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# Performance Analysis of an Omnidirectional Intake Duct Wind turbine using CFD

BodaHadya[a], JaipalreddyPailla[b]
[a]*Associate Professor, Department of Mechanical Engineering, UCE, OU, Hyd., India*
[b]*M.E(Turbomachinery), MED, UCE, Osmania University, Hyd., India*

**Abstract:**At the beginning of $20^{th}$ century, conversion of wind energy to electrical power marked a turning point for the wind power harnessing industry. Among the wind power harnessing systems, horizontal axis tower mounted wind turbines are the most widely used to generate electrical power. These are large, mechanically complex turbines and the huge towers used to hold them are the trend of currently existing wind power industry, and they are also expensive, difficult to move, less efficient, and hazardous to people and environment. Efforts to improve the performance of these wind turbines include introducing different varieties of ducts. Among the ducted wind turbines, Omnidirectional intake duct have recently attracted research interest, partly due to experimental data showing this technology performs much better than the traditional wind turbines. The attractive features associated with this concept include, elimination of large, mechanically complex towers and turbines, elimination of yaw and pitch control units. As this duct is able to capture the wind from any direction ($360^o$) effectively hence, it performs much better than currently existing wind turbine system of the same diameter and aerodynamic characteristics under the same wind conditions and it delivers significantly higher output, at reduced cost. In this work, Omnidirectional intake duct a new concept in wind power harnessing is described, and it's performance has also been investigated in terms of flow characteristics using computational fluid dynamics methods.The objective of the present work is to understand the flow field inside the duct where the actual wind turbine is located as well the external flow field using CFD technique by employing K-ε turbulence model with Finite volume method in simulation by using ANSYS 15 FLUENT software code. The present computations involves cases with different real time incoming wind velocities varying from 1.5 m/s to 6.7m/s. The results show that it is possible to increase the wind velocities by accelerating inside the venturi section of the duct, thus the increased wind velocities results in significant improvement in the power output of the wind turbines.
**Keywords:**Ducted Wind Turbines, Omnidirectional intake duct, Wind energy, Renewable energy

## 1. Introduction

Since a very long time, people have been utilizing wind energy, initially for propelling boats, pumping water and grinding grain,cooling, running machinery in farms, and even small production facilities. In late 1800s and early 1900s, conversion of wind energy to electrical power marked a turning point for the wind power generation industry. Due to energy crises and changes in the political and social climates, wind turbines started to rapidly spread across the globe in the last three decades. However, wind power is far from reaching its full potential. Scientists have been consistently putting the efforts to improve the conventional wind turbines in the last two decades but the maximum energy output gains have come from constructinglarger turbines. As the size and height of turbine and tower increase, the cost of power generated from wind continues to exceed the cost of power generated by hydropower and thermal power plants. The major problems associated with the current wind power industry include, excessive downtime, failure and repair costs are high, high decibel-low frequency sound waves, propeller noise, flickering of light, the visual nuisances of large wind farms, etc. are damaging human health and environment.

Conversion of wind power to electrical energy depends on free stream wind speed, blade shape, blade orientation and blade radius, etc. Because of these design parameters, the height of thetower and size of the bladesare kept on increasing to excessive range in conventional wind turbines due to high energy demands. The horizontal wind turbine theoretically converts maximum of 59.3% (Betz Limit) of available kinetic energy. In practice, the conversion efficiency may be in the range of only 30 to 35%. Hence, there is an excellent opportunity to increase the efficiency of wind turbine using a nozzle system. The concept of duct system is introduced to increase the efficiency of wind turbine using funnel or conduit around the rotor. Rise in air velocity at the inlet of turbine increases the efficiency of wind turbines, since power in the wind is directly proportionate to the cube of air velocity at the inlet of rotor.

### 1.1 Omnidirectional Intake Duct

Wind is collected at the top of the duct i.e. Omnidirectional intake area, which can collect wind from any direction. Wind is then directed through the system, which concentrates and further accelerates in the venturi section. The venturi effect is the phenomenon that occurs when a fluid is flowing through a pipe is forced through a narrow section, resulting in decrease in pressure and increase in velocity.Then wind is delivered to the turbine to convert the accelerated wind to electrical power. Diffuser then returns the wind to the surrounding environment.The advanced features associated with this concept are, elimination of tower mounted turbines, which are large, mechanically complex and also expensive, difficult to move, less efficient, and hazardous to people and environment. And there is no need for a passive or active yaw control unit and it also provides solutions to all the major problems that have so far faced in the present wind industry, such as low turbine reliability, intermittency issues and adverse environmental and radar impact.The five key parts of Omnidirectional intake duct wind turbine are shown in fig.1: 1) Intake;2) Pipe carrying and accelerating wind;3) Boosting wind speed by a venturi; 4) Wind energy conversions system;5) Diffuser.

Control volume analysis for conservation of mass, axial and angular momentum balances, and energy conservation for inviscid, incompressible axisymmetric flows yields[3]:

$$\oint_A \rho \mathbf{V}.\, d\mathbf{A} = 0 \; ; \oint_A u_x \rho \mathbf{V}.\, d\mathbf{A} = T - \oint_A p\, d\mathbf{A}.\, \mathbf{e}_x$$

$$\oint_A r u_\theta \rho \mathbf{V}.\, d\mathbf{A} = Q \; ; \oint_A \left[\frac{p}{\rho} + \frac{1}{2}\|V^2\|\right] \rho \mathbf{V}.\, d\mathbf{A} = P$$

Where,

**V** = $(u_{x,} u_{r,} u_{\theta})$ is the velocity vector in the axial, radial, and azimuthal direction; r is the radius; ρ is the density of air; **A** is outward pointing area vector of the control surface; $\mathbf{e}_x$ is the unit vector in the X direction; p is the pressure; T is the axial force on the rotor; Q is the torque; P is the power extracted from the rotor.

