



Design and Analysis of Roof Top Wind Mill for Urban Area

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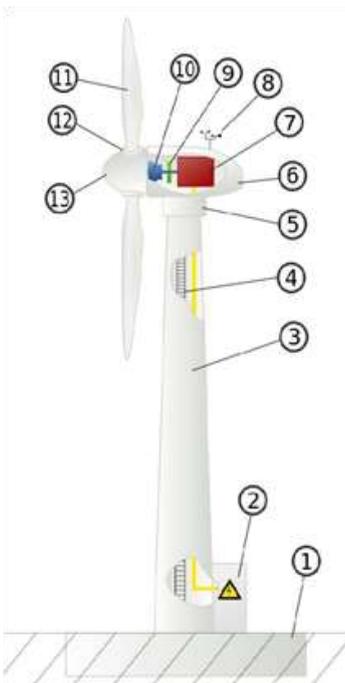
ABSTRACT:

In present work an approach is made to design a hwat for roof top application to ful fill the requirement of a urban household. For achiving the cut-off speed the bernaules theorem is applied by using convergent and divergent duct. Is this NACA-0012 profile is selected for wind turbine blade. This work is consist of two steps of work in first step wind turbine blade is designed by using different correlations and in second step duct with sigle diffuser and double diffuser are analyse and duct with vertex generator is also examines to optimize the design of duct. The site selection for the input parameter is the shri ram institute of technology Jabalpur (mp). The result obtain are compared with the base research paper reviewed. And the result represents the sustainable power production from design

Fundamentals of Wind Energy

Wind Energy: Wind is caused by flow of air from high pressure area to low pressure area and this difference in pressure is result of heating of the uneven earth's surface by sun. So we can say that wind energy is a form of solar energy. **Wind power:**Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electrical power, windmills for mechanical power and wind pumps for water pumping. **Wind Turbine:**A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbo-machine with at least one moving part called a rotor assembly, which is a shaft with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. A wind turbine is a device that converts kinetic energy from the wind into electrical power.

Parts of a Wind Turbine



- 1 Foundation: Its the basement of a wind turbine on which the whole self weight of wind turbine's will come
- 2 To Electric Grid: This is the connection from which the generated power is sent to electric grid with the help of electric wires.
- 3 Tower: It is the supporting structure for nacelle and rotor. The nacelle is placed above this tower.
- 4 Access Ladder: There will be a ladder inside the tower from basement to the top so that one can get access to the nacelle for any kind of repair or inspection work.
- 5 Yaw Control: will place it in the direction of the wind.
- 6 Nacelle: It is a rectangle like structure that contains generator, controller system, cooler etc. When yaw controls activates the whole nacelle is rotated in the direction of wind.
- 7 Generator: It is the unit responsible for power generation.
- 8 Anemometer: It is a device that is used for wind speed measurement.
- 9 Brake: It is used to stop the rotor that is rotating
- 10 Gear Box: It consist of gears that increases the rpm of the rotor to suite to the rpm of generator.
- 11 Rotor Blade: Blades are the rotating member of wind turbine that makes the shaft to rotate which is connected to gearbox and then to generator.
- 12 Pitch Control: It is used to change the angle of inclination, pitch angle which are responsible for getting maximum efficiency.

13 Rotor Hub: It is the one which holds the rotor blade and it will also rotate along with blades.

NACA Profiles: NACA stands for "National Advisory Committee for Aeronautics" which deals with testing and research related to wind turbine blades and aero plane wings. All the blades are given a separate code for example NACA0012, NACA2406 etc.

Objectives of work : In present work the ultimate objective is to design a HAWT for roof top application to fulfill the requirement of a urban household. For achieving the cut-off speed the Bernoulli's theorem is applied by using convergent and divergent duct.

In this work NACA-0012 profile is selected for wind turbine blade. This work consists of two steps of work in first step wind turbine blade is designed by using different correlations and in second step duct with single diffuser and double diffuser are analyzed and duct with vertex generator is also examined to optimize the design of duct. The site selection for the input parameter is the **Shri Ram Institute Of Technology Jabalpur (Mp)**.

METHODOLOGY

SELECTION OF LOCATION: we have evaluated Jabalpur, Madhya Pradesh, India as a case study for the design parameters.

Average Velocity: The average velocity was calculated by considering the values from the 50th and 75th percentile, as shown in the graph. The average wind velocity was thus found to be 10m/s. It is seen from the daily wind speed graph for May and April, (referring to the figure 3.2 and figure 3.3 wind velocity is higher during the month of May and is quite low during the month of April) that the 10 mph wind velocity can be easily achieved for at least 8 hours in the month of April or May (considering the gust wind speeds for the month with low wind velocities). So 10 mph can be considered a good estimation of wind velocity for wind turbine design.

