Comparative Analysis of Diffusers for Micro Wind Turbine

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ABSTRACT

With the increase in demand for clean energy, a micro wind turbine would be the best option for remote and urban residential areas. Installing wind turbines is not feasible in most land areas due to low or inadequate wind speed. The energy generated by the wind turbine is directly proportional to the cube of wind velocity. So, if we manage to increase wind speed slightly, it would increase energy significantly. One approach to solving problems in areas with low wind speed is using Diffuser Augmented Wind Turbine (DAWT). In DAWT, the turbine blades are typically surrounded by a duct which increases the cross-sectional area in the stream-wise direction. Since a diffuser encloses the wind turbine, the pressure behind the turbine will drop, which results in an increasing wind velocity. Different types of diffusers have been introduced to increase wind velocity. The main aim of the research is to perform a comparative analysis of four different types of diffusers to increase the power output of wind turbines. The CFD simulation of Plain Diffuser, Plain Diffuser with Inlet Shroud, Flanged Diffuser, and Flanged Diffuser with Inlet Shroud is performed to determine the maximum velocity each diffuser produced. With the solution from the simulation, a comparative analysis of each diffuser is conducted, and the results are further verified with the previous studies on DWAT. And Flanged Diffuser is found to be optimum with an increase in power generation up to 3.6 times compared to a bare wind turbine.

Keywords: Procyon, Schmidt-Cassegrain telescope, Flux density variation

1. INTRODUCTION

In recent years the development and application of renewable energy sources have become an important concern due to the rapid depletion of fossil fuels and the binding effect of global warming. Various alternative and clean energy methods are being evaluated to mitigate such effects. There is a need to strive for alternative and sustainable sources of energy. Wind energy, being a renewable and inexhaustible energy source, is currently the rapidly growing energy technology worldwide. According to the Solar and Wind Energy Resource Assessment (SWERA), Nepal has a good prospect for wind energy generation with a potential of about 3,000 MW (AEPC 2008). For a few decades, power production from wind turbines has been the focus of interest for scientists and researchers. A wind turbine is an electromechanical device that taps the wind's kinetic energy and converts it into electrical energy. Vertical and horizontal axis types are widely manufactured types of wind turbines. Micro wind turbines are used in micro wind generation and are much smaller than conventional wind generation, making them more appropriate for residential energy production.

In 2019 wind energy of capacity 60.4 GW was installed globally, a 19% increase from installation in 2018. The total capacity for wind energy globally is now over 651 GW, a 10% increment compared to 2018. 2020 was expected to be a record year for wind energy, with GWEC forecasting 76 GW of new installation (GWEC 2020). China and the US are the leading countries in wind production, with 221 GW and 96.4 GW, respectively (The Economic Times 2019). Nepal, a mountainous country, has a high potential for wind energy. The potential area of wind power in Nepal is about 6074 sq. km, with a wind power density greater than 300 watts/m2. More than 3,000 MW at 5 MW per sq. km. could be generated in Nepal. However, the commercially viable wind potential is only about 448 MW (Upreti & Shakya 2010).

The power produced by the wind turbine depends on the Betz limit: no turbine can capture more than 59.3% of the wind's kinetic energy. It is also known that generated power by wind turbines is proportional to the cubic power of the incident wind speed, so any small increase in the incident wind causes a large increase in the energy output. Therefore, researchers proposed several innovative concepts to augment wind turbine power output. Performance of wind turbines can be improved in several ways, such as blade design modification, using vortex type augmentation devices, augmentation by application of tip vanes on the rotor blades, and using diffusers shrouds concentrators to make a ducted wind turbine. Compared to other augmentation solutions, Diffuser Augmented Wind Turbine (DWAT) exhibits advantages compared to the various other augmentation solutions and is one of the most prominent used techniques to enhance power captured.

The ducted turbine can accelerate the airflow through a converging intake; hence, more power will be generated for a given turbine diameter and wind speed, exceeding the Betz limit. In other words, the diffuser generates separation regions behind it, which create a low-pressure region to draw more wind through the rotors than a bare wind turbine (Bet & Grassmann 2003). DAWTs were a hot topic in the 1979 wind energy innovative system conference and gained recognition as a valid potential for augmented power of conventional wind power systems. However, DAWT's popularity quickly slowed down due to unfavourable capital, operation, and maintenance costs, and the focus was shifted to developing horizontal axis wind turbines (HAWT) (Bussel 2007). An improvement in analysis and simulation tools for fluid dynamics s led to a re-appearance in interest for DAWT's in a range of studies such as aerodynamic shape, size, and diffuser design.

