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# Influence of inflow turbulence intensity on the performance of bare and diffuser-augmented micro wind turbine model

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ABSTRACT

The performance of a wind turbine is directly affected by the site wind condition. In urban-built locality, the wind is typified by fluctuating velocity and direction, and high turbulence intensity (*TI*). This paper investigates the impact of turbulence intensity on micro wind turbine efficiency in converting the wind energy to power. The performance of bare micro wind turbine (MWT) and diffuser-augmented micro wind turbine (DAMWT) models subject to different level of turbulence intensities is reported. Turbulence intensities ranging from ≈2% to 29% were generated by means of turbulence grids. The turbine performance is assessed in terms of the relationship between the coefficient of performance, $C_P$ and tip speed ratio, $\lambda$. Computational fluid dynamics (CFD) simulations and wind tunnel tests show that shrouding the turbine with diffuser increases the peak $C_P$ by approximately two times. Beyond a certain tip speed ratio, the performance of both MWT and DAMWT is shown to decrease with turbulence intensity, however the $C_p$ of the DAMWT is still greater than bare MWT wind indicating the diffuser augmentation is still achievable even at high level of freestream turbulence.

## 1. Introduction

Horizontal axis micro wind turbines are wind turbines with rated capacity less than 2.5 kW [15] or with rotor diameter less than 1.25 m [4]. This type of turbine is potential wind based power generation system in urban built-environment. For example, they can be used in roof-top micro wind farm either as stand-alone system or as hybrid system integrated with photovoltaic system. However, micro wind turbines urban environment based power generation has many practical challenges. The main ones concern with: *(1)* fluctuating wind direction; *(2)* low wind velocity; and *(3)* high turbulence intensity, which are site specific and dependent on building roof geometry [10,16]. Wind turbulence intensity (*TI*) above the roof-top of buildings can be as high as 60% [10] with typical *TI* ranges from 5% to 20% depending on the roof geometry. The take up of micro-wind turbine based power generation may be stimulated if the device can be made to tolerate and produce power economically given the difficult built-environment wind condition.

Subject to high freestream turbulence intensity, fluctuating wind direction and velocity, the blade aerofoil aerodynamic displays complex behavior. In steady wind condition, turbulence intensity shifts the stall angle to higher value and the associated peak lift, but has little effect in the pre-stall region. Under fluctuating wind condition, angle of attack changes dynamically and the lift variation exhibits hysteresis loop. The size of the loop is reduced by turbulence intensity [6,1,7]. As wind turbine in built environment often subject to wind with significant turbulence level, consequently the performance of wind turbine will also be affected. However there is still lack of understanding of the effect of turbulence intensity on the performance of micro wind turbine.

It is known that the extent of the separation zone on turbine blade is affected by the rotation of the blade as well [21] *i.e.* the separation tends to occur only in the in-board region. Yang et al. [22] calculated lift and drag coefficients of wind turbine blade of MEXICO rotor indicating stall delay phenomenon albeit with lower lift compared to 2D airfoil. On the contrary Sicot et al. [19] showed that the lift augmentation in rotating blade under turbulence is related to smaller pressure separated region rather than stall delay phenomenon. Despite of the expected synergistic power augmentation from the rotational effect and turbulence intensity, the actual measured power of the wind turbine is lower than the rated power, and turbulence has been attributed to the loss of power up to 20% [18,3,13]. In another study, very low effect of turbulence intensity on the coefficient of performance was observed [20]. Based on the

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literature, it is clear that turbulence effect on turbine's performance needs to be investigated further. As power production of roof-top micro wind turbines sited within built environment is subject to varying level of turbulence [11,18]; this clearly reinforces the needs of understanding the effect of freestream turbulence.

Performance of wind turbine can be improved by placing the turbine in a shroud. Several researchers have experimentally measured power augmentation of diffuser augmented turbine with a factor of 2–5 [14] and 1.5–2 [9]. The latter found that the coefficient of performance and the optimum tip speed ratio of diffuser augmented turbine are greater than the comparable size wind turbine. The increase of tip speed ratio indicates that the turbine needs to spin with higher rotational speed to capture the greater available wind mass flow, the result of low pressure region induced by the formation of energetic vortices by the flange [14]. The power augmentation by diffuser shrouded horizontal axis wind turbine is well known now, however the effect of high free stream turbulence wind condition on the performance of micro DAMWT and the question whether the performance of shrouded turbine can still be maintained under such condition have not been reported. This paper aims to shed some light to answer this question as well.

