
Experimental study of shrouded micro-wind turbine

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Elsevier use only: Revised 24th July 2012; accepted 30th July 2012

Abstract

Shrouding (diffuser augmented) horizontal axis micro-wind turbine has been shown to be an effective way to potentially improve the performance of micro wind turbine for applications in built environments. It is well understood that the degree of the performance enhancement depends on several factors including the diffuser shape and geometries, blade airfoils, and the wind condition at the mounting site. The effect of diffuser shape and geometries is reported in this paper. Performance of diffuser with three different geometrical features namely: straight diffuser, nozzle-diffuser combination, and diffuser-brim (brimmed diffuser) combination have been investigated. This paper aims to compare the performance of bare and diffuser augmented turbine; and investigate the effect of the diffuser geometrical parameters: diffuser lengths ($L/D = 0.63$ to $1.5$) and flange heights ($H/D = 0$ to $0.2$). Tests confirmed that placing the micro turbine model inside a shroud can substantially improve its performance. The diffuser only shroud improves the performance by 60% compared to the bare turbine and the nozzle-diffuser enhancement of 63% is slightly better than diffuser only. The improvement with brimmed diffuser also shows substantial performance enhancement. Increasing the diffuser length ($L/D$) does not affect the optimum $C_p$ of the wind turbine but shifts the performance curve and the optimum $C_p$ to higher tip-speed-ratio, $\lambda$. But adding brim (flange) at the exit plane of the diffuser increase the performance, $C_p$ as well as reduce the cut in speed and shift optimum $\lambda$ to higher value. The finding from this work demonstrates that shrouding micro wind turbine not only improves its performance but also points out how diffuser geometrical features ($L/D$) and/or ($H/D$) can be used to design a turbine with performance curve to suit the location.

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Keywords: micro wind turbine; shrouded wind turbine

1. Introduction

Domestic renewable power generation is expected to become important contributor in reducing the world’s $CO_2$ emissions. Domestic micro generation not only directly produce the power generation but also cut down the transmission losses, which can amount up to 65% of the energy input, in the supply system from the centralized power generation plant. Micro-wind turbines based domestic power generation is still new technology and has many challenges including high capital costs and low performance issues. The technical challenges are mainly to overcome (1) the high frequency of changes of wind direction; (2) the unpredictable and low wind velocity; and (3) the high turbulence flow which are very site specific. The take up of micro-wind turbine based power generation can be stimulated if the device can be made to produce power in the difficult wind conditions encountered in built environment and alternative utilization of the technology can be developed, for example: as power source of rechargeable device, domestic sensor/automation smart technology, power for low energy consuming device in urban environment. For the technology to be accepted in the urban environment, it must

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also be safe and not cause any undue inconveniences to the public. This may be related the safety of the device i.e. any
defect or pieces from the turbine will not cause any injury and the effect on wild life is minimal. The turbine must be quiet
e.g. noise level is not significantly above the background level. And the turbines must blend aesthetically with the
environment.

Diffuser augmented micro-wind turbine (DAWT) can offer solution to the first two challenges. Placing a diffuser around
a horizontal axis wind turbine has been shown to increase the power output compared to a bare turbine. There are a number
of mechanisms by which the power output of a turbine can be increased. One of the primary mechanisms is a combination
of increased mass flow rate and reduced wake rotation downstream of the turbine. With diffuser shrouded turbine the mass
flow rate of air through a turbine is increased by virtue of sub-atmospheric pressure at the diffuser exit plane (Foreman et al.
[1], Igra [2], Ohya et al. [3,4], Abe et al. [5]). Diffuser has been shown as the mechanism that control the expansion of
turbine flow which otherwise unrestricted in bare turbine case. Controlled expansion was shown to create significant sub-
atmospheric pressure in the exit plane of the diffuser [1]. When the pressure at the exit plane falls below atmospheric
pressure greater mass flow rate drawn into the diffuser through a kind of vacuuming effect. This effect depends on the
geometry of the diffuser. Ohya et al. [3] showed by adding flange at the exit of a diffuser vortices are induced resulting in
lower the exit pressure. The ability of the diffuser to decrease the base pressure is crucial in drawing more air through a
turbine. The addition of brim will cause significant increase in wind load and weight of the structure. For micro-small wind

turbine greater with diameter greater than 0.7m, Ohya et al. [4] developed modified compact brimmed diffuser which
reduce the size of the diffuser but have the same effect as flanged diffuser. In addition to the increased mass flow rate with
DAWT, compared to bare wind turbine, the tip losses are substantially reduced [2,5].