Several studies were conducted in the 1950s which studied the use of diffusers in wind turbines focused mainly on the flow control mechanism to increase the mass flow rate within the diffuser. Around 1980, Gilbert (1978), Gilbert and Foreman (1983), Igra (1981), and others carried out important research in the examination of diffuser augmented wind turbines (DAWT). These studies focused on concentrating wind energy in a diffuser with a large open-angle and controlling the boundary layer with several flow slots. Thus, the method of boundary layer control increases the mass flow inside the diffuser by preventing pressure loss due to flow separation. Based on this idea, a group in New Zealand developed the vortex 7 diffusers augmented wind turbine (Phillips *et al.*, 2002; Phillips *et al.* (1999). To prevent separation within a diffuser, they used a multi-slotted diffuser. Abe and Ohya (2004) used CFD to investigate the flow fields around flanged diffusers to develop small wind turbines. They found that the performance of a flanged diffuser greatly depends on the loading coefficient and the opening angle. Various other ideas have been reported so far, but most of them do not appear to explain the feasibility of commercialization.

Various factors enhance the performance of DWAT, such as diffuser geometries, blade shape, and the flow of the wind at the mounting site. The geometry of the diffuser is the main parameter to control the wind flow through the rotor. The diffuser enhances the output power of a wind turbine by accelerating the velocity of the wind that approaches the wind turbine. When free stream air passes through a diffuser, air at the outlet region diffuses and develops small vortices with typically lower pressure. A lower pressure region at the back of the wind turbine will act as a vacuum and suck the wind, which is accelerated towards the blade. Thus, there will be an increment in wind velocity. A small increase in wind velocity leads to a significant increase in power generation since power generation is directly proportional to the third power of wind velocity approaching rotor blades. A diffuser can be designed into different shapes, increasing the wind velocity accordingly.

This study has proposed four different shapes of diffusers: plain diffuser, flanged diffuser, plain diffuser with shroud, and flanged diffuser with shroud. Plain diffusers are diverged from inlet to outlet and are simple, with no structures attached to the inlet and exit periphery. A flanged diffuser consists of a diffuser with a ring-shaped flange at the exit periphery. The flanged diffuser generates a low-pressure region at the exit by vortex formation, draws more mass flow to the wind turbine, and increases the wind velocity. Plain diffuser with shroud consists of a converging ring-shaped shroud at the inlet periphery. The shroud directs better streamlines of the airflow through the diffuser. The wind velocity at the entrance will be increased due to the lower pressure generated by the shroud. Flanged diffuser with shroud consists of both shroud and flange at the inlet and exit periphery, respectively.

2. MATERIALS AND METHODS

2.1 Power Generation Formula

The equation to the wind power (P) is given by

$P=0.5*\rho*A*C_p*V^3*N_i*N_e$

Where,

ρ= Air density in kg/m²

A= Rotor swept area m²

C_p= Coefficient of Performance

V = wind velocity

N_i = generator efficiency

N_e = gearbox bearing efficiency

This equation shows that power generation is directly proportional to the third power of wind velocity. So, a slight increase in wind velocity will lead to a significant increase in power generation.

2.2 Ideology

The main idea is to increase the generated power of wind turbines by manipulating aerodynamics around the structure or topography. We can consider basic structures like cylinders, diffusers, and nozzle to utilize fluid properties around the turbine. The cylindrical structure does not significantly change the fluid flow, so it would not be a preferable choice in this context. However, the diffuser and the nozzle play a key role.

When free stream air is allowed to pass through apparatus with small inlet cross-sections and larger outlet cross-sections, the air gets diffused, resulting in the formation of vortices at the outlet. The region surrounding or near the vortex would have lower pressure where the vortex will create the suction force. These pressure drops at the outer section cause air at the inlet section to accelerate towards the outlet section. This pressure drop leads to an increase in wind velocity approaching wind turbines. Since power generated is directly proportional to the wind velocity striking wind turbine blades, a slight increase in wind velocity leads to a significant increase in power generation.