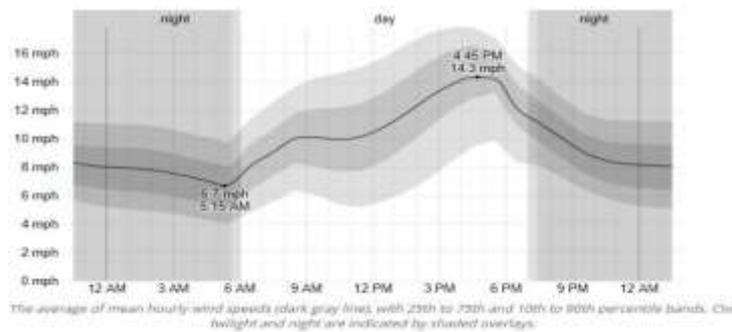


Figure Average Wind velocity profile the month of MAY

POWER REQUIREMENT: for a room :-

Table no.. Power estimation

| Sr. No | Appliance | Number | Maximum Wattage | Minimum Wattage | Hours/ Day | Total Electrical Energy (WH) Required/ Day |
|--------|---------------|--------|-----------------|-----------------|------------|--|
| 1 | Fan | 1 | 75 | 25 | 12 | 800 |
| 2 | Tube light | 2 | 60 | 50 | 6 | 720 |
| 3 | TV | 1 | 100 | 80 | 5 | 450 |
| 4 | Miscellaneous | - | - | - | - | 1000 |
| | Total | | | | | (Approx) 3000 WH |

SIZE OF WIND TURBINE: Before the actual design of wind turbine with the duct, the diameter of the turbine needs to be estimated. With the two pieces of information, the required power output and the average wind speed of the region where it will be installed the diameter D of the wind turbine can be calculated using the following expression: {17}

$$D = \sqrt{\frac{8P}{\rho \pi v^3}} \dots\dots\dots(3.1)$$

The diameter was calculated using the standard density of air at normal temperature and pressure (International Standard Atmosphere). The velocity used, 6m/s, was the average velocity obtained in the chapter 3.1 and the design power, 300 W was as obtained . .

The two main design considerations for turbine size were:

- a. Space constraint
- b. Power requirement

So an inverse method was used to calculate the diameter. The diameter was varied from 1m to 2 m with an assumed duct area factor of 1.5. The table 3.2 shows the data sheet for different throat diameter with area factor of 1.5. As evaluated the 1.5 m turbine gives an optimum size and also helps to achieve the required power, although at wind speeds above the average wind speed. The diameter 1.5 m is quite justified, considering the space constraint.

Table Power Calculation

| Vin mph | V in m/s | Mf | Vth | | Dth | Din | Po |
|---------|----------|-----|-------|--|------|---------|----------|
| 6 | 2.682 | 1.5 | 4.0 | | 1.25 | 1.5309 | 15.66091 |
| 8 | 3.576 | 1.5 | 5.3 | | 1.25 | 1.5309 | 37.12217 |
| 10 | 4.47 | 1.5 | 6.7 | | 1.25 | 1.5309 | 72.50423 |
| 12 | 5.364 | 1.5 | 8.0 | | 1.25 | 1.5309 | 125.2873 |
| 14 | 6.258 | 1.5 | 9.3 | | 1.25 | 1.5309 | 198.9516 |
| 8 | 3.576 | 1.5 | 5.364 | | 2 | 2.44949 | 93.0933 |
| 10 | 4.47 | 1.5 | 6.705 | | 2 | 2.44949 | 181.8229 |
| 12 | 5.364 | 1.5 | 8.046 | | 2 | 2.44949 | 314.1899 |
| 14 | 6.258 | 1.5 | 9.387 | | 2 | 2.44949 | 498.9219 |

Duct Design:

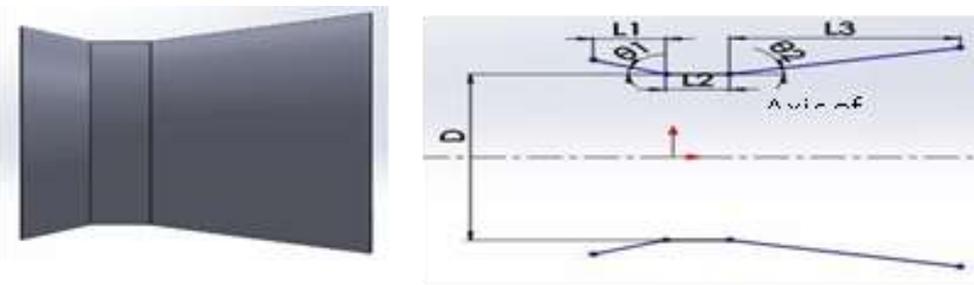


Figure An initial design of Duct

a converging section, a throat and a diverging section. There are four geometrical parameters which needed to be optimized, namely (a) converging section half cone angle θ_1 , (b) diverging section half cone angle θ_2 , (c) area factor and (d) L_3/D ratio. Computational fluid dynamics (CFD) has been used to model the duct design. The effect of each geometrical parameter on the velocity augmentation was extensively examined and an optimal geometry was derived.

