Experimental investigation and performance modeling of centimeter-scale micro-wind turbine energy harvesters

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**Abstract**

Centimeter-scale micro wind turbines have been proposed to power small devices. Design models and operating conditions for large scale wind turbines do not directly apply towards these small harvesters. We perform an experimental investigation of a swirl-type micro-wind turbine. We measure the useful power extracted from this turbine in an open circuit suction type wind tunnel facility. The optimal resistive loads for different flow speeds are determined. A model for the friction, torque drive and generated power is derived and validated. The effect of varying the direction of incident flow on the turbine performance is also determined. The results show an optimal combination between the rotor diameter and the number of rotor revolutions. The power density and efficiency of this turbine were found to be larger than previously tested turbines that have slightly larger diameters. This is true over a broad range of free stream speeds. Finally, because of its shape, the swirl configuration is effective in harvesting power for yaw angles of ±30°.

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1. Introduction

Power needs to operate sensors pose a major limitation when considering their use for monitoring and control. These needs are augmented when the sensors are in remote locations, their number is large, as in the case of wireless sensing networks, or when complementary components, such as cyber security devices, also need to be powered. These needs have raised the interest in developing technologies to harvest energy from ambient media such as solar power, thermal gradients, mechanical vibrations and air and water flows. Table 1 shows approximate values for the power density that can be released from these sources (Mathúna et al., 2008).

Significant advancements have been made in designing wind turbines over the past thirty years to cover a wide range of applications. Clausen and Wood (1999) classified relatively small size wind turbines into three categories based on their typical use by characterizing the wind turbine diameter (D) and the output power (P): micro (1.5 m; 1 kW) to power electric fences, remote telecommunications, equipment on yachts and the like; mid-range (2.5 m; 5 kW) to power a single remote house; and mini (5 m; 20 kW) to power small grids for remote communities. On the other hand, powering individual sensors requires power levels in the range of 10–100 mW. As such, there has been increasing interest in developing centimeter-scale micro-wind turbines (CSMWT). For example, such turbines can be placed in air conditioning and ventilation ducts, without a major obstruction effect (duct cross-sectional area divided by wind turbine disk area < 0.18%), to power micro-wireless sensors, smoke and gas detectors and temperature controllers. At this scale, such turbines need to be carefully designed to operate efficiently at low wind speeds.

Unfortunately, design models and optimal operating conditions proposed for large scale wind turbines do not directly apply towards the design and operation of CSMWT. These turbines have different aerodynamic behavior compared to their large-scale counterparts. The low Reynolds number regime of centimeter-scale micro-wind turbines projects a fundamental shift in flow characteristics and in quantities such as lift and drag coefficients at the small scale from the large-scale wind turbine. The rated speed is an another important parameter in the design of CSMWT. This speed is the incoming flow speed of the wind at which the turbine starts to produce power. It depends on both total inertia and internal friction of the system including the rotor, ball bearings and the generator. The rated speed decreases with decreasing wind turbine size due to lower inertia. However, decreasing the size of wind turbine blades reduces the available aerodynamic torque and, thus, increases the rated speed. These opposing factors should be optimized when designing a centimeter-scale micro-wind turbine with a desired rated speed and output power.
measure of the design quality, the power density (output power per unit area) and the efficiency of a micro-wind turbine should be improved by reducing frictional losses and improving the generator efficiency. This presents another challenge in terms of achieving the desired number of revolutions of the rotor shaft. Therefore, building an effective small size generator with a low starting torque and a high voltage-to-rpm ratio is a critical design criterion. Overcoming these challenges and optimization of the performance of CSMWT requires good estimates of their aerodynamic power, electromechanical coefficients and overall efficiency. In turn, this requires the development of capabilities to model and simulate the output power of small-size wind turbines.