Despite of the well known benefit of shrouding wind turbine there is no systematic study comparing the performance of
bare and diffuser augmented micro wind turbine. This paper aims to systematically study the effects of diffuser geometry
and presents the performance comparison of bare and shrouded (diffuser, nozzle-diffuser, and brimmed diffuser) micro
wind turbine. The mechanical power output is directly measured at the rotor through a special design of rotor set-up. The
experiments carried out in this work are different from the previous reported experiment in several aspects including:
controlled experimental conditions e.g. tip speed ratio, direct measurement of power output under normal and yawed inflow
condition.

2. Experimental Set-up

The experimental rig has been designed with detachable diffuser allowing comparison of bare turbine with shrouded
turbine with various diffuser design variations be made. The model turbine has three blades. The design of the rotor takes
into account the stability consideration. In the current study the blades have NACA 63-210 airfoil profile however the
design of the rotor will allow blades with different profiles be tested in the future. 63-2XX was chosen as this series of
profiles is designed for low Reynolds number flow conditions and have been used in Ohya et al. [3]. The blades are of
constant chord of 25mm and pitched at 5°. The rotor diameter is 190mm. The tip gap is kept as minimum as practically
possible i.e. 2-3mm. The turbine is placed in a wind tunnel with working section of 450mm x 450mm x 1500mm. The wind
tunnel is capable of producing wind speed up to 25ms⁻¹. Note that the size of the rotor was limited by the size of the wind
tunnel and 190mm was chosen based on minimum blockage effect.

In the experiments, performance of the turbine was evaluated in terms of the relation between power coefficient, $C_p$ with
tip-speed-ratio, $\lambda$ i.e. performance curve. To vary and maintain constant, $\lambda$ while measurement was taken, the wind speed in
the tunnel was maintained constant e.g. at 5-6 ms⁻¹ in the brimmed diffuser tests, 7 ms⁻¹ in the diffuser only tests or 10 ms⁻¹
in the bare turbine. The rpm was controlled by the DC 120 Watt Maxon motor. The motor speed was controlled and as such
it acts as rotor resistance. The resistance torque is then transferred to motor body where the turning force is measured by
load cell. In all tests the motor rpm must be ensured to be lower than the free spinning rpm of the rotor at set tunnel wind
speed. The torque exerted by the wind was measured by the load cell then multiplied by the rotational speed to give the
actual mechanical power imparted by the wind on the rotor.

The experimental study reported in this paper consists of two parts. In the first part we compared the performance of
bare turbine with shrouded turbine under normal inflow and yawed inflow condition. The diffuser geometry investigated of
the first part is shown in Fig. 1(a). In the second part, parametric study of diffuser length ($L/D$) and brim height ($H/D$) was
carried out. The diffuser model is shown in Fig. 1(b). Note that the nozzle is removed from the model as the focus of the
second part is only on the length and brim height. Figures 2 show the turbine set-up inside the wind tunnel (a) bare turbine
and (b) with nozzle-diffuser shroud. Other arrangements were achieved by modifying the diffusers.
3. Comparison of Bare and Shrouded Turbine

The initial diffuser model used in our previous study is of 120mm length with \( L/D \) of 0.62. The diffuser expansion angle, \( \alpha \) is 12° giving diffuser outlet and inlet area ratio of 1.61. The performance of the bare, diffuser and nozzle-diffuser augmented micro-wind turbine have been compared and shown in Figs. 3 and 4. In all comparison, the area used in the denominator of \( C_p \) definition is the diffuser exit area.

\[
C_p = \frac{T \omega}{0.5 \rho A u^3}
\]  

Where: \( T \) (N.m) is torque, \( \rho \) (kg.m\(^{-3}\)) is density of air, \( A \) (m\(^2\)) is area of the rotor or diffuser exit area. Testing wind turbine in wind tunnel is somewhat affected by the wind tunnel wall known as "blockage effect" due to restriction of the flow to expand. In the bare turbine tests, the blockage effect was assessed by calculating the wake area and compared that with the tunnel cross sectional area. In all tests from \( \lambda = 0.5 \) to 2.5, the ratio of tunnel area to wake area range from 7.03 in \( \lambda = 0.5 \) to 6.35 in \( \lambda = 2.5 \). With these ratios it is believed that the tunnel wall interference with the wake expansion is insignificant.

Fig. 1. Typical shroud designs for wind turbine: (a) nozzle-diffuser [1] and (b) diffuser-brim shroud.