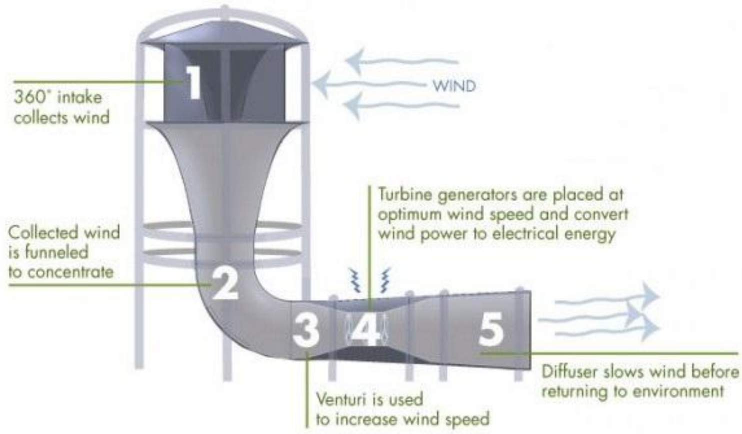


**Fig.1**: Omnidirectional duct with its key components and it's working mechanism[3].

### 1.2 One-dimensional Momentum Theory and the Betz Limit

A simple model, generally attributed to Betz (1926), can be used to determine the power from an ideal turbine rotor.This analysis assumes homogenous, incompressible, steady state fluid flow with no frictional drag and infinite number of blades, uniform thrust over the disc or rotor area and a non-rotating wake.

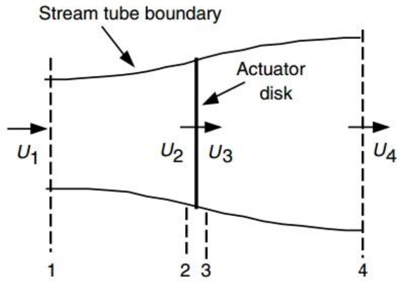


**Fig.2**: Actuator disc model of a wind turbine; U, mean air velocity; 1, 2, 3, and 4 indicate locations[2].

Applying the conservation of linear momentum to the control volume enclosing the whole system, one can find the net force on the contents of the control volume. And then after differentiating it for obtaining maximum power, we get optimum power coefficient as

$$C_{Pmax} = \frac{16}{27} \approx 0.59259$$

$$P_{max} = \frac{1}{2} C_P \rho A V^3 \; ; P_{max} = \frac{2}{27} \pi \rho D^2 V^3$$

Where,D is the diameter of the swept area A and V is the free stream wind speed[2].

## 2. Solution methodology

### 2.1 Wind Turbine Blade Model

National Renewable Energy Laboratory has tested over 1600 airfoils and suggested the best performing among them as NREL's S-series airfoilfamilies[7].As the internal diameter of the duct at the end of venturi section is 6ft(1.829m), it falls under the category of 1-3m. Hence NREL's S-series airfoils of S835, S833, S834 are chosen at root, body and tip respectively to develop a wind turbine model.Using the NREL's airfoil tool, different airfoils are generated at different sections of the blade as follows:

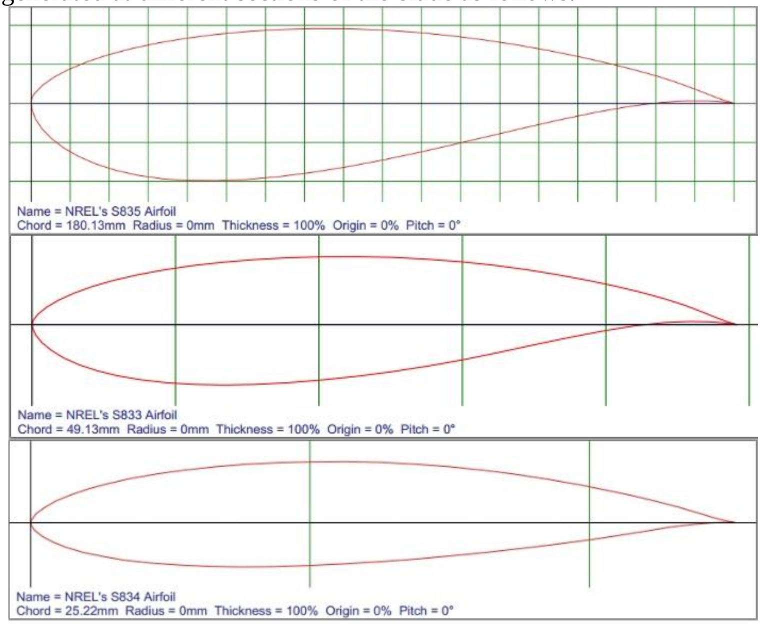


**Fig.3**:NREL's S835,S833,S834Airfoil Plots

**Table.1**:Twist and chord distribution for Betz optimum blade[2]

| **r/R** | **c/R** | **Twist angle(°)** | **Angle of rel. wind(°)** | **Section pitch (°)** |
|---|---|---|---|---|
| 0.1 | 0.275 | 38.2 | 43.6 | 36.6 |
| 0.2 | 0.172 | 20.0 | 25.5 | 18.5 |
| 0.3 | 0.121 | 12.2 | 17.6 | 10.6 |
| 0.4 | 0.092 | 8.0 | 13.4 | 6.4 |
| 0.5 | 0.075 | 5.3 | 10.8 | 3.8 |
| 0.6 | 0.063 | 3.6 | 9.0 | 2.0 |
| 0.7 | 0.054 | 2.3 | 7.7 | 0.7 |
| 0.8 | 0.047 | 1.3 | 6.8 | -0.2 |
| 0.9 | 0.042 | 0.6 | 6.0 | -1.0 |
| 1 | 0.039 | 0 | 5.4 | -1.6 |

Using the Solidworks 2012 software the model of the wind turbine is developed in accordance with the specifications mentioned in table.1 by using NREL's S-series airfoils by employing Betz optimum blade conditions.