Computational Fluid Dynamics

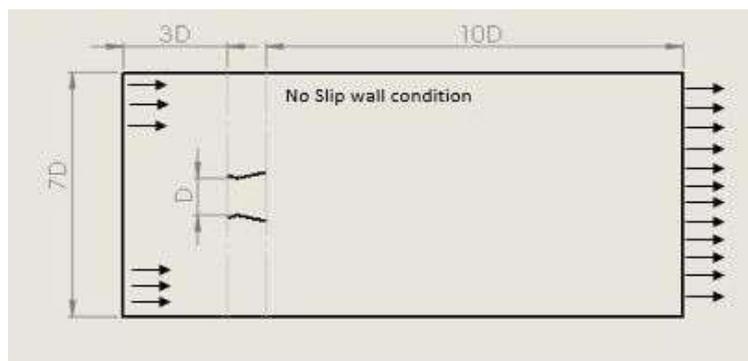


Figure. Two-dimensional computational domain with boundary conditions

Velocity inlet and pressure outlet boundary conditions were specified at the entrance and exit of the fluid domain respectively. The walls of the duct were assigned no slip boundary condition.

Pressure based solver was used considering incompressible flows. The free stream velocity of 4.47 m/s was taken for all the numerical calculations. Turbulence intensity as 5% with hydraulic diameter as 10m has been assumed at the velocity inlet boundary condition. The shear-stress transport (SST) $k-\omega$ turbulence model has been used, which provides

'Enhanced wall treatments' to the wall boundary conditions i.e., all the boundary conditions for the coarse mesh are treated as the wall function approach, while for the fine meshes the appropriate low-Reynolds-number boundary conditions are applied [22]. The advantage of using SST $k-\omega$ over the standard turbulence models like $k-\omega$ and $k-\epsilon$ is that it effectively blends the robustness and accurate formation of the $k-\omega$ model in the near-wall region with the free stream independency of the $k-\epsilon$ model in the far field [22]. It is believed that the use of SST $k-\omega$ model provides better results for the flow field predictions with the adverse pressure gradient.

Figure 3.6 shows the 2-dimensional grid system generated using Ansys Inc. Total no. of elements was 22683 with very fine meshing in the region inside the duct and relatively coarse mesh outside.

All the following analysis were performed with the above specified parameters and computational schemes. The figure 3.6 shows the velocity contour obtained for area factor of 1.4, convergent angle 20° , L/D ratio 0.5, and the divergent angle 12° .

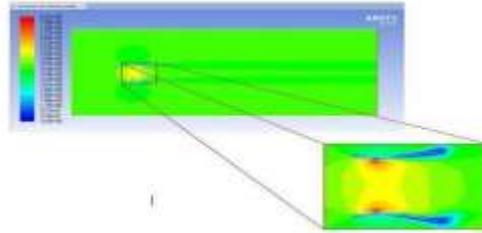


Figure. Velocity contours

The velocity contour gives the overall variation of velocity in the control volume. However, the main aim was to evaluate the velocity at the throat, which would be the wind velocity interacting with the wind turbine. The velocity at the throat was obtained by plotting the velocity profile at a linear location at the center of the throat. The average velocity at the throat was further calculated by taking the average of the velocities obtained after dividing the linear location into eight parts. The figure 3.8 and 3.9 shows the linear location and the corresponding velocity profile.



Figure Location of throat

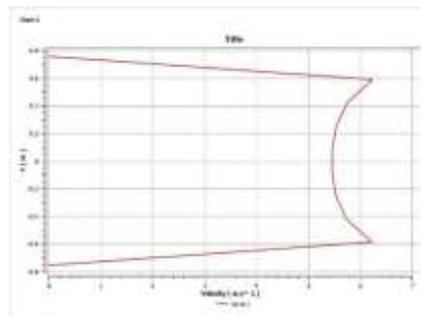


Figure. Velocity at the throat

In the above specified case the average velocity at the throat was found to be 5.74 m/s. This average velocity will further be used to select the aerofoil and derive the blade parameters.

Convergent Angle and Area factor:

The first step in the design of duct was to decide the convergent parameters viz. convergent angle and area factor. The convergent angle is the half cone angle of the convergent portion denoted by Θ_1 in the figure 3.10. The area factor is the factor by which the wind velocity at the entrance of the duct is augmented at the throat. The area factor and the convergent angle together define the inlet diameter with respect to the throat diameter.

