Performance of Shrouded Micro Wind Turbine for Low Wind Velocity

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Abstract - *The growing demand for electrical energy for industrial and domestic use, coupled with the limited amount of available fossil fuel reserves and its negative effects on the environment, have made it necessary to seek alternative and renewable energy sources. The use of renewable energy is promoted worldwide to be less dependent on conventional fuels and nuclear energy. Therefore research in the field is motivated to increase efficiency of renewable energy systems. Wind energy is the kinetic energy associated with movement of large masses of air. These motions result from uneven heating of atmosphere by sun creating temperature, density, pressure differences. It is an indirect form of solar energy The device used to convert kinetic energy of wind into electrical power is called a wind turbine. This study paying attention on the design of a new concept to improve wind turbines to be appropriate for the low wind speeds in India. The concept involves the implementation of a concentrator and diffuser to a wind turbine, to increase the power coefficient.*

***Key Words*: micro wind turbine; power; shrouded; wind speed; wind turbine.**

1.INTRODUCTION

Of late electricity is the major problem in this world especially in rural areas of India. In the present era of steadily rising fuel costs, wind energy is becoming an increasingly attractive component of future energy systems. The wind potential of India is very high. The wind turbines have been installed and wind energy is being harvested, predominantly in the high wind velocity areas. However, due tothe restriction of space, the comparatively lower wind areas are beginning to populate with similar wind turbines In order to ensure the extraction of maximum wind potential even at lower wind speeds, the turbine have to be designed and analyzed to suit the low wind areas. At present India stands fifth in the world of wind power generation. Taking into consideration that a large portion of the Indian land will not be viable for theuse of traditional windmills due to low wind speeds, a generator which would produce the energy even at low wind speed is required.

Shrouding (diffuser augmentation) might be an effective way to improve the performance of micro wind turbine for applications in built environments. By the application of Nozzle diffuser augmentation pressure at the diffuser exit is lowered, approaching wind is accelerated, and wind velocity at the diffuser inlet is increased. It is well understood that the degree of the performance enhancement depends on several factors including the nozzle - diffuser shape and geometries, blade airfoils, and the wind condition at the mounting site. Small wind turbines need to be inexpensive, reliable and almost maintenance free for the average person to consider installing one. Small-scale wind turbines produce more costly electricity than large and medium-scale wind turbines, especially in poor wind sites and in autonomous applications that require a high level of reliability. However, when sized properly and used at optimal working conditions, small-scale wind turbines could be a reliable energy source and produce socio-economically valuable energy not only in developing countries but also in autonomous applications in locations that are far away from the grid power in developed countries. Small-scale wind turbines are in fact becoming an increasingly promising way to supply electricity in developing countries. The small-scale wind turbines have quite different aerodynamic behavior than their large-scale counterparts.

1.1 Potential of micro-wind turbines

As a replacement, wind turbine technology may offer electricity in these rural locations. In particular, small wind turbines are an attractive option for developing markets that currently lack electricity or are energy deficient. As a general guideline, micro wind turbines are classified within the range of 0 - 500W. Micro-wind turbines have many benefits. They are easy and quick to set up as they come in small sizes and have a shorter construction lead time than extending the utility grid lines.

Small wind turbines can operate for delayed periods without attention; with only a few moving parts, these systems have very low maintenance necessities compared to other energy options. In addition, small wind turbines are not difficult to produce. In this respect, local manufacturing is often a suitable option for developing countries that could, in turn, stimulate local economic development and lower production costs. Wind systems replace existing household expenses for kerosene, candles and dry-cell batteries. last of all, wind systems require little to no water to operate and do not put in greenhouse gases or other toxins to the atmosphere.
Average Wind speed between 15m/s and 25m/s is categorized as high speed, between 7m/s and 15m/s as moderate speed and 2.5m/s and 7m/s falls in low wind speed region. Turbines having generation capacity between 2KW and 10KW are known as small wind turbines and generation capacity up to 2KW as micro wind turbines or domestic micro wind turbines.

Small wind turbines need to be affordable, reliable and almost maintenance free for the average person to consider installing one. This often means a surrender of optimal performance for simplicity in design and operation. Thus, rather than using the generator as a motor to start and accelerate the rotor when the wind is strong enough to begin producing power, small wind turbines rely solely on the torque produced by the wind acting on the blades. Furthermore, small wind turbines are often located where the generated power is required, and not necessarily where the wind resource is best.