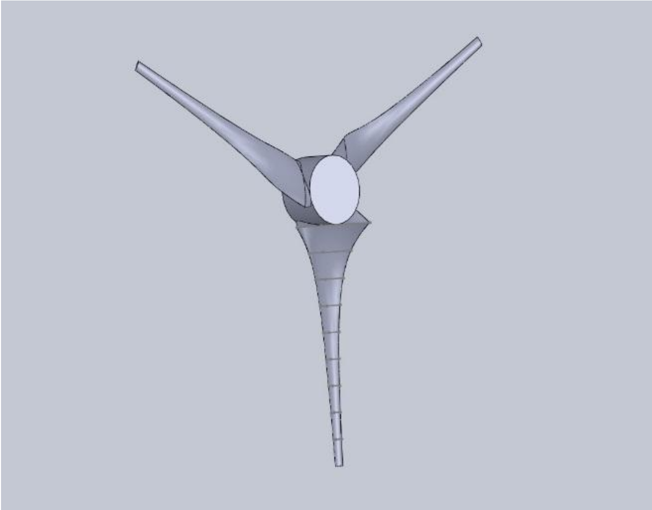

**Fig.4**: Small wind turbine model (Solidworks 2012)

### 2.2 Omnidirectional Intake DuctModel

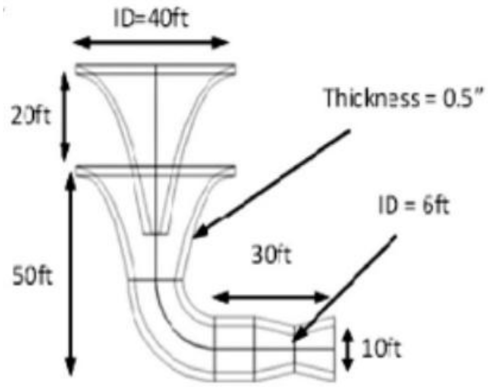


**Fig.5**: Geometry of omnidirectional intake duct[4].

Using the Solidworks 2012 software the model of the duct with blade model is developed in accordance with the dimensions mentioned in Fig.5.

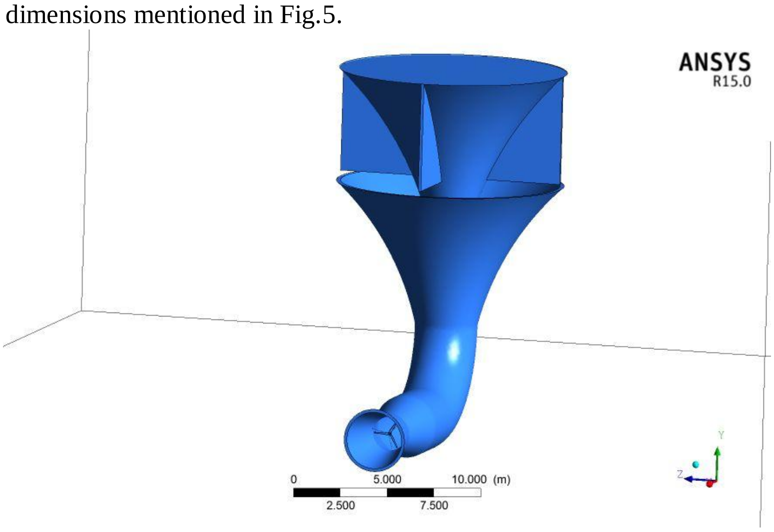


**Fig.6**: Omnidirectional duct with three bladed wind turbine model inside.

**2.3Mesh Generation**

Mesh generation is one of the most critical aspects of engineering simulation. Too many cells may result in longer solver runs, and too few may lead to inaccurate results.Thus, a compromise between the grid size on one hand and convergence and accuracy on the other hand is required. Hence, a grid independence study was carried out to ensure that the numerical solutions are grid-independent.

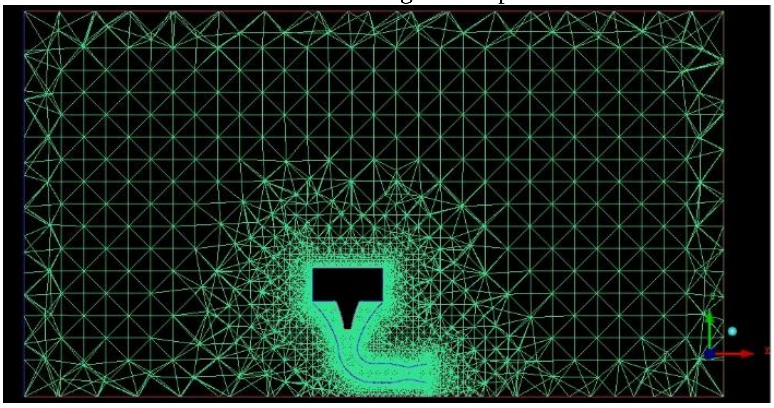

**Fig.7**: Meshed model of duct with turbine model inside

**Table.2**: Mesh statistics for the current model

| | |
|---|---|
| Cells/Elements | 2523597 |
| Faces | 5161444 |
| Nodes | 487319 |
| Positions | 48 |
| 1 Cell zone | 14 Face zones |