The blockage effect for the diffuser augmented is different from bare wind turbine. Here the tunnel walls inhibit the fluid flow path around the diffuser and hence forcing it to flow through it. This effect is more significant for heavily loaded turbine. Loeffler and Steinhoff [6] showed that the wall effects can be significant i.e. up to 10% for tunnel area to diffuser
area ratio ($\beta$) less than 5. With this diffuser, $\beta$ is 4.5 so the measured $C_p$ in the wind tunnel tests is higher than if the turbine is exposed to open unconstrained flow condition.

The augmentation effect of diffuser and nozzle is significant compared to bare turbine. Not only the conversion is improved but also the optimum $\lambda$ is shifted to higher value (Fig. 3). The coefficient of performance of the micro wind turbine increased by approximately 60% with the addition of a diffuser, and 63% with the addition of a nozzle - diffuser shroud compared to the performance of the bare turbine. The optimal tip speed ratio also increased by 33% for the diffuser and nozzle-diffuser augmentations compared to the bare turbine results. Note that as $\lambda$ is based on free stream velocity higher optimum $\lambda$ means DAWT performs better than bare turbine at the same free stream wind speed. The addition of nozzle is only slightly better than diffuser only under normal inflow condition. The main advantage of having nozzle shaped inlet is seen under yawed inflow condition (Fig. 4). It is clear that adding nozzle (converging shape) at the front of the shroud will be beneficial in variable wind direction flow condition which is typical condition in urban built-environment.

4. Parametric Study of Shrouded Turbine

This section presents the result of parametric study of diffuser length ($L/D$). In the study of the effect of diffuser length ($L/D$) diffuser shape is the same as that used in section 3 i.e. the expansion angle is maintained at 12°. The length is varied by lengthening the diffuser. As diffuser length increases the exit diameter also increases (hence reducing $\beta$). The range of $L/D$ is limited between 0.5 and 1.5. In practice it is desirable to have diffuser with $L/D$ as small as possible. The actual $L/D$s obtained were listed in Table 1. This is followed by reduction of the cut-in speed as shown by the data in Table 1. The lower cut-in speed indicates that the wind speed at the rotor plane is greater than the free stream wind speed. This may be due to the combined effect of the wind tunnel blockage and also the existence of sub-atmospheric static pressure condition at the exit of the turbine which tends to force and draw the air flow through the diffuser and hence lowering the cut-in speed of free spinning turbine.

![Graph showing the effect of diffuser and nozzle on coefficient of performance (Cp) under normal inflow condition.](image-url)

**Fig 3.** Comparison of bare, diffuser only, and nozzle-diffuser shrouded micro wind-turbine coefficient of performance, $C_p$ under normal inflow condition i.e. yaw angle = 0°.
Fig. 4. Comparison of bare, diffuser only, and nozzle-diffuser shrouded micro wind-turbine coefficient of performance, $C_p$ under 5° yawed inflow condition.

The effect of increasing the length of the diffuser on the turbine performance is illustrated in Fig. 5. Although by adding diffuser it is proven that more air drawn. Lengthening the diffuser does not appear to increase the turbine optimum $C_p$ within the investigated range. The obvious effect is shown to be the shifting of the performance curve to higher tip-speed-ratio only. The shifting starts from $\lambda$ as low as 1. As velocity is increased at the rotor plane the rotor must spin faster to capture the wind energy hence greater $\lambda$.

Table 1. Variation of diffuser $L/D$ investigated in the experiments.

<table>
<thead>
<tr>
<th>Label</th>
<th>$L/D$</th>
<th>$D_0$ (m)</th>
<th>$\beta = A_{\text{tunnel}}/A_{\text{exit}}$</th>
<th>$U_{\text{cut-in}}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>0.63</td>
<td>240</td>
<td>4.47</td>
<td>5.02</td>
</tr>
<tr>
<td>D1</td>
<td>0.98</td>
<td>269</td>
<td>3.56</td>
<td>4.98</td>
</tr>
<tr>
<td>D2</td>
<td>1.22</td>
<td>289</td>
<td>3.01</td>
<td>4.25</td>
</tr>
<tr>
<td>D3</td>
<td>1.47</td>
<td>309</td>
<td>2.71</td>
<td>4.10</td>
</tr>
</tbody>
</table>