Similarly, air converses toward the outlet section when free stream air is allowed to pass through a nozzle with a larger inlet cross-section and relatively smaller cross-section area. This conversion of air causes air pressure to increase at the outlet section. This pressure difference results in the deceleration of free stream air. Thus, decreasing the power output of wind turbines.

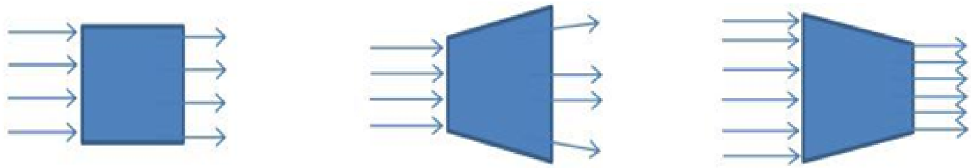

Fig. 1. Cylinder, Diffuser, and Nozzle

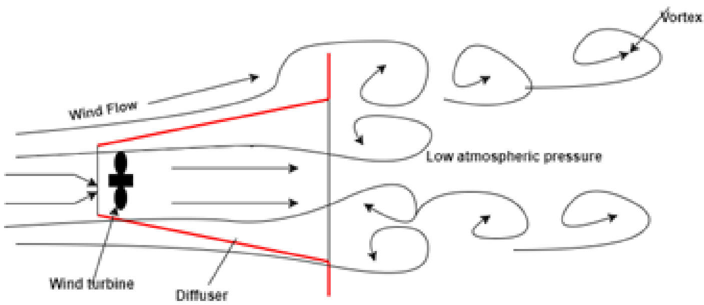

Fig. 2. Schematic sectional view of the flanged diffuser and its flow accelerating mechanism (Matsushima 2006)

2.3 Design Study

This research was carried out in two stages. First, we determined the optimum parameters at which they give the best performance for each diffuser under study. Secondly, we designed, simulated, and then analyzed each model.

We consider four different types of diffusers under research. Diffusers were mainly designed for horizontal axis micro wind turbines with a rotor diameter of 900mm and a power output of 220W. Wind speed augmentation in diffusers depends on the geometrical shape parameters of the diffuser, mainly the diffuser expansion angle (ɵ) and the non-dimensional length (μ). Based on the literature review, the length of the diffuser is taken as 0.5 times rotor diameter. The diffuser angle of 14.5º, the flanged height of 0.25 times rotor diameter, the shroud angle of 45º, and the length of 100 mm were taken. The following are four different types of diffusers considered:

a) Plane diffuser
b) Plane diffuser with inlet shroud
c) Flanged diffuser
d) Flanged diffuser with inlet shroud

2.3 Different Design Models

We designed four different diffusers on Solid Works based on the above-considered parameters.

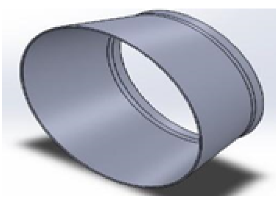

Fig. 3. Plain Diffuser

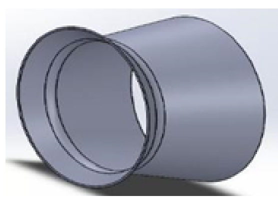

Fig. 4. Plain Diffuser with Inlet Shroud

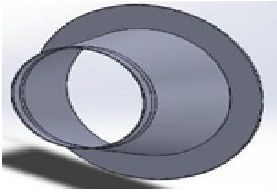

Fig. 5. Flanged Diffuser

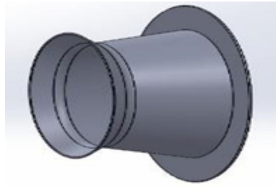

Fig. 6. Flanged Diffuser with Inlet Shroud

2.3 CFD Simulation

Performance analysis of each diffuser was done using CFD on Ansys Fluent. Inlet velocity of 5m/s was set as boundary conditions.

3. RESULTS AND DISCUSSION

3.1 Simulation Result of Plain Diffuser

From the CFD analysis of the plain diffuser, we found that velocity at the inlet section increases to a maximum value of 8m/s, mainly due to pressure drop in the rear end of the diffuser. The average velocity at the inlet section is around 6.75m/s.