**2.4Methodology**

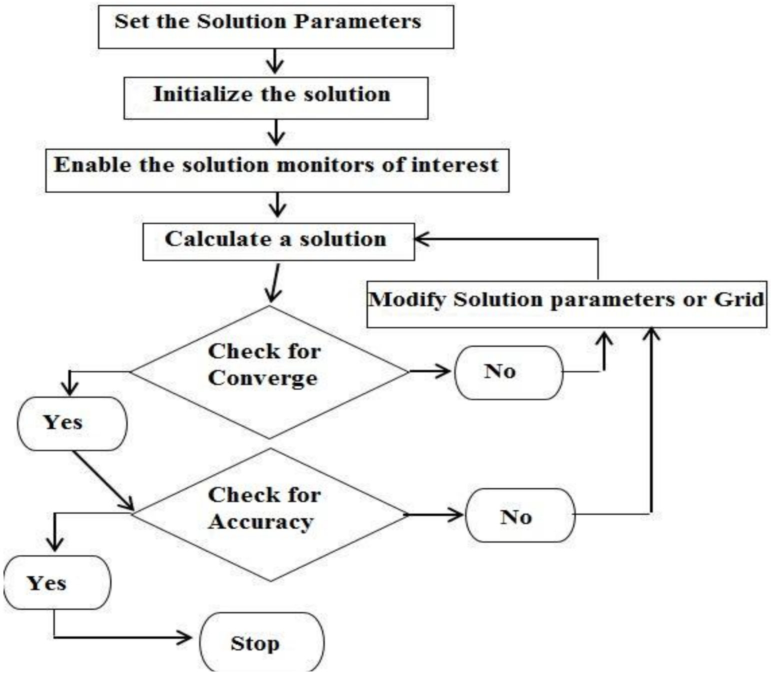


**Fig.8**: Solution procedure to solve Governing equations.

FLUENT 15.0 used for solver execution and post processing of CFD simulation, which is carried out for Turbulent flow, so finite volume method with the k-ε turbulence model is employed for solving the Navier-stokes equations. Pressure based (segregated) solver is used by defining boundary conditions(stationary wall with no slip shear condition) with SIMPLE-pressure velocity coupling, second order upwind discretization scheme by assuming three dimensional, turbulent flow, steady state, and air as the working fluid.

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## 3. Results and Discussions

The Numerical simulations are carried out for Omnidirectional intake duct with turbine model inside with different inlet velocity conditions.

### 3.1Contours of Velocity and Pressure at $V_{in}$ of1.5 m/s

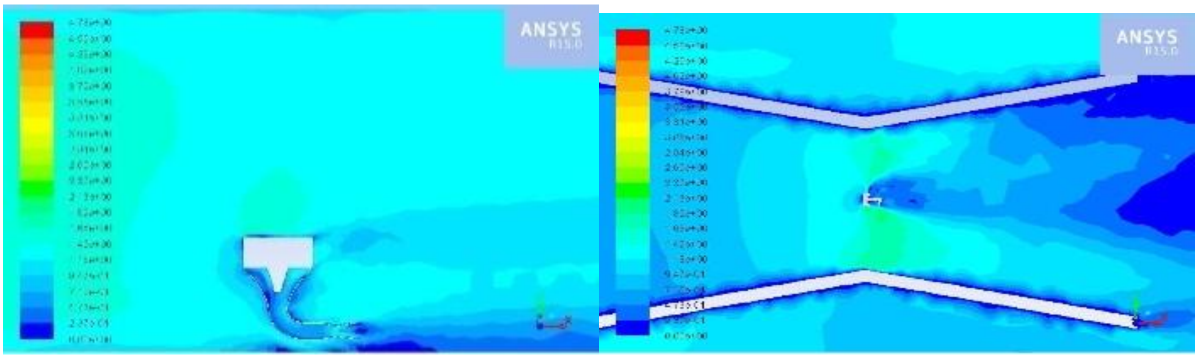


**Fig.9**:Velocity contour ofduct at $V_{in}$of 1.5 m/s

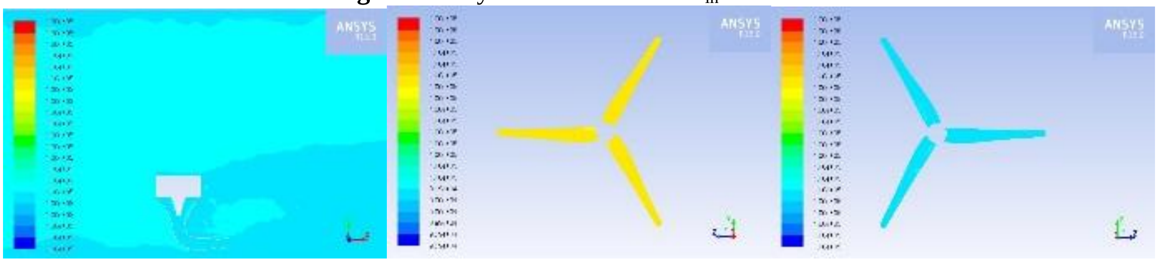

**Fig.10**: Pressure contour of duct& blade at $V_{in}$of 1.5 m/s

It is observed that there is a significant increase in the velocity of the wind from inlet(1.5 m/s) to venture exit(2.83 m/s). $P_{max}$on blade is 100013 Pa, $P_{min}$on blade is 99834.4 Pa and $F_{avg}$on blade is 0.416 N.