Many investigations have been performed to evaluate the performance of CSMWT. Howey et al. (2011) investigated experimentally and numerically a miniature shrouded ducted type micro-wind turbine with a 2 cm rotor diameter and a 3.2 cm outer diameter. They showed that the fabricated MWT can deliver power levels from 80μW to 2.5 mW over a wind speed range from 3 m/s to 7 m/s. The overall efficiency of that turbine was less than 2%. Hossain et al. (2007) studied the effects of scaled MWT in single and grid arrangements using PIV, hot-wire and ultrasonic anemometers. Particularly, they investigated the downwash flow pattern for the smaller scale wind turbine (D = 5 cm) in an array arrangement. They calculated the wake deficit ratio for the inner region, outer region and intermediate region to control the wake by using a suitable architecture of the micro-wind turbines. However, they did not give power levels associated with the different arrangements. Carli et al. (2010) maximized the efficiency of their micro-wind turbine (D = 6 cm) using a buck-boost converter based maximum power point (MPP) circuit with fixed-frequency discontinuous current mode (FF DCM) to emulate a fixed resistance for minimizing the power loss. They were able to increase their conversion efficiency to 87% and the overall efficiency of their turbine to about 5%. Leung et al. (2010) connected fan-bladed micro-wind turbines side by side by using geared meshing to add up the power. They concluded that turbines with high-solidity had higher power coefficients at a specific blade angle. They showed that the five-bladed micro-wind turbine with 60° blade subtended angle yields an optimal power output. Rancourt et al. (2007) examined the effect of the sweep angle on three types of micro-wind turbines. They showed that the efficiency of the wind turbine follows the Schmitz theory, even at small size (4.2 cm diameter). They obtained an efficiency of 9.5% in 11.83 m/s wind speed. They also asserted that at low wind speeds the friction in the generator and electric resistance reduced the energy conversion so the maximum efficiency was only 1.85% and the power provided was 2.4 mW at 5.5 m/s air speed. Table 2 summarizes the operating conditions for previous studies related to CSMWTs.

The above discussion shows that there must be an optimal relation between the rotor type, its diameter, number of blades and flow speed. Developing a model to predict the generated power from CSMWT is important for optimizing its performance. In this work, we test and model the performance of a swirl-type centimeter-scale micro-wind turbine. Particularly, we measure the harvested power at different speeds, electric loads and yaw angles. Then, we present a model for predicting and evaluating the different losses. This model would serve in optimizing the design of centimeter-scale micro-wind turbines. Comparisons of the performance of this turbine with others in terms of efficiency and power density over a broad range of wind speeds are also performed. Tests are also conducted to assess the effects of varying the direction of incident flow on the turbine performance.

### Table 1
Energy harvesting sources typical data used for remote wireless environmental sensing.

<table>
<thead>
<tr>
<th>Power source</th>
<th>Operating condition</th>
<th>Power density Area or volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Outdoors</td>
<td>7500 μW/cm² 1 cm²</td>
</tr>
<tr>
<td>Solar</td>
<td>Indoors</td>
<td>100 μW/cm² 1 cm²</td>
</tr>
<tr>
<td>Vibration</td>
<td>1 m/s</td>
<td>100 μW/cm² 1 cm³</td>
</tr>
<tr>
<td>Thermal</td>
<td>ΔT = 5 °C</td>
<td>60 μW/cm³ 1 cm³</td>
</tr>
</tbody>
</table>

### Table 2
Recent studies and experiments on centimeter-scale MWTs (Maximum performance operating conditions).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>D (cm)</th>
<th>Number of blades</th>
<th>Air speed U (m/s)</th>
<th>Power P (mW)</th>
<th>Efficiency (%)</th>
<th>Power density (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howey et al.</td>
<td>3.2</td>
<td>3–6–12</td>
<td>10</td>
<td>4.3</td>
<td>1.5</td>
<td>1.37</td>
</tr>
<tr>
<td>Rancourt et al.</td>
<td>4.2</td>
<td>3</td>
<td>11.8</td>
<td>130</td>
<td>9.5</td>
<td>9.39</td>
</tr>
<tr>
<td>Carli et al.</td>
<td>4.3</td>
<td>4</td>
<td>4.7</td>
<td>9.97</td>
<td>5.36</td>
<td>0.52</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>6.3</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>7.6</td>
<td>0.055</td>
</tr>
<tr>
<td>Leung et al.</td>
<td>3.67</td>
<td>8</td>
<td>15</td>
<td>295</td>
<td>1.37</td>
<td>2.74</td>
</tr>
</tbody>
</table>

### Fig. 1.
Various types of centimeter-scale micro-wind turbines. (a) Fan blade with shroud type (Leung et al., 2010), (b) fan type, (c) ducted fan type (Howey et al., 2011) and (d) swirl type used in the present study.