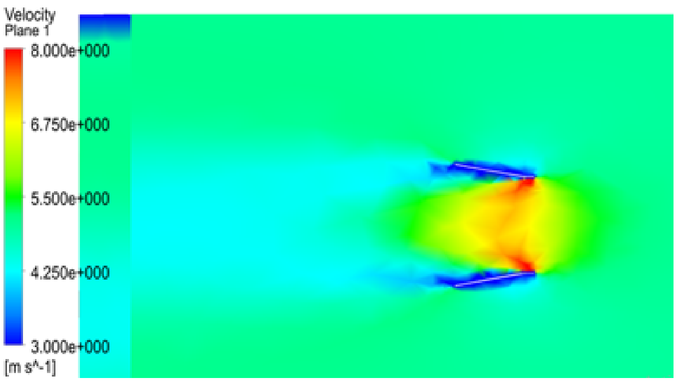

Fig. 7. CFD simulation of plain diffuser

3.2 Simulation Result of Flanged Diffuser

The velocity profile of the flanged diffuser shows an increase in velocity up to 8m/s with an average velocity around 7.7m/s at the inlet periphery. This increase in velocity is mainly due to the addition of flange, which helps create vortices.

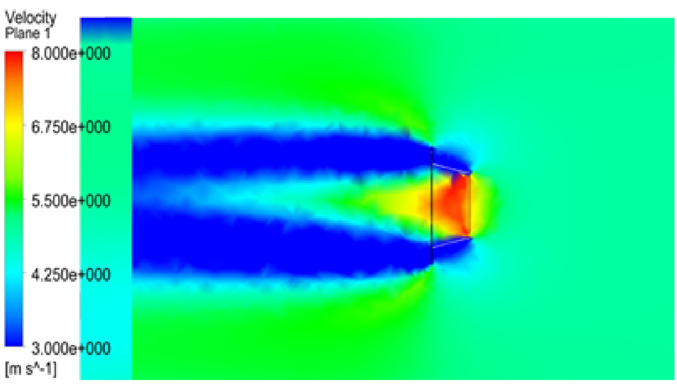

Fig. 8. CFD simulation of Flanged Diffuser

3.3 Simulation of the Flanged Diffuser with Inlet Shroud

The addition of an Inlet shroud in a flanged diffuser helped increase wind velocity only by a small amount than a flanged diffuser. In this type, maximum velocity reached 8m/s with an average velocity of around 7.8m/sat the inlet periphery.

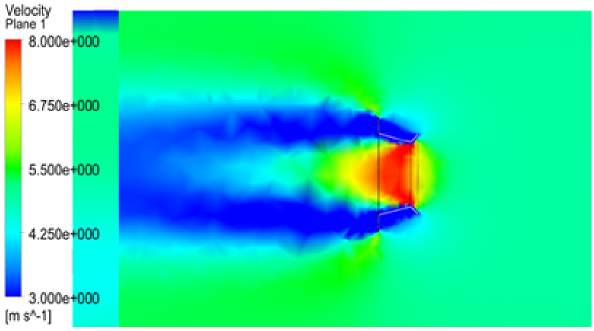

Fig. 9. CFD simulation of Flanged Diffuser with Inlet Shroud

3.4 Simulation Result of Plain Diffuser with Inlet Shroud

The CFD analysis of plain diffuser with inlet shroud shows that inlet shroud does not help accelerate inlet air for plain. Analysis shows that the maximum velocity reached 8 m/s, but the average velocity is around 6.5 m/s.

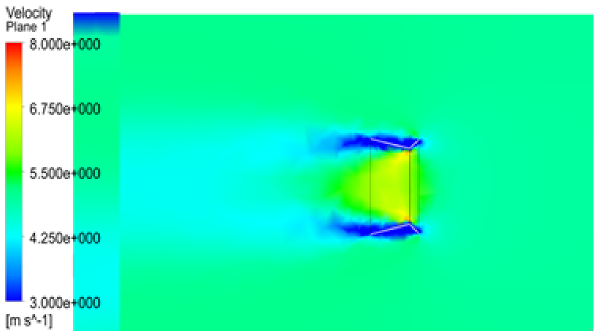

Fig. 10. Plain Diffuser with Inlet Shroud

Figure 11 shows the plot of each diffuser's velocity at a different diffuser length. This plot shows that the Flanged diffuser and flanged diffuser with inlet shroud perform best among the four diffusers with an increase in velocity up to 7.9 m/s at the optimum location of the diffuser. This plot also helps position the micro wind turbine to obtain the best result.