### 3.2Contours of velocity and pressure at $V_{in}$of 2.5 m/s

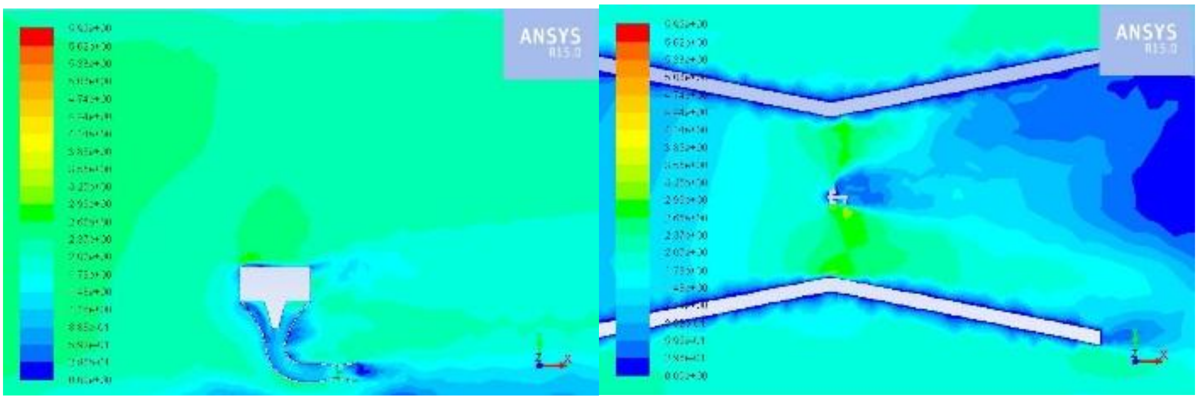


**Fig.11**: Velocity contour of duct at $V_{in}$ of 2.5 m/s

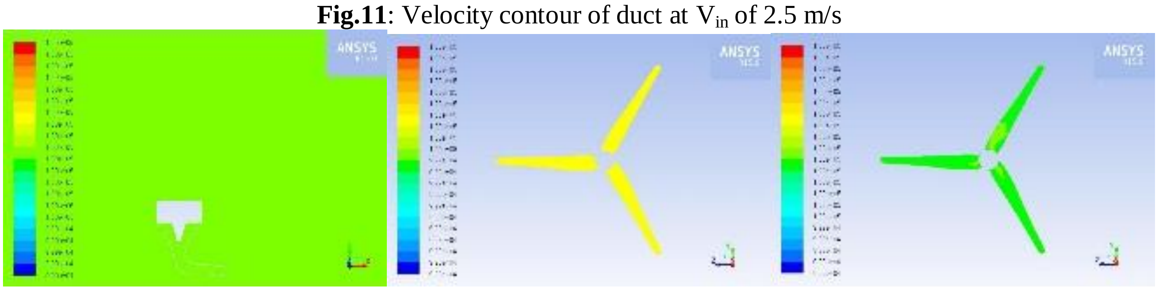

**Fig.12**: Pressure contour of duct & blade at$V_{in}$ of 2.5 m/s

It is observed that there is a significant increase in the velocity of the wind from inlet(2.5 m/s) to venturi exit(3.85 m/s). $P_{max}$on blade is 100010 Pa, $P_{min}$ on blade is 99750.4 Pa and $F_{avg}$on blade is 1.00227 N.

### 3.3Contours of velocity and pressure at $V_{in}$of 3m/s

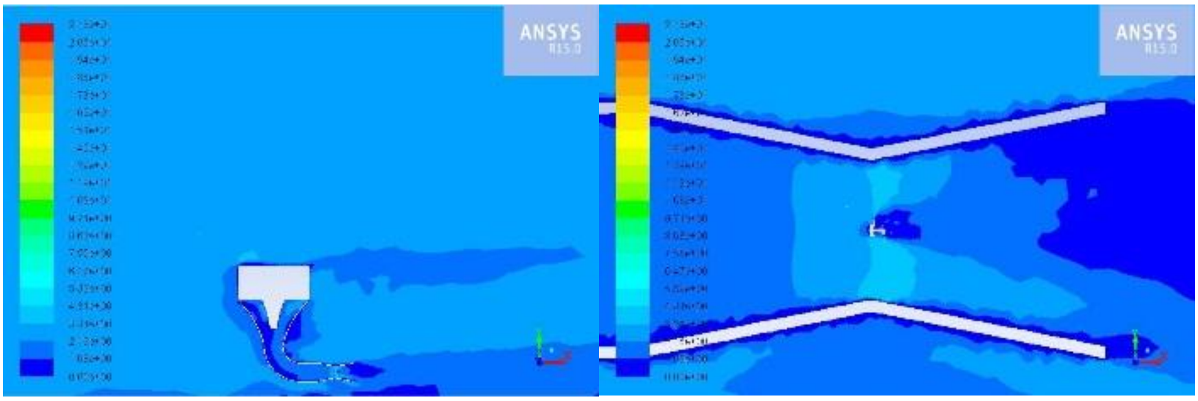

**Fig.13**: Velocity contour of duct at $V_{in}$of 3 m/s

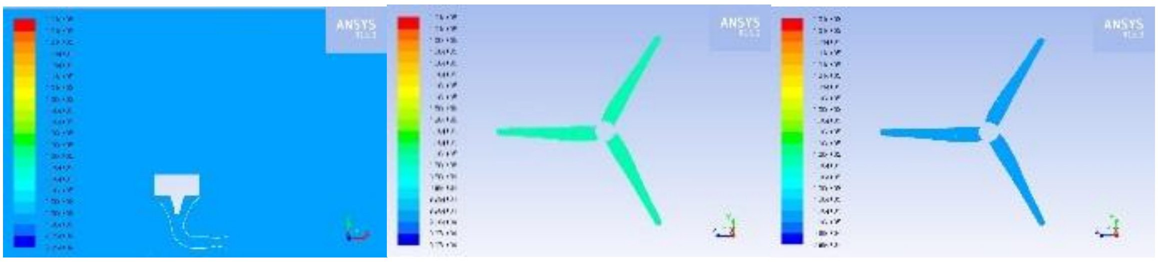

**Fig.14**: Pressure contour of duct & blade at $V_{in}$of 3 m/s

It is observed that there is a significant increase in the velocity of the wind from inlet(3 m/s) to venturi exit(5.39 m/s). $P_{max}$on blade is 100910 Pa, $P_{min}$on blade is 99968.7 Pa and $F_{avg}$ on blade is 1.7146 N.