### 2. Experimental setup

#### 2.1. Swirl type CSMWT

The performance of a centimeter-scale micro-wind turbine is based on three major aspects: its geometry, the generator and operating conditions. Various types of CSMWT are shown in Fig. 1.
The geometric constraints include the blade twist angle, number of blades, chord length and the prospect of connecting the blade tips with a circular shroud to increase the aerodynamic efficiency by decreasing the tip losses. The fan type is characterized by a small twist angle and few blades, which makes it easy to fabricate. The ducted type (also referred to as shrouded type) studied by Howey et al. (2011) has more complicated design elements than the fan type turbine. It consists of a rotor, an inlet shroud, a casing, bearings and an exit diffuser. The MWT generator is embedded between the rear and front casing as bearing magnets (integrated into the shroud). The swirl type used in this study is shown on the right side of Fig. 1. A CAD drawing of this turbine is presented in Fig. 2. Its specifications are presented in Table 3.

### Table 3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator volume size (cm)</td>
<td>1 × 1.4 × 1</td>
</tr>
<tr>
<td>Generator material</td>
<td>Permanent magnet</td>
</tr>
<tr>
<td>Rotor-blade diameter D (cm)</td>
<td>2.6 ± 0.01</td>
</tr>
<tr>
<td>Blade chord c (mm)</td>
<td>5 ± 0.05</td>
</tr>
<tr>
<td>Number of blades N</td>
<td>8</td>
</tr>
<tr>
<td>Rotor mass (g)</td>
<td>2</td>
</tr>
<tr>
<td>Generator mass (g)</td>
<td>5</td>
</tr>
<tr>
<td>Rated speed (m/s)</td>
<td>3 ± 0.02</td>
</tr>
</tbody>
</table>

2.2. Wind tunnel testing

All experiments were performed in the subsonic wind tunnel facility of the Department of Engineering Science and Mechanics at Virginia Tech. Pictures of the wind tunnel and turbine are presented in Fig. 3. The tunnel is a suction-type open circuit wind tunnel. It is powered by a 15 hp Leeson motor driving a 1 m centrifugal fan. The air flow is discharged by the fan which forces the flow to pass through a square (1.5 m × 1.5 m) honeycomb inlet that has a 0.001 m cell size and is 0.09 m long. This inlet is followed by three turbulence reduction screens that ensure a uniform flow with a turbulence intensity that is less than 2%. The test section dimension is 52 cm × 52 cm. The maximum attainable speed of the wind tunnel is 25 m/s. The flow velocity is measured with an accuracy of ± 0.5% based on the reading recorded from a pitot-static tube connected to a differential pressure scani-valve. All tests were performed in the center of the test section with the Pitot-static tube set 10 cm away from the axis of rotation and 20 cm ahead of the tested CSMWT. The velocity variation across the test section is less than 2.5%. A data reduction program was implemented to calculate the uncertainties based on Moffat (1985) method that considers both bias and precision errors. The results are presented for all experimental data points in the form of error bars.

Fig. 4 shows a schematic of the experimental setup, test-rig and devices used. The swirling CSMWT is connected to a microgenerator that has an area of 1 cm². This whole system is connected to a micro-servo motor that can be used to rotate the CSMWT in the yaw direction. The output voltage of the wind turbine generator was measured using a digital multimeter and was also connected in parallel to a USB 6009 National Instruments data acquisition card to measure the generated voltage. The data sampling rate was set to 200 Hz and data segments were recorded over a period of three seconds. The resistor box was connected to the output wire of the generator to study the performance of the wind turbine under various loading conditions. The measured internal resistance for the whole setup (generator and wire connection) was found to be \( R_m = 134 \, \Omega \). Thus, we selected to measure the output power over a broad range of loading resistance from 20 \( \Omega \) to 2 k\( \Omega \). This range includes the internal resistance of the CSMWT and covers a wide range of small batteries, sensors and controllers. At fixed wind speeds, the load resistance was varied and the corresponding output voltage was recorded. We conducted experiments at six different wind speeds between 3.9 m/s and 8.8 m/s. The angular velocity of the CSMWT was measured using a laser tachometer. The results of these measurements were confirmed by comparing them with the frequency of the generated AC output voltage as shown in Fig. 5. The results in Fig. 5 show a good agreement between the two measurement methods. Of particular interest is the dip around 6 m/s. Because energy is extracted from the rotation of the turbine, one could assume that the rotational speed is dependent on both free stream velocity and the efficiency of energy extraction. That is, the coupled effect of the energy extraction and incoming speed impacts the angular velocity of the turbine. The results presented below will show that the maximum efficiency of power extraction is also near 6 m/s. As such, the dip, observed in Fig. 5, can be related to the fact that the efficiency of the energy extraction is maximum in this range.