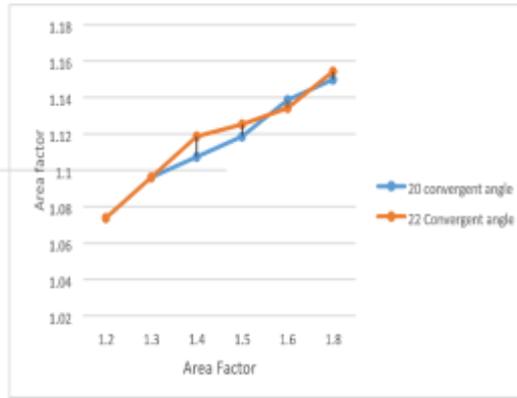


Figure. Velocity Augmentation for different convergent angle and area factor

The convergent section parameters were evaluated by keeping the divergent section fixed and varying convergent parameters. The area factor was varied from 1.2 to 1.8 with convergent angle 20° and 22°. The 18° convergent angle gave larger length for the same area factor so only 20° and 22° were considered. However, as described by the above figure.3.10, the change in the convergent angle hardly had any effect on the velocity augmentation. The maximum change in augmentation with change in convergent angle can be seen for 1.4 area factor, which being 0.01 can be considered insignificant. Increasing the convergent angle increases the inlet diameter of duct so 20° is considered optimum value of convergent angle. The velocity augmentation increases with an increase in the area factor from 1.2 to 1.8. Again the increase in the augmentation value is quite less. The velocity augmentation increases from 1.06 to 1.15 for change in area factor from 1.2 to 1.8. It must be noted that with increase in area factor for the same convergent angle the inlet diameter of the duct increases. It is evident from the figure.3.11 that the increase in the augmentation factor is not as much as the increase in the inlet diameter. So considering the space constraint the area factor of 1.4 was selected.

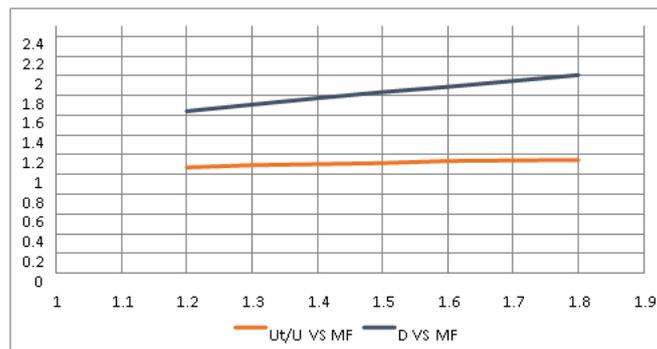


Figure. Comparison of increase in augmentation factor and inlet diameter for different area factor

Thus, it can be concluded that the convergent section has very less effect on the velocity augmentation. So for optimum value of area factor and considering the space constraints the convergent section was designed with the convergent angle 20° and area factor 1.4.

Divergent angle and L/D ratio:

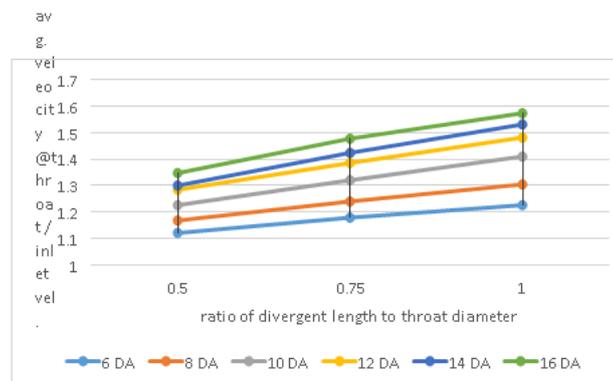


Figure. Velocity Augmentation for different divergent angle and L/D ratio

The main parameters considered for designing the divergent section were the divergent angle and the ratio of the length of divergent section to the throat diameter (L/D ratio). The optimum values of divergent angle and the L/D ratio were evaluated by keeping the convergent section constant. The constant convergent section was the one that was designed in 3.5.b. Divergent angle was varied from 6° to 16° for different L/D ratio of 0.5, 0.75 and 1.

From the above figure 4.8, it was observed that the velocity augmentation factor increases as the L/D ratio increases keeping the divergent angle constant. It is evident from the graph that the increase in the augmentation factor for L/D ratio varying from 0.75 to 1 is less than that achieved with change of L/D ratio from 0.5 to 0.75. Further, the increase in L/D ratio leads to increase in the overall length of the duct. So 0.75 was considered the optimum L/D ratio for the divergent section. The L/D 0.75 ratio not only gives a good augmentation factor but also keeps dimensions within the space constraint.

For the L/D 0.75, the augmentation factor increases with increase in the divergent angle. However, the increase is significant only till 12° divergent angle. For divergent angles higher than 12° there is a rise in augmentation factor but the increase is not as much as the increase in the outlet diameter. For divergent angle beyond a certain limit the flow tends to separate from the wall of diffuser which leads to lower velocity augmentation. The flow separation is more especially for the larger L/D ratio [2]. So from the above discussion the 12° divergent angle was considered to be the optimum value.

Table Velocities for different no. of elements

| No. of elements | Avg. Velocity @ throat (m/s) | Max Velocity (m/s) |
|-----------------|------------------------------|--------------------|
| 2840 | 6.08 | 8.74 |
| 2989 | 6.08 | 8.74 |
| 22683 | 6.10 | 8.79 |
| 35160 | 6.10 | 8.85 |

It is interesting to note that in contrast with the convergent section, the divergent section has very strong effect on the velocity augmentation, which can be attributed to the strong diffusion action. However, the use of convergent section is still justified as it makes the flow more concentrated before it starts to expand in the diverging section.