### 3.4Contours of velocity and pressure at $V_{in}$of 4.5 m/s

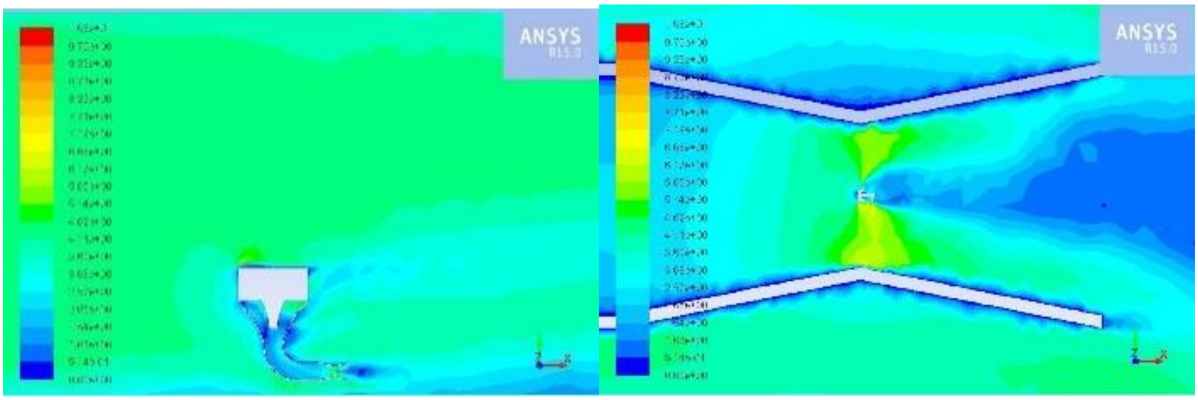

**Fig.15**: Velocity contour of duct at $V_{in}$of 4.5 m/s

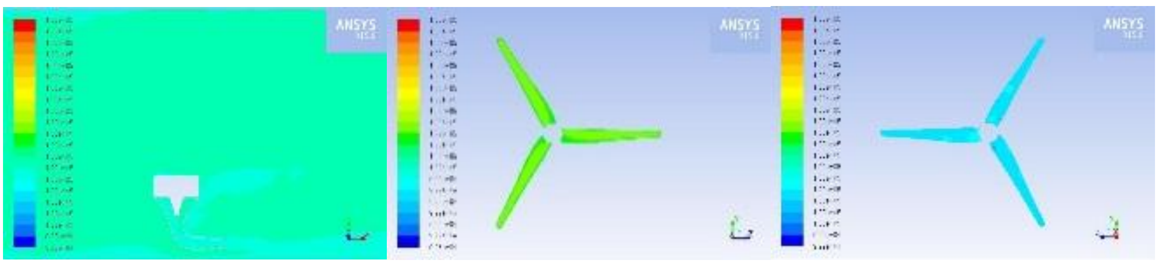

**Fig.16**: Pressure contour of duct& blade at $V_{in}$of 4.5 m/s

It is observed that there is a significant increase in the velocity of the wind from inlet(4.5 m/s) to venturi exit(6.68 m/s). $P_{max}$on blade is 100008 Pa, $P_{min}$ on blade is 99702.4 Pa and $F_{avg}$on blade is 4.2131 N.