3. Electronic based circuit model

#### 3.1. Power and optimal load resistance

We aim to use the experimental measurements to develop a model for predicting the output power harvested from a microwind turbine. The model is based on understanding of the electronic circuit of the overall system and the perquisites set by Xu
et al. (2013). When the kinetic energy of the incident air is captured by the micro-wind turbine, the rotor rotates with a certain angular velocity and the torque generated by the air power, referred to as drive torque, is given by

$$T_{\text{drive}} = \frac{P_{\text{aero}}}{\omega}$$

where $P_{\text{aero}}$ is the aerodynamic power of the incident wind and $\omega$ is the angular velocity of the rotor. The driving torque can be subdivided into three components and written as

$$T_{\text{drive}} = T_g + T_a + T_f$$

where $T_g$ is the torque associated with the generated power and is given by

$$T_g = Gi$$

Here, $i$ is the generated electric current and $G$ is the electromechanical coefficient. It is obtained by assuming a linear relation between the generated voltage, $V$, and the angular velocity, $\omega$; i.e. $V = Go$. The inertial torque, $T_a$, is proportional to the angular
acceleration of the rotor \( \dot{\omega} \), and is given by

\[
T_a = I \dot{\omega}
\]

(4)

where \( I \) is the mass moment of inertia. Finally, \( T_f \) is the torque used to overcome the frictional damping between the shaft and the rotor casing. This damping is a function of the angular velocity and is written as

\[
T_f = C_2 \dot{\omega}^2 + C_1 \omega + C_0
\]

(5)

The dependence of \( T_f \) on the square of the angular velocity is due to the air friction between the shaft and the rotor casing. Its linear dependence on the angular velocity is due to the friction in the generator. The constant value is due to the start-up friction required to initiate the angular motion. Substituting Eqs. (3), (4) and (5) in Eq. (2), the total driving torque is re-written as

\[
T_{\text{drive}} = Gi + I \dot{\omega} + C_2 \dot{\omega}^2 + C_1 \omega + C_0
\]

(6)

where \( C_0 \) is independent of the shaft speed (\( \omega \)). As such, we define

\[
T_{\text{drive}}^* = T_{\text{drive}} - C_0
\]

(7)

and write

\[
T_{\text{drive}}^* = Gi + I \dot{\omega} + C_2 \dot{\omega}^2 + C_1 \omega
\]

(8)

Given that the generated voltage is related to the angular velocity, i.e. \( V = G \omega \), the generated current is written as

\[
i = \frac{G \omega}{R_{\text{in}} + R_L}
\]

(9)

where \( R_{\text{in}} \) is the internal resistance of the wind turbine and \( R_L \) is the load resistance. Substituting Eq. (9) into Eq. (8), the drive torque as a function of \( \omega \) and \( \dot{\omega} \) is re-written as

\[
T_{\text{drive}}^* = \frac{G^2 \dot{\omega}}{R_{\text{in}} + R_L} + I \dot{\omega} + C_2 \dot{\omega}^2 + C_1 \omega
\]

(10)

For a constant angular velocity, the inertia torque is zero and \( T_{\text{drive}}^* \) is written as

\[
T_{\text{drive}}^* = C_2 \dot{\omega}^2 + \left( \frac{G^2 + C_1 (R_{\text{in}} + R_L)}{R_{\text{in}} + R_L} \right) \omega.
\]

(11)

