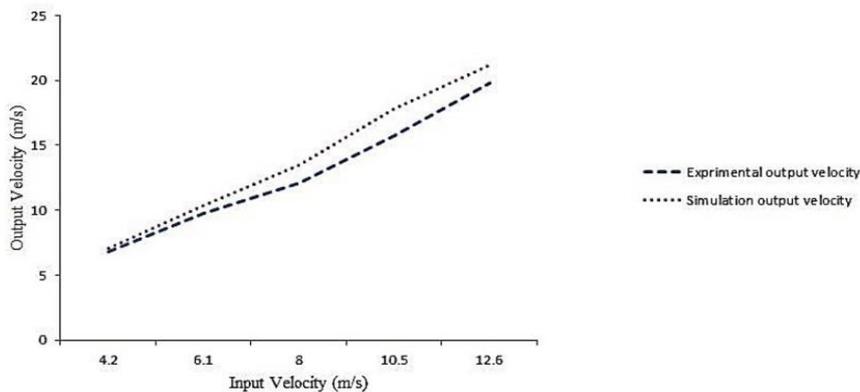


Figure 22. Comparison of experimental and simulation results of bared VAWT

In diffuser based VAWT, the Figure 18 shows that the deviation between experimental and simulation results. In both cases, diffuser1 generate more velocity than diffuser2 because the blade of the rotor rotates in the clockwise direction. So it collects more amount of wind velocity than diffuser2. This uncertainty reflects on the graph shown in Figure 23 and Figure 24.

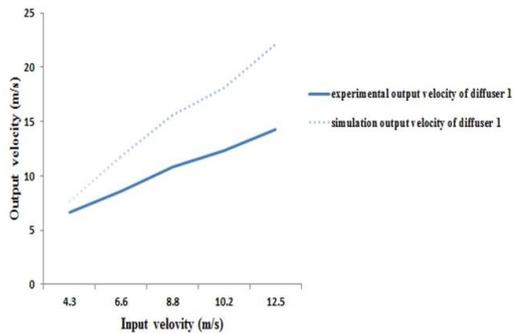


Figure 23. Experimental and simulation results for diffuser 1 of VAWT

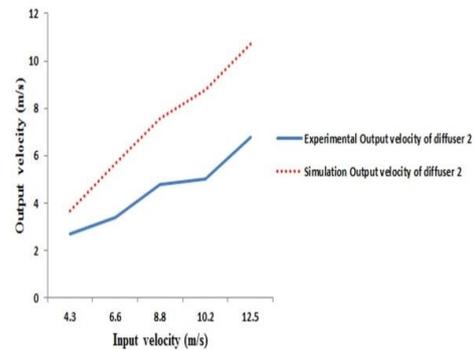


Figure 24. Experimental and simulation results for diffuser 2 of VAWT

6. Conclusion

Among various renewable resources wind power is economic and environmental impacts are very little when compared to other renewable resources. Our special addition to this format is a diffuser surrounded by it, which increases the wind blade velocity and delivering more power output for the same atmospheric wind conditions. With a relatively long diffuser, an increase in the output power of about and approximately two times that of a conventional wind turbine is achieved in both experimental and analytical. Because an increase in the flow velocity due to diffuser effect and a low-pressure region due to a robust vortex formed in the back of the large brim draws extra mass flow to the wind turbine within the diffuser.

Nomenclature

| | |
|-----------|--|
| P | Power (KW) |
| p | Pressure (Bar) |
| ρ | Density of air (Kg/m^3) |
| D | Diameter of the turbine blade (m) |
| H | Height of the turbine (m) |
| A | Area covered by turbine (m^2) |
| V | Velocity of air (m/s) |
| N | Rotation of rotor (rpm) |
| λ | Tip speed ratio |
| C_p | Power coefficient |
| HAWT | Horizontal Axis Wind Turbine |
| VAWT | Vertical Axis Wind Turbine |
| MRF | Moving Reference Frame |

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