**3.5Contours of velocity and pressure at $V_{in}$of 5 m/s**

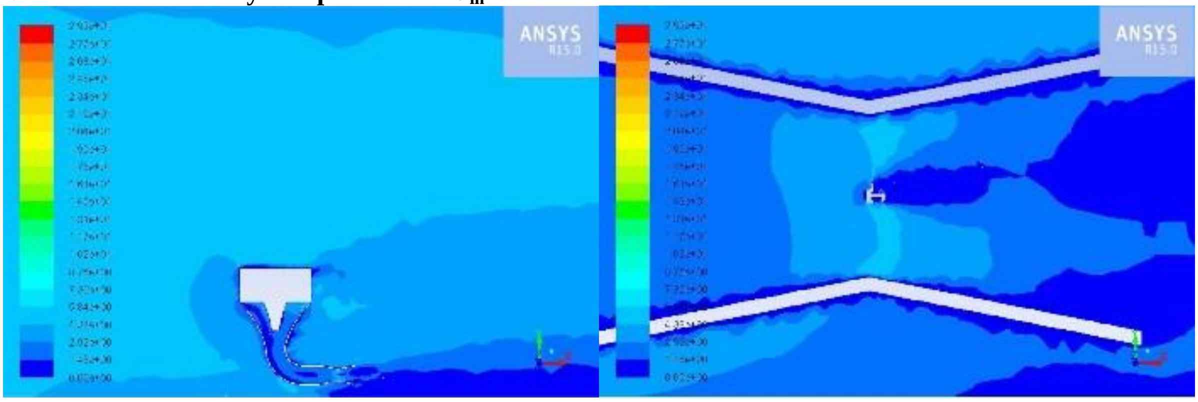


**Fig.17**: Velocity contour of duct at $V_{in}$of 5 m/s

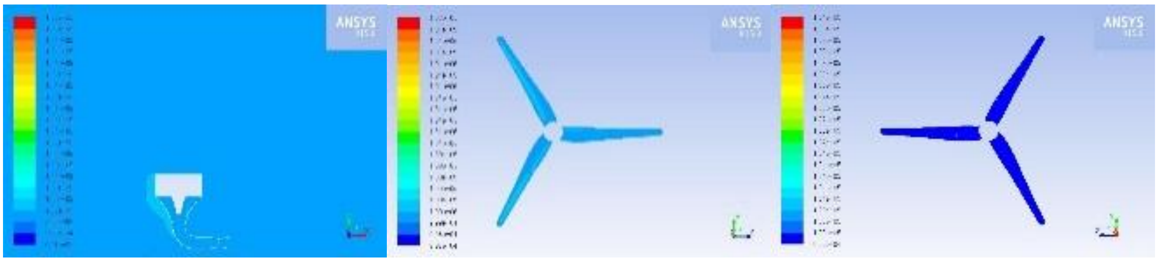


**Fig.18**: Pressure contour of duct & blade at $V_{in}$of 5 m/s

It is observed that there is a significant increase in the velocity of the wind from inlet(5 m/s) to venturi exit(7.8 m/s). $P_{max}$on blade is 122108 Pa, $P_{min}$on blade is 99954.1 Pa and $F_{avg}$on blade is 2.9668 N.

**3.6Contours of velocity and pressure at $V_{in}$of 6.7 m/s**

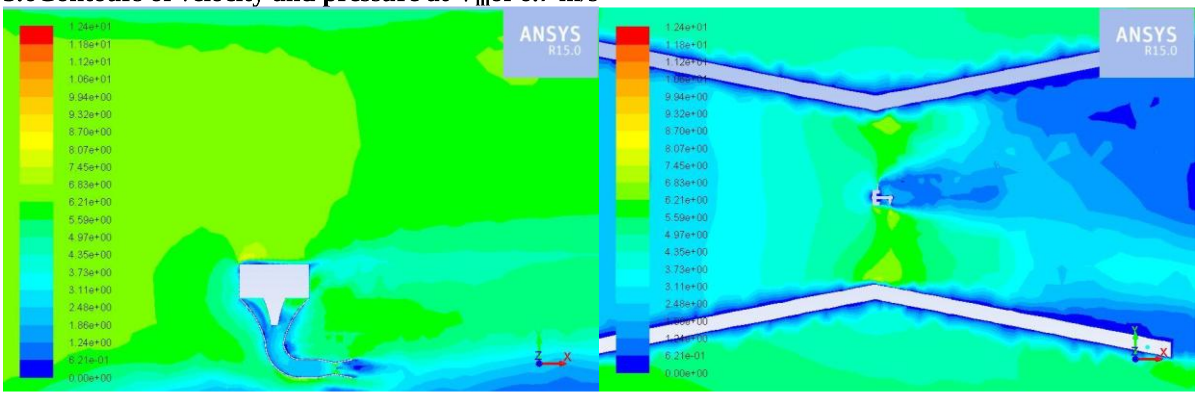


**Fig.19**: Velocity contour of duct at $V_{in}$of 6.7 m/s

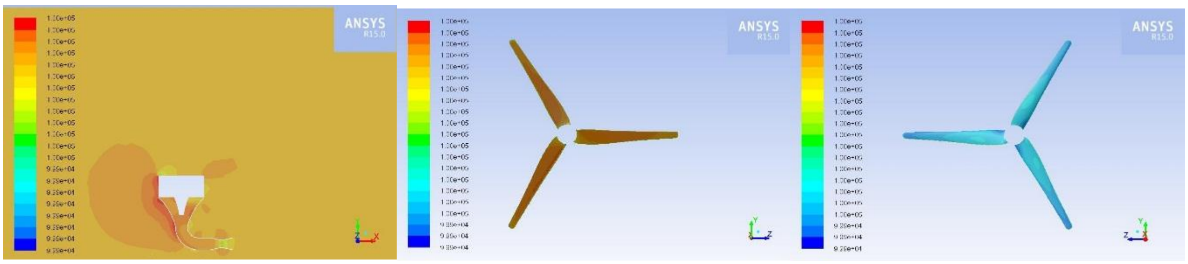


**Fig.20**: Pressure contour of duct & blade at $V_{in}$of6.7 m/s

**Table.3**: Theoretical$P_{max}$for different inlet velocities.

| S No | Inlet Velocity | Theoretical$P_{max}$ (W) | Outlet Velocity | Theoretical $P_{max}$ (W) |
|---|---|---|---|---|
| 1 | 1.5 m/s | 3.15 W | 2.83 m/s | 21.14 W |
| 2 | 2.5 m/s | 14.57 W | 3.85 m/s | 53.27 W |
| 3 | 3 m/s | 25.18 W | 5.39 m/s | 146.05 W |
| 4 | 4.5 m/s | 84.99 W | 6.68 m/s | 278.02 W |
| 5 | 5 m/s | 116.59 W | 7.81 m/s | 442.62 W |
| 6 | 6.7 m/s | 280.53 W | 9.32 m/s | 755.08 W |