Eqs. (9) and (11) can then be used to relate the generated power \( P_L \) to the torque. As such, we write

\[
P_L = \frac{G^2 \omega^2 R_L}{(R_{\text{in}} + R_L)^2} = \frac{G^2 T_{\text{drive}}^* R_L}{(G^2 + (C_1 + C_2 \omega) (R_{\text{in}} + R_L))^2}
\]

(12)

The optimal resistive load can be obtained by setting the derivative of the output power with respect to the resistive load to zero; i.e. \( d(P_L)/d(R_L) = 0 \). This yields an expression for the optimum resistive load \( R_{\text{opt}} \), that is given by

\[
R_{\text{opt}} = R_{\text{in}} + \frac{G^2}{(C_1 + C_2 \omega)}
\]

(13)

3.2. Electro-mechanical coefficient

To determine the electromechanical coefficient, we measure the open circuit voltage as a function of the angular velocity \( \omega \). For this, we measured the open circuit voltage and the angular velocity for different free-stream velocities. Then, we divided the voltage by the angular velocity to obtain the electro-mechanical coefficient over a broad range. The results are plotted in Fig. 6 which give an average value for \( G \) of \( 8.3 \times 10^{-3} \) V/(rad/s).

\[
C_2 \omega + C_1 = \frac{G^2}{R_{\text{opt}} - R_{\text{in}}}
\]

(14)

Fig. 7 shows a curve-fit of the torque from measurements over a broad range of angular velocities. The results show a quadratic relation, as expected from the model presented above. The curve-fit is given by

\[
T_f = 1.7227 \times 10^{-9} \omega^2 - 3.7404 \times 10^{-9} \omega + 3.294 \times 10^{-5}
\]

Table 4

<table>
<thead>
<tr>
<th>( U ) (m/s)</th>
<th>( \omega_c ) (rad/s)</th>
<th>( \omega_m ) (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>184</td>
<td>0.56</td>
</tr>
<tr>
<td>4.3</td>
<td>208</td>
<td>0.61</td>
</tr>
<tr>
<td>4.8</td>
<td>228</td>
<td>0.61</td>
</tr>
<tr>
<td>5.2</td>
<td>238</td>
<td>0.61</td>
</tr>
<tr>
<td>5.7</td>
<td>252</td>
<td>0.56</td>
</tr>
<tr>
<td>6.1</td>
<td>287</td>
<td>0.61</td>
</tr>
<tr>
<td>6.5</td>
<td>314</td>
<td>0.61</td>
</tr>
<tr>
<td>7</td>
<td>328</td>
<td>0.61</td>
</tr>
<tr>
<td>7.4</td>
<td>343</td>
<td>0.61</td>
</tr>
<tr>
<td>7.9</td>
<td>360</td>
<td>0.61</td>
</tr>
<tr>
<td>8.3</td>
<td>382</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Fig. 8. Efficiency at different stages of power generation.

![Figure 8](image-url)
fit with a value of 0.99 correlation coefficient yields
\[ T_{\text{area}} = T_p = 1.7272 \times 10^{-3} \omega^2 - 3.7404 \times 10^{-7} \omega + 3.294 \times 10^{-5} \]  
(15)
which is in agreement with the model presented in Eq. (5). The values of \( C_1 \) and \( C_2 \) in Eq. (5) are determined from the curve fit presented in Eq. (15). These values are then used in Eq. (14) to determine the optimal load resistance as a function of the angular velocity with the corresponding free stream velocity as shown in Table 4.

3.3. Aerodynamic and overall efficiency

The main components of a typical wind turbine are the alternator and the rotor consisting of the blades with aerodynamic surfaces. According to the Betz law, the theoretical maximum aerodynamic power coefficient (\( C_p \)) is 59.26%. In centimeter-scale micro-wind turbines the total efficiency is significantly smaller. The major losses are due to (1) the relatively high viscous drag on the blades at low Reynolds number, (2) the friction and thermal losses which can be significant in a centimeter-scale micro-wind turbines and (3) the high electromagnetic interference. These losses reduce the total efficiency of small-scale wind turbine having a rotor-tip-diameter of less than 10 cm and a direct drive generator without a gearbox to about 14.8% (Xu et al., 2013).