GRID INDEPENDENCE OF DUCT:

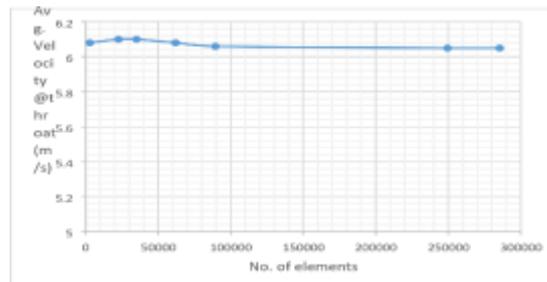


Fig. grid independence test

The mesh independency test was performed to ensure that variation in the number of elements does not affect the solution. The simulations were run at different number of elements between 2800 to 300000 and it was found that the variation in result from element count of 62038 to 285439 was less than 0.5%. Figure 3.13 shows the effect of element count on the velocity at throat by one of the duct model at the wind speed of $V_0=4.47\text{m/s}$.

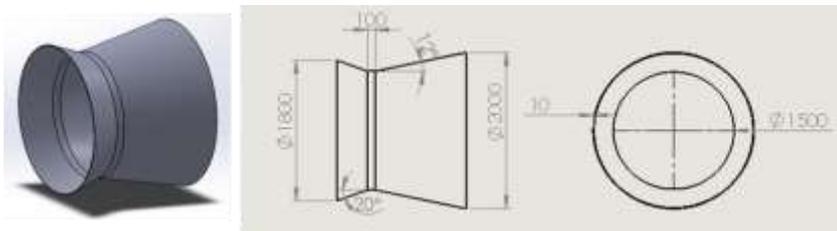


Figure. Final design of duct (All dimensions are in mm)

Area factor – 1.4

Convergent angle $\theta_1 = 20^\circ$

Divergent angle $\theta_2 = 12^\circ$ L/D = 0.75 3.5.2 Numerical Method:

Results and Discussion

Theoretical predictions:

The following results were predicted from the model during the starting phase of the design:

1. Area factor (ratio of velocity at throat to the inlet wind velocity) for the duct to be 1.4
2. Coefficient of power for the ducted turbine with tip speed ratio 5 to be 0.4
3. Power output of 300W at 10mph wind speed.

The further results show the extent to which the prediction were met and the reasons for deviation if any.

Analysis of Duct:

After the several failure attempts, the optimum shape of the duct was finalized. It was necessary to see how the final design was better as compared to initial assumptions.

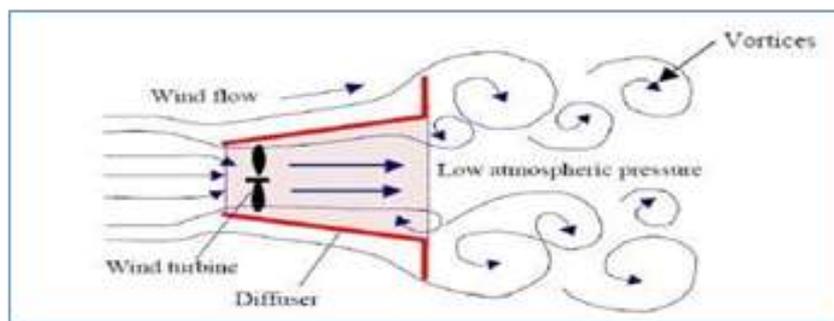


Fig. Schematic Cross-Sectional View of a Flanged Diffuser and Wind Speed Increasing Flow Mechanism

The flow through a diffuser forms a number of vortices near the end of the diffuser, which is mainly due to the flow separation. Further the areas surrounding the vortex would have typically lower pressure where the suction force will be formed by the vortex. Therefore, it will act as an accelerator to accelerate the wind velocity approaching the wind turbine. Hence the duct must have a diffuser for better velocity augmentation.

5.2.1 Simple diffuser section:

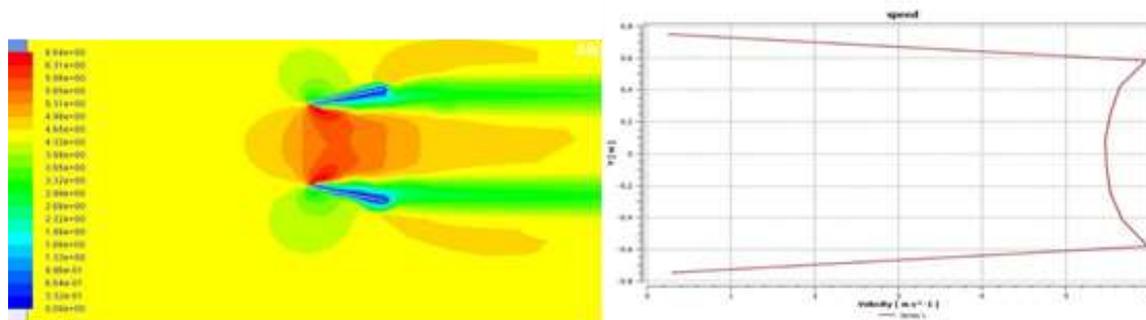


Figure . Velocity contour and profile at the throat for simple diffuser

From above simulation of the simple diffuser, it can be concluded that the 'no slip' area was more, i.e. velocity= 0. Even the velocity at the throat does not show much difference from the inlet velocity, hence there was need for determining more reliable shape of the duct to get desired results.