Table 1: Results Obtained from Four Diffusers

Concepts	Inlet Velocity simulated (U_1) (m/s)	Average velocity obtained (U_2) (m/s)	Percent increase in velocity	Increment in Power
Plain Diffuser	5	6.75	35%	2.46 times
Plain Diffuser with Inlet Shroud	5	6.5	30%	2.20 times
Flanged Diffuser	5	7.7	54%	3.65 times
Flanged Diffuser with Inlet Shroud	5	7.8	56%	3.80 times

Figure 12 shows the plot between powers generated by bare wind turbine vs. power generated by Flanged Diffuser augmented micro wind turbine of 220W. The graph shows that with the addition of a diffuser, power production reached 180W compared to a bare wind turbine, which only produces 50W.

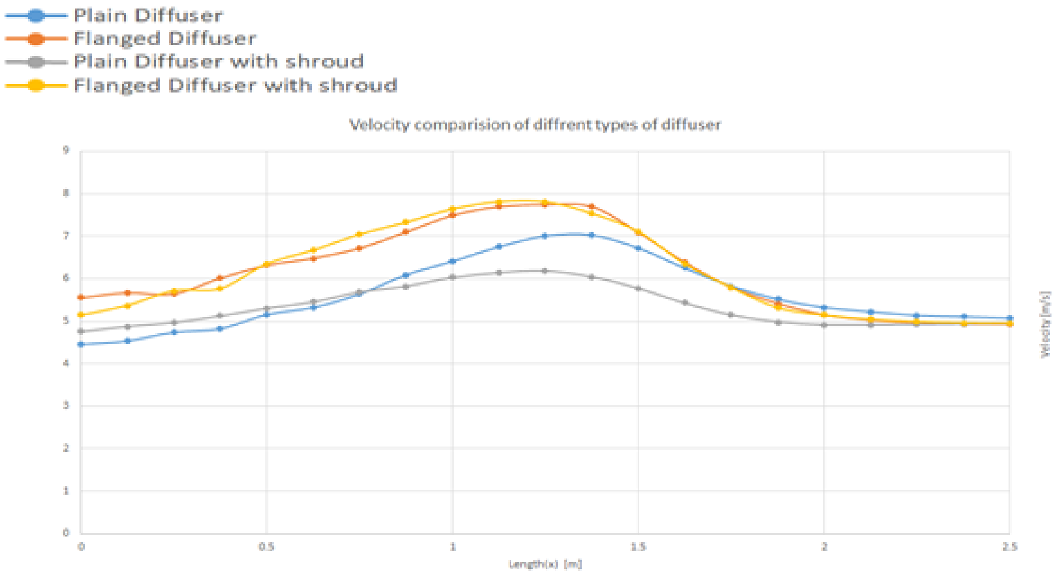

Fig. 11. Velocity vs. Length of different diffusers

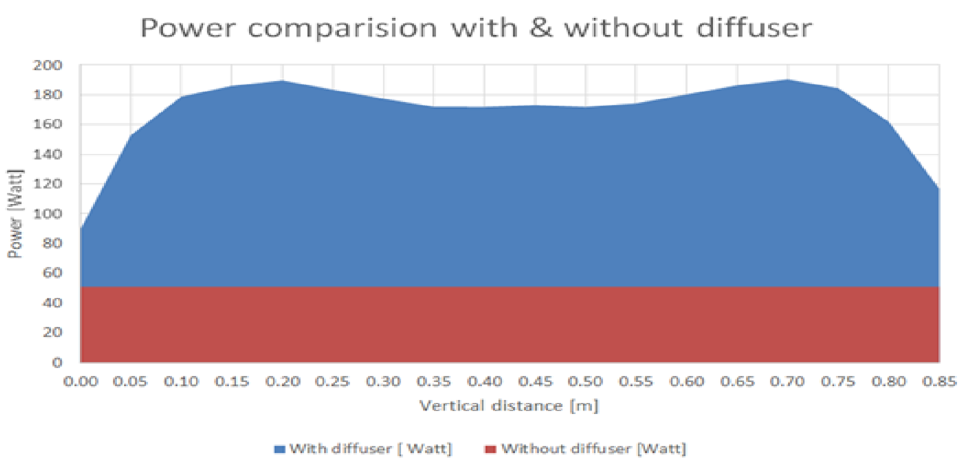

Fig. 12. Power generated by DWAT Vs. bare wind turbine

4. MODEL VERIFICATION

It was found that the flanged diffuser with an inlet shroud increases wind velocity slightly more than the flanged diffuser. However, geometric complexity and manufacturing cost might not justify an increase in wind velocity. Therefore, the flanged diffuser was found to be the most optimum diffuser. The efficiency of the flanged diffuser, obtained from CFD simulation, is further verified with experimental results done (Ohya *et al.* 2008). They used a subsonic open wind tunnel to avoid the blockage effect with a test section: 15m long, 3.6m wide, and 2m high, having a maximum wind velocity of 30m/s. To measure velocity distributions of wind velocity (U_1), Hot-wire I-type was used. For the flow visualization experiment, the smoke-wire technique was employed.

They examined the diffuser model's inner flow with both ends of the hollow structure. Both ends had a square cross-section; the diameter of the narrow end was $D_1 = 12$ cm, and the wide end was $D_2 = 24$ cm. The value of area ratio μ, defined as the outlet area/inlet area was 4 four, and the inclination angle was 3.71. The length ratio L/D was 7.7, where L is the model length. From the experimental result, a remarkable effect was obtained on the collection and acceleration of the approaching wind. A maximum of $U_2/U_1 = 1.8$ is shown in the neighborhood immediately after the entrance. The CFD simulation result for a flanged diffuser in the paper is $U_2/U_1 = 1.54$. These two values indicate a good agreement between the present simulation result and Ohya *et al.* (2008)'s experimental results considering that the dimensions taken for both experiments were relative.