2. Methodology

The maximum theoretical power which can be extracted from the wind is set out below. This law is derived from the principles of conservation of mass and momentum and is generally attributed to Betz (1926), although there was three independent discoveries. The following assumptions are made in order to derive the maximum power available.

1. Homogeneous, incompressible, steady state fluid flow
2. No frictional drag
3. An infinite number of blades
4. Non rotating wake
5. Uniform thrust over the rotor area
6. Static pressure far upstream and downstream is equal

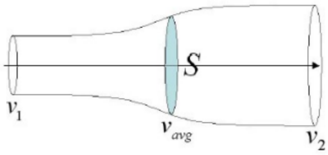

Fig -2.1: Actuator disk model for a wind turbine

2.1 Total power available in a shroud

To determine the total power available in a diffuser or concentrator as proposed by Orosa et al. (2009), Wang et al. (2007), Bernard Frankovic_ &Vrsalovic (2001) and Ohya&Karasudani (2010) (naming only a few). The average velocity where the wind turbine should be situated in the shroud is measured and substituted in the place of v1 in equation to determine the total power available. The total blade area of the turbine in the shroud is denoted as *S*.

2.2 Blade design

The variables as depicted in Figure 2.2 can be used to determine the torque per blade element. *UT* is the relative velocity. *Uo* is the axial velocity, a the axial induction factor, *a'* the rotational induction factor, *r* the radius at the centre of the blade element and Ω in rad/s.

The torque (dQ) available for a blade element from the velocity of the air, for the annular area (dA) can be determined. N is the number of blades of the wind turbine.

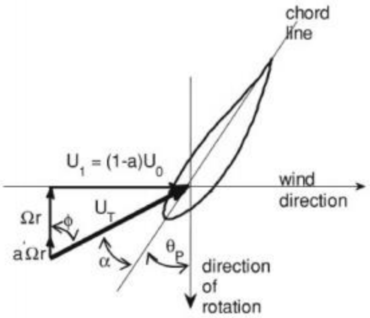

Fig -2.2: Velocities for a cross-section blade element at radius r (Wood 2011).

$$dP = \Omega . dQ$$

$$dP = C_p . \rho . U_o^3 . dA$$

$$dQ = \frac{C_p . \rho . U_o^3 . dA}{\Omega . N}$$

The angle φ in Figure 2.2 can be determined with (Wood 2011, 47).

$$\tan \varphi = \frac{\rho . (1-a)}{\Omega . r . (1+a')}$$

The torque per blade element (Wood 2011, 46) can also be determined with the drag and lift forces on the blade element. The two dimensional lift (Cl) and drag (Cd) ratios should be determined for the airfoil after the Re is determined with c (chord length) and UT .

$$dQ = 0.5 . \rho . U_T^2 . c . (C_l \sin \varphi - C_d \cos \varphi) . r . dr$$

Therefore designing each blade element requires a iterative process.

3. CFD simulation Set-up

The simulations that were done with the Star-CCM+ software necessitate an elaboration on the set-up of the wind turbine models in this CFD code. Section 2.6 on page 19 dealt with simulations of shrouded wind turbines in CFD and explained the way in which wind turbines in shrouds were simulated in a CFD Code. This was used as a basis to set-up the wind turbine configurations in CFD. The set-up explained in this section was used in the validation of the computational modeling as well as the simulations to design the shrouded wind turbine.

A three dimensional CAD package Solidworks was used to draw the wind turbine configurations. The drawings were then imported into Star-CCM+ as a surface mesh. The whole domain was volume meshed with a polyhedral mesh. On the surfaces of the diffuser and blades a prism-layer mesh was used to mesh the boundary layer. The three dimensional flow field was simulated as steady state. A uniform velocity inlet and pressure outlet was chosen as inlet and outlet boundaries. As the wind turbine configurations are cylindrical, the wall boundary was also drawn cylindrically.