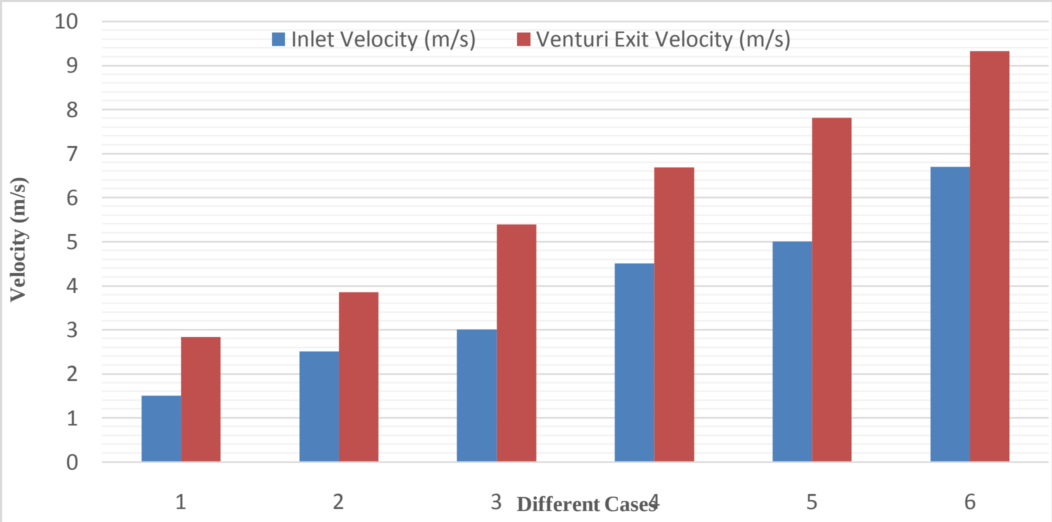


**Fig.24**: Variation of Venturiexit velocity w.r.t $V_{in}$ (m/s)

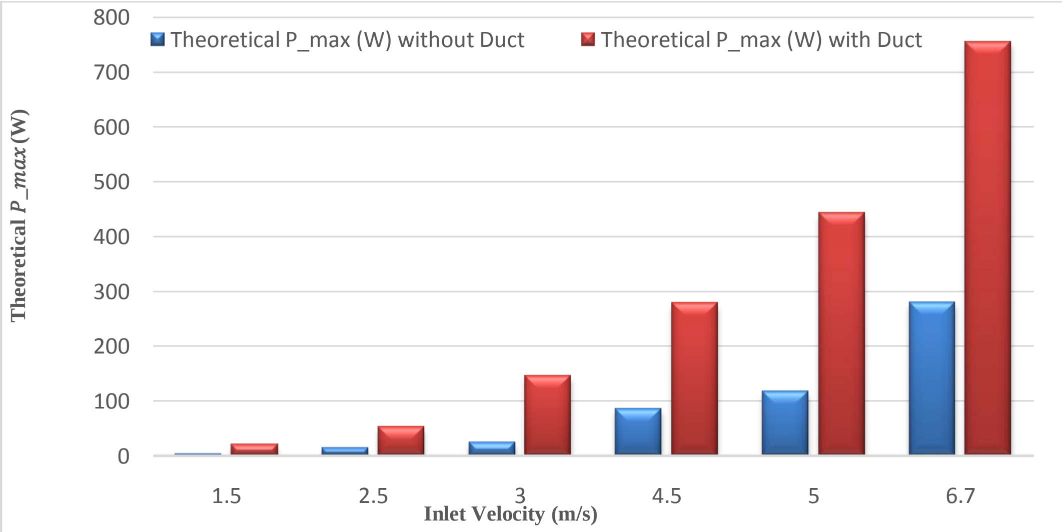


**Fig.25**: Variation of Theoretical$P_{max}$(W) w.r.t $V_{in}$ (m/s)

From above graphs it is observed that with aninput wind velocities varying from 1.5 m/s to 6.7 m/s the venturi exit velocities are obtained as 2.83 m/s to 9.32 m/s. It is observed that with the presence of Omnidirectional intake duct the velocity at exit of venturi section i.e. at inlet to wind turbine is getting increased by as high as 88% at an inlet velocity of 1.5 m/s and as low as 39% at an inlet velocity of 6.7 m/s, with an average increase of 60%. With the use of Omnidirectional intake duct the theoretically maximum possible power (obtained from Betz limit) for inlet velocities varying from 1.5 m/s to 6.7 m/s is 21.14 W to 755.08 W. It is observed that with the use of Omnidirectional intake duct the theoretically maximum possible power for the case of $V_{in}$ 6.7 m/s is 170% more compared to the case of without using the duct. On an average with the use of Omnidirectional intake duct the theoretically maximum possible power is more than 2.5times than that we obtain from conventional wind turbine under similar conditions.

## 4. Conclusions

Based on this study, it is shown that the addition of Omnidirectional intake duct to horizontal axis wind turbines results in significant improvement in the power outputs. Different cases of incoming wind velocities are studies to observe the results. It is always difficult to predict accurately the amount of increase in outputs as the study is conducted using many ideal case assumptions. In reality many other real time parameters comes in to the picture and effects the results in many ways.From the Computational flow analysis of Omnidirectional intake duct with three bladed wind turbine model inside, it is observed thatthere is a significant increase in the wind velocities at the exit of the Venturi section i.e. at inlet to the three bladed wind turbine model and there is a pressure drop is observed across the three bladed wind turbine model on pressure side and suction side.Thus the increased wind velocities will result in significant improvement in the power outputs. Though in this study we have assumed the ideal Betz case ($C_{Pmax}$=0.59) but in actual practice the power coefficient will be in the range of 0.3 to 0.35 then also we can observe that the power output will increase. But not as much as we have observed in this case, even if we reduce the results to be in proportionate with the actual $C_{Pmax,}$then also there will be more than 100% improvement in the power outputs. The processes of power generation from renewable sources of energy seem to pervade all aspects of human life. So there is always scope for research and development in this area.

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