Double Diffuser:

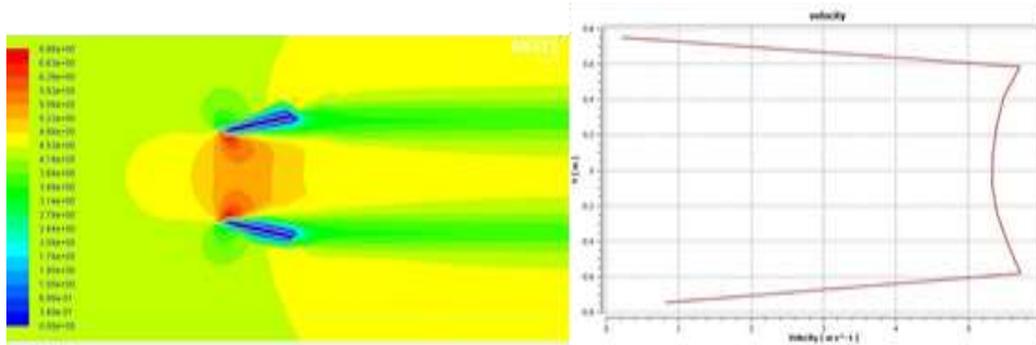


Figure Velocity contour and profile at the throat for double diffuser

The attempt was made to increase the suction of air by introducing one more diffuser inside or outside but no significant changes had been recorded. The average velocity at the throat was lesser as compared to single diffuser section which concludes adding another diffuser does not affect the incoming air velocity

Convergent Divergent duct: After introducing convergent section to the simple diffuser section, the obtained results were very close to the theoretically predicted one. The obtained area factor 1.34 achieved by the simulation was almost closer to the theoretical factor of 1.4. Hence this model was giving better performance than the only diffuser and double diffuser sections as it helped in giving air a desired path and minimizing the losses. Hence this section was finalized.

Table no. 5.1 Average velocity for different diffuser

| Section | Average Velocity (m/s) |
|-----------------|------------------------|
| Single Diffuser | 5.67 |
| Double Diffuser | 5.5 |
| CD duct | 6 |

DUCT RESULTS: Figure shows the velocity contour of the final duct design for inlet wind velocity of 4.47m/s with MF of 1.4, convergent angle 20°, divergent angle 12° and L/D ratio of 0.75. The maximum velocity was getting near the throat.

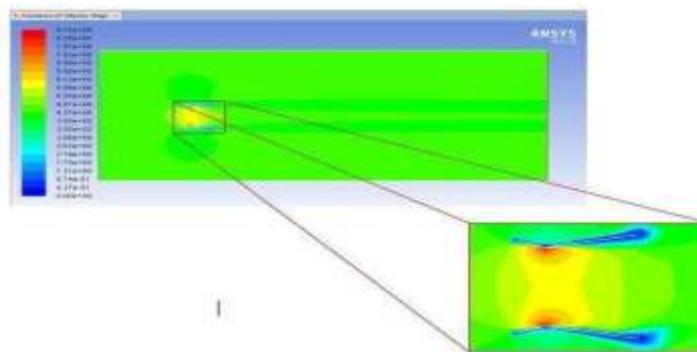


Figure Velocity contour for final duct

So the velocity at the throat was obtained by plotting the velocity profile at a linear location at the centre of the throat as shown in figure 3.8. The average velocity the throat was calculated by taking the average of velocities obtained by dividing the throat into eight parts. Velocities at eight parts shown in table no.4.2 and the average velocity profile shown in figure

Table Area factor for different inlet velocity

| Inlet velocity (mph) | Inlet velocity (m/s) | Velocity @ throat (m/s) | ea factor |
|----------------------|----------------------|-------------------------|-----------|
| 6 | 2.68 | 3.22 | 1.20 |
| 8 | 3.57 | 4.83 | 1.35 |
| 10 | 4.47 | 6.02 | 1.346 |

| | | | |
|----|------|------|-------|
| 12 | 5.36 | 7.24 | 1.350 |
|----|------|------|-------|