As a boundary layer was not necessary, the shear stress specifications were chosen as slip on these boundaries.
In some simulations, a chosen angle of this cylindrical domain was simulated to reduce computing time. Periodic interfaces (Wang & Chen 2008) were used to model some of the shrouds with blades. For six blades only 600 of the cylindrical domain was modeled and for three blades 1200 . Symmetrical boundary conditions were applied when an angle of the domain was modeled for only the shroud (without a wind turbine).

The low Mach numbers lead to the use of constant density (incompressible flow) to model wind turbines either with or without a shroud as well as the shrouds with no wind turbine (Wang et al. 2008).

The flow fields were defined with the Reynolds-Averaged Navier-Stokes (RANS) equations. The equations were completed with the use of additional turbulent models. This additional transport equations that were solved along with the RANS flow equations was the k - Ɛ turbulence or k - ω turbulence models (Versteeg & Malalasekera 2007, 66).

The two layer k - Ɛ model with standard wall function was used to obtain cell independence, but near-wall performance is unsatisfactory. Thus for increase accuracy a k - ω model with a Gamma RE the ta transition model (Langtry 2006) was introduced after cell independence was reached. The model was implemented with a field function that defines the free stream edge. The k - ω model required more computing resources, therefore cell independence was initially reached with the two layer k - Ɛ model.

The Star (2014) help file proposed a segregated flow model to solve the incompressible flow, which also saved computing costs. Criteria for meaningful CFD results In order for a simulation to generate results that are meaningful, requires primarily that a value of significance converge from a number of iterations and that cell independence is maintained (Versteeg & Malalasekera 2007, 5). This was accomplished by plotting these values (velocity at a point in the shroud and torque for the wind turbine blades) against iterations. Each time a surface mesh changed, this value (the solver) should converge. If these values converged, the surface mesh size was reduced and the model was again simulated until the same values converged again. If this process is followed and the converged values remain the same, cell independence is reached.

Another value of importance is the Wall Y+ value that indicates if the boundary layer was sufficiently discredited with prism-layer cells. Wang & Chen (2008) indicated that the Wall Y+ value should be in the range of one and zero to solve the laminar sub-layer accurately.

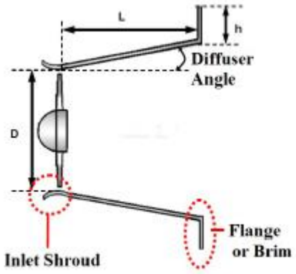

Fig -3.1: Schematic of a wind turbine equipped with a Flanged diffuser shroud (Ohya et al. 2008)

Residuals are produced after each one of the iterations. This indicates how well the governing equations are numerically satisfied for each solver. According to the (Stern et al. 1999), a value below 0.001 is more likely for complex geometry and conditions than values nearer to 0.

As the measured values and simulated values were different it was necessary to define tolerances for these differences. Babuska & Oden (2004) proposed in their study on validation and verification.

In computational engineering and science that these tolerances are user defined and will vary with the purpose of the values obtained. In the study on a wind turbine in a shroud Wang et al. (2008b) showed that a 5% difference existed between the measured and simulated results.

3.1 Diffuser parameters

Ohya et al. (2008) performed wind tunnel experiments on diffusers with a brim attached to the outlet. The wind tunnel velocity U0 was 5m=s. The length(L), inlet diameter(D) and brim length(h) is depicted in Figure

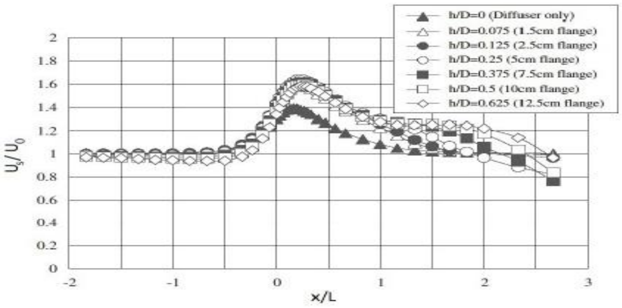

Fig -3.2: Wind velocity distribution on the central axis of a circular-diffuser with different brim heights (Ohya et al. 2008).