The next parametric study looks at the effect of the brim height $(H/D)$. The variation of brim height and the resulting $\beta$ and turbine cut-in speed is shown in Table 2. The height of the brim is limited to 0.2 as higher $H$ cause the blockage effect to be significant. The effect of increasing the brim height is illustrated in Fig. 6. Increasing $H/D$ increases both $C_p$ and shift $\lambda$ at which the optimum $C_p$ occurs towards higher $\lambda$. These phenomena may be explained as follow. The brim causes vortices to appear at the exit of the diffuser [3]. The vortices increase the kinetic energy at the exit region and induce sub-atmospheric back pressure i.e. lowering $C_{pe}$, which results in increased mass flow rate for a given free stream wind speed. As with the effect of lengthening $L$, velocity is increased at the rotor plane with increasing $H$. Because of this the rotor must spin faster to capture the wind energy hence shifting $\lambda$ toward higher value. However unlike the effect of $L/D$ increasing $H/D$ also increase the optimum $C_p$.

Table 2. Variation of diffuser $H/D$ investigated.

<table>
<thead>
<tr>
<th>Label</th>
<th>$H/D$</th>
<th>$D_0$ (m)</th>
<th>$\beta = A_{\text{tunnel}}/A_{\text{exit}}$</th>
<th>$U_{\text{cut-in}}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H0</td>
<td>0</td>
<td>240</td>
<td>4.47</td>
<td>5.02</td>
</tr>
<tr>
<td>H1</td>
<td>0.15</td>
<td>283</td>
<td>3.21</td>
<td>4.98</td>
</tr>
<tr>
<td>H2</td>
<td>0.20</td>
<td>327</td>
<td>2.41</td>
<td>4.25</td>
</tr>
</tbody>
</table>
The reason why the optimum $C_p$ does not seem to be affected by $L/D$ is not clear although both increasing $L/D$ and $H/D$ demonstrates higher velocity at the rotor plane as shown by lower cut-in speed (Tables 1 and 2). The explanation may be found by considering the augmentation factor, $r$ which is related to diffuser exit pressure and diffuser pressure recovery as follows [2]

$$r = \frac{C_D}{0.593} \left( \frac{l - C_{pe}}{l + C_D - C_{pr}} \right)^{3/2}$$

where $C_{pe} = \frac{P_e - P_2}{0.5 \rho V_d^2}$ is diffuser exit pressure coefficient and $C_{pr} = \frac{P_l - P_2}{0.5 \rho V_d^2}$ is effective diffuser recovery coefficient. $C_D$ is loading coefficient, $V_d$ is the velocity at the rotor plane. $P_{in}, P_e$ and $P_2$ are static pressure at the far upstream, diffuser exit plane and downstream of the rotor respectively. By extending the length of the diffuser, $C_{pr}$ will increase and hence with $C_D$ and $C_{pe}$ constants $r$ increases. But at the same time extending the length of the diffuser also allow the flow to expand longer inside the diffuser and increase the diffuser exit pressure, $P_e$, which results in $C_{pe}$ becoming less negative. This has the effect of reducing the augmentation factor. The combined effect of increasing $C_{pr}$ and $C_{pe}$ seems to be the reason why variation of $L/D$ does not affect $C_p$. To verify this hypothesis computational fluid dynamic of shrouded micro-wind turbine will be carried out.

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Fig 5. The effect of $L/D$ on the performance comparison of diffuser shrouded micro wind-turbine.
5. Conclusions

The coefficient of performance of the micro wind turbine increased by approximately 60% with the addition of simple conical diffuser, and 63% with the addition of nozzle – conical diffuser shroud compared to the performance of the bare turbine. The optimal tip speed ratio also increased by 33% for the diffuser and nozzle-diffuser augmentations compared to the bare turbine results. The nozzle-diffuser augmentation was found to exhibit only slightly superior performance compared to the diffuser augmented i.e. only 1.7% compared to the diffuser augmented turbine. However contrary to the diffuser only, the nozzle-diffuser augmentation hold its performance very well under yawed inflow with only slight decreases in maximum coefficient of performance. Diffuser length and brim height can affect the performance augmentation of a micro-wind turbine. Increasing diffuser length only shifts the performance curve towards higher $\lambda$. Brim height can shift the performance curve toward higher $\lambda$ as well as increase the optimum $C_p$. This demonstrates that shrouding micro wind turbine, albeit in the present work we only considered straight conical diffuser, not only improves its performance but also points out how diffuser geometrical features (L/D) and/or (H/D) can be used to design a turbine with performance curve to suit the location.

Acknowledgments

The authors acknowledge the financial support from the 2012 UoW URC small grant for this project.

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