Fig. 8 shows a schematic for the efficiency at different stages in power generation from the swirl-micro-wind turbine for a specific speed of 6.5 m/s. The white boxes show the values that were measured experimentally. The gray ones show the predicted values for the different efficiencies, which include the aerodynamic efficiencies of the wind turbine (\( C_p \)) of the generator power (\( \eta_g \)) and of the rectifier (\( \eta_{i\text{oc}} \)).

Given the diameter of the wind turbine (\( D = 2.6 \) cm) and for a free-stream velocity of 6.5 m/s, the total power of the incoming flow is 79.4 mW. The maximum power that can be extracted from the ambient wind, \( P_{\text{area}} \), can be expressed by
\[ P_{\text{area}} = \frac{C_p(\lambda, \theta)\rho A U^3}{2} \]  
(16)

<table>
<thead>
<tr>
<th>( C_p ) coefficient</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( c_4 )</th>
<th>( c_5 )</th>
<th>( c_6 )</th>
<th>( c_7 )</th>
<th>( c_8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSMWT</td>
<td>0.6</td>
<td>0.93</td>
<td>0.037</td>
<td>0</td>
<td>0</td>
<td>9.3</td>
<td>9.8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5

Values of the constants \((c_1 - c_8)\) used in the estimation of the aerodynamic efficiency of the rotor of a centimeter scale micro-wind turbine (Xu et al., 2013).

where \( C_p(\lambda, \theta) \) is the aerodynamic efficiency of the rotor. It is a function of the pitch angle \( \theta \) and the tip speed ratio \( \lambda \), which represents the dimensionless relation between the tangential speed of the tip of the rotor blade and the incoming flow \( \lambda = \omega D/2U \). Following Xu et al. (2013) and Heier (1998), \( C_p \) is given by
\[ C_p(\lambda, \theta) = c_1 \left[ \frac{c_2}{\lambda^2} - c_3 \theta - c_4 \theta^5 - c_5 \right] e^{-c_6/\lambda}, \]  
(17)
where
\[ \lambda_i = \frac{1}{\lambda + c_9 \theta - \frac{c_9}{\theta^4 + 1}}, \]  
(18)
and \((c_1 - c_9)\) are constants. Xu et al. (2013) obtained experimentally the values of these constants for a small wind turbine of 7.6 cm diameter over a range of different air speed velocities. These values, presented in Table 5, were also shown to be independent of the free-stream velocity. In this work, we use them as approximations of \( C_p \) coefficients in Eqs. (17) and (18). Based on a tip speed ratio of \( \lambda = 0.55 \) and a mean pitch angle (\( \theta \)) of 32\(^o\), we estimated the value of \( C_p \) to be 0.11. This is a slightly smaller value than the theoretical value of 0.148 presented by Xu et al. (2013).

4. Results and discussion

Fig. 9(a) shows the measured and modeled variations of the output DC voltage as a function of the load resistance for different incident flow speeds. The plots show that the output voltage increases as the incident velocity is increased. Furthermore, the output voltage increases as the load resistance is increased and asymptotically approaches a maximum value at high values of the load resistance. Fig. 9(b) shows the measured and modeled variations of the output power as a function of the resistive load for different incident flow speeds. The results show that, for each speed, there is a maximum power level at a specific load resistance; as expected from Eq. (14). Fig. 10 shows a plot of the normalized output power (\( P_{\text{out}}/\frac{1}{2} \rho U^3 \)), also referred to as total efficiency, as a function of the load resistance for three free stream velocities. The plots show a maximum value of 3.2% at \( U = 6.5 \) m/s (\( Re = 1810 \) based on the chord of the blade, c). Comparing Figs. 9b and 10, we note that although increasing the free stream velocity increases the level of harvested power, there is an optimal value of the free stream velocity for which the normalized power efficiency is maximized. This difference is also noted when looking at the plots in Fig. 11a and b which respectively show the maximum

Fig. 9. Experimental and predicted (solid lines) variations of the output voltage and power of the tested swirl CSMWT with the load resistance.
output and maximum normalized power as a function of the Reynolds number. Although the maximum power level increases as the Reynolds number is increased, the normalized level reaches a maximum value at \( Re = 1810 \). This is because the friction losses are a quadratic function of the angular velocity.