The inlet diameter of the diffuser was D = 20cm and the ratio to obtain the length was L/D = 1:5. The area ratio was 1.44 for the inlet and outlet diffuser surface area. The velocity in the diffuser was measured at the central axis with a I-type hot wire and a static pressure tube. The size of the brim was varied to obtain a optimum height for a maximum velocity at the inlet of the diffuser. The height of the brim is given as a ratio h/D . Figure 4.2 illustrates the values obtained through the experiment. For the values obtained by Ohya et al.

(2008) the validation is done on the diffuser with a brim that had a height of h/D = 0:25.

3.2 Shroud design

The importance of a diffuser with inlet nozzle and a brim were shown. Ohya et al. (2008) tested a pole mounted wind turbine with diffuser and brim. These ratios were selected for implementation to the new design as it proved well tested. Tests showed that an angle of 150 (Figure 5.4) for the diffuser was the most effective angle. It was noted that a long diffuser had a "remarkable" increase in flow velocity at the inlet of the diffuser but from a practical viewpoint a diffuser with a ratio L1/ D1 = 0.75 was proposed as depicted. An inlet shroud with length (L2) 0.25 times the diffuser inlet diameter(D1) was used with a total inlet diameter (D2) of 1.14 times the diffuser diameter(D1). With the development of the brimmed diffuser the total diameter (DT) of the configuration was not considered.

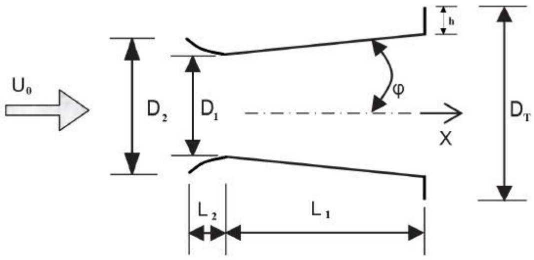

Fig -2.2: Shroud dimensions

The optimum brim length (h) and diffuser angle was determined after an inlet diameter was specified. Therefore h/ D = 0.025 was chosen although was not the optimum brim height as seen in Figure. This would have increased the inlet diameter and thus the area of the wind turbine in the arrangement.

This resulted in a diffuser length of 305 mm with a inlet diffuser diameter of 400 mm (D1), an inlet nozzle with a length of 102 mm (L2)with a diameter D2 440 mm and a brim height of 10 mm (h) and total diameter of600 mm (DT).

The airflow in the brim was concentrated to the wall of the diffuser with the use of an revolved airfoil body. The use of this body for a center hub reduces drag and thus increased the flow of air through the diffuser. A low Re airfoil was chosen for the inner concentrator. AEppler 862 strut airfoil with a maximum thickness of 32.4 % at 28.5% chord was chosen.

4. Experimental Setup

The Shrouded micro wind Turbine has components viz. blade, shaft, gears, PMDC motor, nozzle and diffuser (shroud), measuring instruments – Anemometer, multimeter, Tachometer for the measurement purpose.

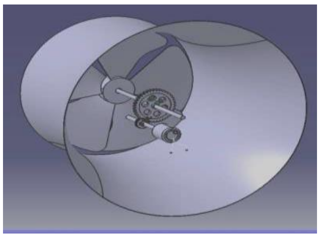

Fig -4.1: Assembly of components in CATIA

4.1 Rotor

The 10-blade rotor has been taken as the size of the turbine and number of blades required for efficient performance are inversely proportional. It also facilates the lower starting speed of the turbine.

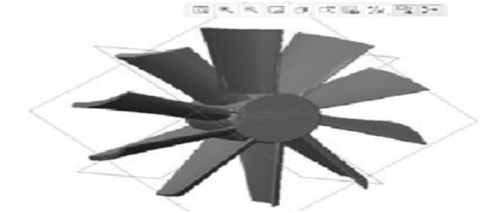

Fig -4.2: 3D rendering of turbine rotor

4.2 Shaft

The M.S. Shaft of diameter 14 mm, 500mm long has been taken and turned to fit into the blade aperture and to fit into bearings. Another shaft of 14mm, 200 mm turned to fit into mashing gear (Pinion), bearings and to couple with PMDC motor.

4.3 Gears

Two meshing Gears on e with 67 teeth and 120 mm diameter and another with 18
teeth and 36 mm diameters are used to achieve the gear ratio of 4.