## 2. Methodology

### 2.1. Experimental set-up

The model micro wind turbine used in the experiment has three blades of NACA 63-210 airfoil profile. The rotor diameter is 190 mm. The tip gap is kept as minimum as practically possible to 2–3 mm. The diffuser length is 120 mm resulting in length/throat diameter ratio (L/D) of 0.63. The diffuser expansion angle is 12° giving diffuser outlet and inlet area ratio of 1.61. Turbine performance was tested with and without diffuser (Fig. 1). The major dimensions of the turbine studied are given in Table 1. The turbine is placed in a wind tunnel with working section of 450 mm × 450 mm × 1500 mm. The wind tunnel is capable of producing wind speed up to 25 $\mathrm{ms}^{-1}$.

The wind energy conversion to power is directly calculated from the torque and rpm measurement. The torque measured is the torque exerted on the motor stator [5]. The reaction forces that oppose the electromagnetic torque create an equal but opposite directional torque that is applied to the stator. Careful static calibration of the torque measurement was done before the experiment.

The turbine is attached to a DC 120 Watt Maxon motor with matching motor controller (4-q-EC Servo amplifier DES70/10). The rotational speed of the rotor can be precisely controlled. As the wind flow over the blades, the induced lift produces torque rotating the rotor. The reaction torque of the same magnitude acting on the stator is measured by the load cell. The wind speed in the wind tunnel is controllable within 5–25 $\mathrm{ms}^{-1}$ range. The freestream wind through the test tunnel section is measured and monitored by an anemometer that is inserted into the center of the tunnel section.

Due to the size of the turbine diameter of 190 mm, the maximum practically attainable tip speed ratio, $\lambda$ is 2.5 for the bare turbine case and 3.5 for the diffuser augmented turbine. The experimental procedure is as follows. The wind speed needed to spin the rotor to 2500 rpm was initially determined. It was found that 10 $\mathrm{ms}^{-1}$ and 7 $\mathrm{ms}^{-1}$ were the required wind speed to spin the rotor at 2500 rpm under no load other than motor resistive load for bare turbine and diffuser shrouded turbine respectively. Once these wind speeds were found, the speed was maintained constant. The rotational speed of the rotor, $\Omega$ was then set at an rpm but must be below 2500 rpm. Thus the variation of $\Omega$ was achieved by varying rpm at the chosen wind speeds.

The power captured by the turbine is given by the reaction torque measured by the load cell multiplied by the rotor rpm registered by the controller. The coefficient of performance is given by the definition:

$$C_p = \frac{T\omega}{0.5\rho A U^3} \tag{1}$$

In the case of bare turbine, $A$ is the turbine swept area whilst in the case of diffuser augmented turbine it is the diffuser outlet area. Hence comparison between diffuser augmented turbine to bare turbine is made on the basis of the swept area equal to the diffuser outlet area.

Grids were used to generate turbulence in the tunnel. Turbulence grid technique has been used by Refs. [1,19,7]. Three grids with different spacing sizes were used and the turbulence intensity decay is shown in Fig. 2. Roach [17] developed turbulence intensity prediction equation:

$$TI = C\left(\frac{x}{d}\right)^{-5/7} \tag{2}$$

$x$ is the distance downstream of the grid and $d$ is the width of the grid bar. The constant, $C$ is a function of the grid geometry and was found to be 1.13 for square bars and perforated plates. Roach's prediction of turbulence decay has some restrictions such as: low background turbulence of the inlet flow to the grid (1.7%–2% in the present case); limited to the isotropic downstream of the grid (around 5–10 mesh width); grid must be placed normal to the flow; the test section of the wind tunnel should be significantly large compared to the grid mesh width; and the grid solidity should be less than 0.5 (0.438 in the present case). $TI$ was also calculated from the CFD turbulent kinetic energy values:

$$TI = \frac{\sqrt{\frac{2}{3}k}}{U} \tag{3}$$

The CFD area-averaged turbulence intensities follow similar trends as Roach's prediction (1987) where the larger the bar width, the higher the turbulence intensity. However discrepancies start to emerge as the flow move downstream of the grid. Roach's prediction is valid for open flow where turbulence decays much faster than the confined flow as in this study. In this study, the turbine was placed downstream of the grid at a distance in the range between 0.1 m and 0.3 m which gives variation of turbulence intensity approximately between 5 and 29%.

### 2.2. CFD model

Computational fluid dynamics approach is employed to calculate the time-averaged wind turbine coefficient of performance, $C_p$. As this is considered as quasi-steady data, the well-established Reynolds-Averaged Navier–Stokes (RANS) equations are adopted. The RANS equations comprise the continuity equation and the Navier–Stokes equations, which may be expressed in terms of the mean quantities.

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{4}$$

$$u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) \tag{5}$$

The terms $\overline{u_i' u_j'}$ are known as the Reynolds stresses, which