A comparison of the power density of the tested wind turbines with those of previously tested wind turbines is presented in Fig. 12. A closer look at the results shows that the power density is also a function of the diameter of the micro-wind turbine. The tested wind turbine with a diameter of 2.6 cm has a power density that varies between 0.1 mW/cm\(^2\) and 2 mW/cm\(^2\) over a range of incident wind speeds between 4 and 10 m/s. The wind turbine of Howey et al. (2011), with a diameter of 3.2 cm, has a relatively smaller power density but in the same range. Larger wind turbines have power densities that varied between 0.2 and 10 mW/cm\(^2\). Fig. 13 shows the efficiency of the tested and previously investigated micro-wind turbines as a function of the diameter of the turbine. The plot shows that the efficiency increases from about 2% to 3% for wind turbines having a diameter of 2–3 cm to about 6–8% for turbines with diameters between 6 and 8 cm and to higher efficiency of about 12–16% for turbines with diameters between 10 and 12 cm. The experiments of Rancourt et al. (2007) show a higher efficiency of 9.5% at 11.83 m/s but the maximum efficiency at the lower speed near 5.5 m/s was relatively low with a value near 1.85%. The dependence of the efficiency level on the size of the turbine raises a question as to whether staggering relatively small wind turbines would be more efficient than using a single turbine when the size is a constraining parameter. Issues such as cost and mutual interference between the turbines would need to be balanced against the levels of generated power from different configurations or designs.

4.1. Effect of yaw angle

Another performance metric for the operation of the tested centimeter-scale micro-wind turbine would be to determine its effectiveness under varying incident flow directions. Experiments...
were conducted over a range of yaw angles from 0 to 30°. The motion was automated using a micro-controller-based device connected to a computer. Fig. 14 shows the total output power vs the flow speed operating at different yaw angles, β, for the case of optimum resistive load of 330 Ω.

Fig. 14 (a), which presents the power as a function of the air speed, shows that the output power at 0° and ±10° yaw angles are almost equal. At larger yaw angles, the generated power decreases by about 25% for yaw angles of ±20° and by 52% for yaw angles of ±30°. Furthermore, there is no difference in the power generated for positive and negative yaw angles. The reason is that the geometry of the swirl is axisymmetric. Fig. 14 (b) presents the output power as a function of \( U \cos \beta \), where \( U \cos \beta \) is the velocity component that is perpendicular to the plane of the swirl. We note that over the range of relatively low speeds, the power output is proportional to \( U^3 \cos^3 \beta \) indicating that the total efficiency is constant.

There is a departure from the linear relation at the higher speeds indicating a reduction in the efficiency of particular importance is the significant drop in the generated output power as the yaw angle is increased to 30° in comparison to the values obtained at 0°, 10°, and 20° yaw angles. This drop shows that the total efficiency decreases significantly as the yaw angle is increased beyond 20°. This reduction is in qualitative agreement with published data in Grant et al. (1997) and Adaramola and Krogstad (2011). Still, these numbers represent a satisfactory performance when compared to other small-scale micro-wind turbines. Also, we tested the swirl type wind turbine in a turbulent flow by using a simple commercial bladed fan with screen, the output power from the turbine is higher compared to the tunnel flow in which we assume laminar flow.

5. Conclusions

We investigated experimentally the performance of a swirl type centimeter-scale micro-wind turbine. The results in terms of power density and efficiency show that its performance is better than the performance of ducted turbines of similar size. The results show an optimal combination between the rotor diameter and the number of rotor revolutions. The maximum output power of the CSMWT was 2.72 mW with a wind speed of 6.5 m/s at an operating resistive load of 330 Ω, which corresponds to a maximum system efficiency of 3.42%. We also modeled and validated the performance of the tested turbine and its dependence on the angular velocity. The results show that the torque in the tested turbine is a function of the square of the angular velocity which becomes significant at high angular velocities. As such, the generated power starts to decrease once a critical speed is surpassed for a specific load resistance. Finally, we tested the effects of varying incident flow direction on the turbine performance. The results showed no reduction in the power generated for yaw angles less than 10° which is quite significant.

References