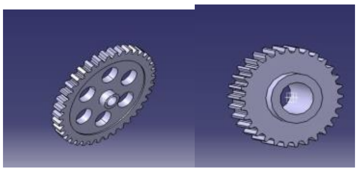

Fig -4.3: a) Gear b) Pinion in CATIA

4.4 Frame

Square pipe 1 Inch, 20 feet long is used to fabricate frame to support two shafts for power transmission from rotor to PMDC motor and shroud.

4.5 Shroud

The shroud design consists of three main features: the shroud inlet is essentially the nozzle portion of the design and will be used to increase the incoming velocity by decreasing the cross sectional area of the shroud, the shroud outlet is a diffuser which causes the air to experience a decrease in pressure, which creates a pressure differential between the inlet and outlet air, thus causing an increase in wind speed through the turbine, and the shroud flange is located at the back edge of the shroud and creates a low pressure point that also increases the wind speed through the shroud. Below, both an assembly and exploded view of a representative wind turbine shroud are shown.

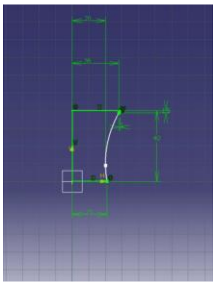

Fig -4.4: Drawing of Shroud

4.6 Nozzle (Concentrator)

GI sheet (24 gauge) is shaped to form Nozzle with inlet diameter of 440 mm and outlet diameter 420 mm where the rotor is located. The 420 mm diameter is extended straight for 102 mm so that this element can be fitted into diffuser.

4.7 Diffuser

Diffuser with inlet diameter 420 mm and outlet diameter 580 mm with length of305 mm has been formed from GI sheet (24 gauge) with same matching element to fit outside nozzle. Flange is made integrated part of diffuser.

Fig -4.5: Nozzle Diffuser Assembly (Shroud)

4.8 PMDC Motor

In electricity generation, an Permanent Magnet Direct Current (PMDC) is advice that converts mechanical energy to electrical energy. A generator forces electric charge (usually carried by electrons) to flow through an external electrical circuit.

Fig -4.6: PMDC Motor

5. Results and Discussion

The primary analysis included four factors: flange angle, angle of openings, nozzle length, and diffuser length. The factors were measured at a maximum and minimum value selected based on insights provided in available literature. In this case, wind velocity at the location of the turbine blades was used as the output for each iteration. The two levels analyzed for each factor were as follows:

Table-5.1: High and Low Values of Four-Factor DoE

Isolated Factor	High Value	Low Value
A) Flange Angle	25°	0°
B) Opening Angle	25°	5°
C) Nozzle Length	5.0 in	0.20 in
D) Diffuser Length	14.0 in	0.50 in

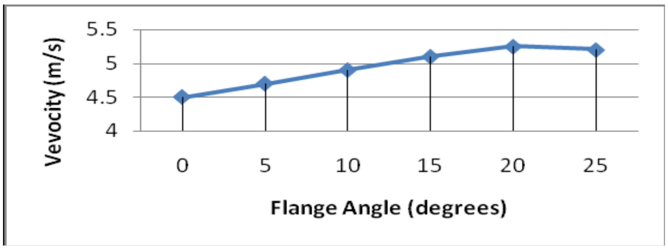

Chart -5.1: Effect of the flange angle on the average velocity.

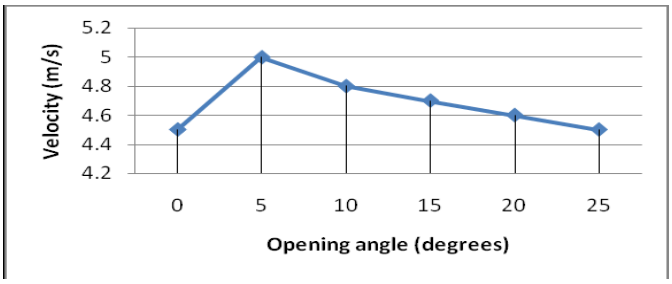

Chart -5.2: Effect of the opening angle on the average velocity.