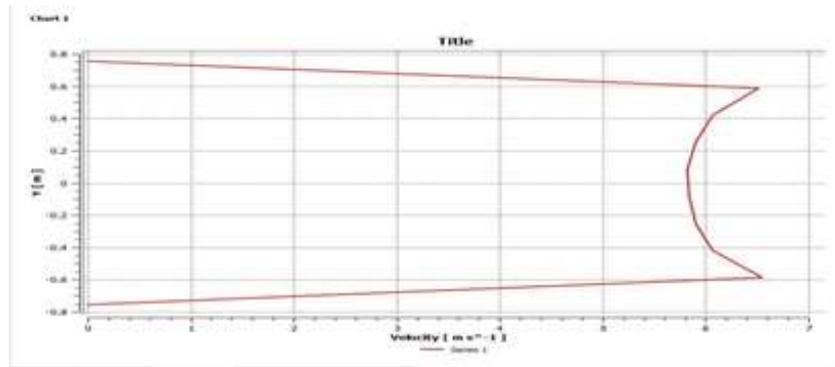


Figure Velocity profile at the throat

The average velocity was found to be 6.08m/s. Figure 5.5. shows the variation of throat velocity with different inlet wind velocity. As section 3.4 describes the wind velocity profile throughout the year, the wind velocity varies from 6 mph to 20 mph. From the below figure 5.6 it can be depicted that as the inlet velocity increases the throat velocity increases linearly with almost constant slope. The CFD analysis of the duct for different inlet wind velocities showed that an average augmentation factor (v_{throat}/v_{inlet}) of 1.3 was achieved for the designed duct. However, the duct was designed considering an augmentation factor of 1.4. This variation in the augmentation factor was because the predicted value was based on the laminar flow of wind within the duct (prediction was done considering only the continuity equation), but the actual flow was turbulent during the CFD analysis. Also the CFD analysis of the duct involved analyzing the flow in a control volume with the duct. Thus, the interaction of the flow with the duct and the vortices formation in the turbulence region can be some of the reasons for the variation in predicted value and the actual value achieved.

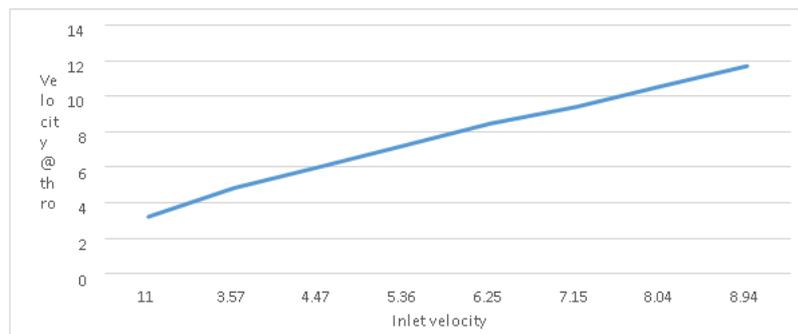


Figure. Variation of throat velocity with inlet wind velocity

Duct with vortex generator:

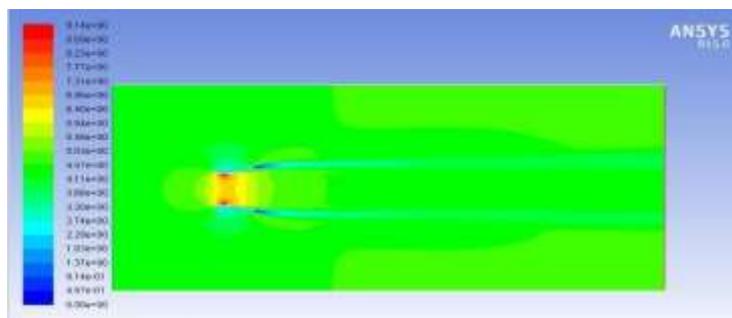


Figure Velocity contours of duct with vortex generator

The duct with the vortex generator was analyzed in Fluent Ansys, and it was found that the average velocity obtained to be 6.89m/s which was almost 15% higher than the velocity obtained for the simple duct, used in the design. However, the duct with generator was used only for qualitative analysis, to understand its possibility for any further scope, so value was obtained at coarse mesh and no grid independence was done. Therefore, the value obtained in reality may not be as high as predicted by the model.

Design specifications Of Turbine: The following characteristic curves for the turbine designed in the chapter (3.5) were obtained by changing the inlet velocity to the turbine. The inlet velocity for the turbine was the velocity obtained at the throat for different wind velocities.

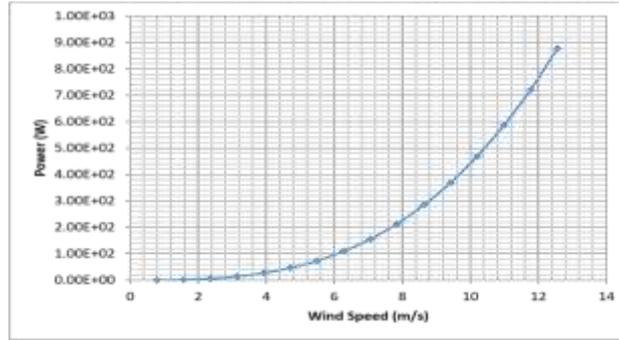


Figure Power developed by turbine vs wind speed at the throat.

The above plots were obtained as result of power calculation from the numerical code. The specifications of the turbine coupled with the generator are as follows:

Table Specification of the turbine

| | |
|-------------------|--------------------|
| Rated Power | 400W |
| Rated Wind Speed | 22mph |
| Cut in wind speed | 6mph |
| Rotor Diameter | 1.5m |
| Number of blades | 3 |
| Tip Speed ratio | 5 |
| Generator | AFPM AC generator. |
| Poles | 12 |
| Hub diameter | 200mm |

The 3 blade turbine designed for 1.5 m diameter and a tip speed ratio 5 gives a coefficient of power of 0.41. The coefficient of power achieved matches quite well with the value initially predicted. However, practically the value would be lesser as no mechanical losses have been considered during the study. It must be noted that the mechanical losses are reduce significantly due to the elimination of gear box.