5. COMPARISON WITH THE PREVIOUS STUDIES ON DWAT

A review is done on different diffuser augmented wind turbines designs from previous studies, including simulation (S) and theoretical (T) procedures. In addition, these results were compared with the findings from this paper to check the degree of agreement between the results. The findings from this paper indicate a good agreement with the results from the previous studies on DWAT.

Table 2: Comparison with the Previous Studies on DWAT

Author	Research Method	Technique/ Features	A_e/A_i	Total-L (m)	Results	Results from this paper	Remarks
G.M. Lilly (1956)	T	Simple shroud	3.5	-	Increase in power up to 65%	Increase in power up to 61% in a plain diffuser	Good agreement
A. Tourlidakis -2013	S	Diffuser without, within the flange	1.65	4.8	Increase in power coefficient up to 2-5 times of bare turbine	Increase in power coefficient up to 3 times in flanged diffuser as compared to bare turbine	Good agreement
K Mansour -2014	S	Flanged Diffuser with Inlet shroud	1.2	0.2	Upstream wind speed increases up to 1.6-2.1 times	Upstream wind speed increases up to 1.6 times in flanged diffuser with inlet shroud	Good agreement
B. Ahmed -2016	S	Flanged diffuser	2	0.12	Upstream wind speed increases up to 125.666%, increase in power by 1.6 – 1.7 times	Upstream wind speed increases up to 154% and increases in power by 3.65 times in flanged diffuser	Good agreement with a much better result

6. CONCLUSION

Irrespective of type, augmenting any diffuser on a bare wind turbine will increase power generation. Flange on the exit periphery of the diffuser helps further increase vortex formation and thus increase wind velocity. Addingan inlet shroud to a flanged diffuser seems to increase wind velocity slightly more than a flanged diffuser, but geometric complexity and manufacturing cost might not justify an increase in wind velocity. A flanged diffuser with diffuser angles of 14.5º and 0.5 L/D was found to be the optimum diffuser by increasing wind velocity by 60%, leading to an increase in power generation by 3.6 times.

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