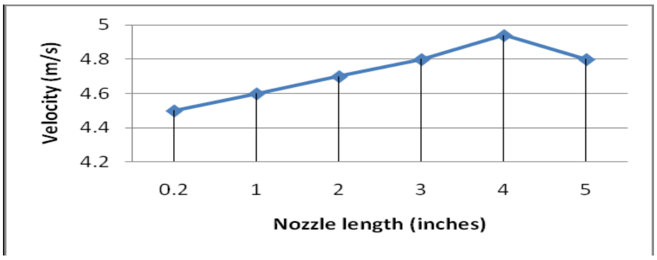

Chart -5.3: Effect of the nozzle length on the average velocity

The length of the diffuser alone had the most significant impact on the performance; a longer diffuser creates a higher velocity through the shroud. The flange angle was determined to be relatively insignificant in affecting the velocity through the shroud. Figures 6.1 – 6.4 demonstrate the impact that each factor had on the performance of the shroud based on the average velocity of the sixteen trials that were run.

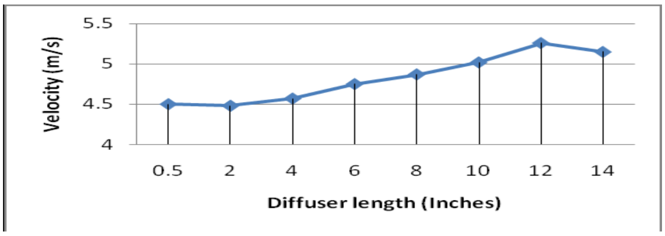

Chart -5.4: Effect of the diffuser length on the average velocity.

The run order and output values for the three-factor DoE can be observed in Table.

Table-5.2: Two-Factor Two-Level DoE Results

Standard Run Order	Nozzle Angle (A)	Diffuser Angle (B)	Output Velocity
1	5	5	5.63
2	10	5	5.44
3	5	15	5.94
4	10	15	5.58

Table-5.3: New Cp values determined with Equation as maximum available Power

Wind speed(m/s)	Air speed in shroud(m/s)	Available power(Watt)	Cp Values
2	4.49	32	0.24
3.5	8.07	174	0.35
5	11.34	497	0.39
7	15.03	1292	0.4
9	20.16	2864	0.45

Table-5.4: Total available power for a shrouded and open wind turbine

6. Conclusions and recommendations for future studies

6.1 Conclusions

It can be concluded that if the objective was to design a shrouded wind turbine with a higher power output than a open wind turbine with the reverence diameter to be taken as the total diameter of the configuration, then the objective was not met. If the surface at the blades was taken as the reference, the Cp value corresponded well with other shrouded wind turbines (Cp = 0.72 to Cp = 0.88 was at a generator efficiency of 88%). Calculated with Equation with the air speed in the shroud and the turbine area in the shroud (As elaborated on in Chapter 6). If the Cp values is calculated with the actual available power as described in Chapter 6.3 the values were Cp = 0.24 at 2m/s and Cp = 0.45 at 9m/s for a non optimum design. These values reflect well to modern wind turbines. For a low wind speed of 2m/s and a total diameter of 3.6m (10.18m2), without a wind turbine the mass flow is 24.02kg/s. The mass flow for the diffuser concentrator arrangement is 18.5kg/s with the area as 3.49m2, where the wind turbine should be situated in the shroud at a average air velocity of 4.49m/s in the shroud for the wind speed of 2m/s. For a total diameter of 2.47m, the same as the wind turbine in the shroud, at a free wind speed of 2m/s the mass flow is 8.23kg/s.

6.2 Recommendations for Future studies

The total or stagnation pressure at the far front, back of a shroud and in the shroud is equal if no energy is extracted. If energy is extracted either by a wind turbine or friction in a shroud, it will reduce the total pressure in the shroud. This, together with the fact that the available power is the product of the mass flow and the total pressure that has been divided by the density, it can be concluded that a configuration with a larger mass flow in a shroud will have more energy available. To increase the mass flow it is recommended that a shroud with brim or an airfoil that forms a shroud be tested. The increase of air speed to a maximum is not of importance, but the overall mass flow at the surface where the wind turbine should be situated has to increase. Therefore the possibility of increasing the mass towards a wind turbine with the use of a shroud should be investigated.

Thus it can be recommended that further research for a shrouded wind turbine should be implemented. This should include blades with complex shape design, structural design for tower and the economical feasibility of such a configuration.

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