The designed turbine would be directly coupled with the AFPM generator (chapter 3.6). The efficiency of the system is further reduced after considering the losses in the generator. The selected generator has an efficiency of 73% at the operating speeds of 400 to 500 rpm. Thus, the net power coefficient is further reduced to almost 0.3.

The system consists of a duct to augment the wind velocity. As already specified in the chapter 3.4 the average velocity augmentation achieved at the throat is 1.3, thus the velocity obtained at the throat is 1.3 times the wind velocity at the inlet of the duct. Thus, the cut in speed of 3 m/s for the bare turbine is reduced to 2.6m/s (6mph) for the ducted turbine.

The optimum point of operation occurs in the wind velocity range of 10.7 mph to 12 mph. The average velocity of wind in the area of Jabalpur is almost 10mph and therefore the optimum point of operation lies well within the average velocity limit, thus the direct coupling of the generator to the turbine is justified. The elimination of the gear box not only reduces the weight, and the overall size, but also reduces the losses that occur during power transmission.

The power output of the turbine is less than that predicted at the start of the design. The predicted values were based on the theoretical value of coefficient of power and the predicted value of area factor. The deviation of the actual area factor from the predicted (actual value: 1.3, predicted value: 1.4) value led to reduction in the velocity at the throat. The power from the turbine varied as third power of the velocity at the throat (in case of the ducted wind turbine). So small change in the velocity at the throat has a significant effect on the power. Thus, the reduced area factor is the major reason for the reduction in power output, as the coefficient of power is almost same as the predicted.

VALIDATION OF RESULT:

The numerical code designed for the evaluation of blade parameters, was successfully validated with the design obtained from, Modelling and Optimal Design of Small HAWT Blades for analyzing the starting torque' The given research paper delineates the design of a 5 m wind turbine with tip speed ratio of 8. The aero foil NACA 63-415 has been used. The results of the above-mentioned research paper were used to validate the numerical code. The values from the code were obtained by entering the input values, as provided in the above-mentioned research paper.

Table Axial induction factor, values from research paper vs the values predicted by numerical code

| <i>a</i> by base paper | <i>a</i> by code | %devialtion(<i>a</i>) |
|------------------------|------------------|-------------------------|
| 0.3195 | 0.378011 | 18.31317 |

| | | |
|--------|----------|----------|
| 0.3245 | 0.350748 | 8.088884 |
| 0.3272 | 0.33734 | 3.099067 |
| 0.3289 | 0.33006 | 0.352788 |

Table Tangential induction factor, values from research paper vs the values predicted by numerical code

| a _t by base paper | a _t by code | %deviation(a _t) |
|------------------------------|------------------------|-----------------------------|
| 0.1494 | 0.152267 | 1.91921 |
| 0.0894 | 0.089074 | 0.365051 |
| 0.0591 | 0.057946 | 1.953124 |
| 0.0419 | 0.040506 | 3.326486 |

Table Lift values from research paper vs the values predicted by numerical

| lift by paper | lift by code | %deviation |
|---------------|--------------|------------|
| 23.64 | 24.13337 | 2.087011 |
| 30.43 | 30.80252 | 1.224178 |
| 37.27 | 37.40646 | 0.366134 |
| 44.18 | 44.03588 | 0.326202 |

All the further turbine parameters viz. torque, axial force, angle of attack, chord length and the angle of twist, depend primarily on the induction factors. So correct estimation of induction factor is very vital for the results. From the above validation of the code, it can be concluded that the values predicted by the code hold good in the scope of its application. Therefore, as the code could successfully be validated with an already available model, it can be estimated that the results obtained from the code are correct, provided that the scope of application is within the assumptions.

Conclusion

Different designs of duct with varying length to diameter ratio and convergent divergent angles were studied using SolidWorks and Ansys Fluent. It was found that the convergent section had negligible effect on the velocity augmentation factor as compared to divergent section, so the convergent section was used only to concentrate the flow whereas the required augmentation was achieved by the divergent section. With the optimized design of the duct the augmentation factor of 1.35 was achieved against the desired value of 1.4. With wind velocities obtained at the throat of the duct appropriate blade parameters were derived for the selected aerofoil and a generator was selected to achieve the required power output.

The final design of the duct and blade had the following configuration:

Throat Diameter: 1.5m, Area factor (convergent section) = 1.4, Convergent angle $\theta_1 = 20^\circ$, Divergent angle $\theta_2 = 12^\circ$, L/D (divergent section) = 0.75

Blade specifications: Tip speed ratio: 5, Number of blades: 3, Aero-foil: NACA 0012, chord length : 17cm at hub to 4cm at tip, blade length: 650mm.

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