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Effect of turbulence on the performance of VAWTs: an experimental study in two different wind tunnels

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Abstract

Turbulence is one of the main characteristics of urban flows, but its effect on the performance of small VAWTs (often used in urban wind installations) has not been thoroughly researched. This experimental study focuses in testing a H-Darrieus VAWT prototype in different turbulent conditions inside the wind tunnel, in order to study the influence of turbulence intensity, integral length scales and Reynolds number. Passive grids are used to increase the wind tunnel free stream turbulence up to \( I_u = 15 \% \), with integral length scales of \( L_u = 0.18 \text{ m} \) and Reynolds numbers of \( \text{Re}_o \approx 300,000 \). The measurements are repeated in two wind tunnels of different size, which strengthens the results and helps quantify the effect of blockage on the turbine ratings. The results show power coefficient increases up to 20 % from smooth (\( I_u =0.5 \% \)) to turbulent (\( I_u = 15 \% \)) flows, an effect that is enhanced at low \( \lambda \) but that fades as \( \text{Re}_o > 400,000 \).

The study of the crossed influence of \( \text{Re}_D, I_u \) and \( L_u \) offers valuable data in the process of optimizing the operation of small VAWTs inside urban environments.

Keywords: VAWT, Wind Tunnel, Turbulence, Urban Flows, Blockage

1. Introduction

In addition to the large wind farms that provide most of the wind energy worldwide, small wind turbines inside the cities could become a complement by providing on-site and distributed energy to buildings. The top of skyscrapers, park hills or large avenues could be advantageous locations for the installation of wind turbines (Barlow and Drew, 2015). By on-site consumption, the costs of energy transportation and tower building would be also drastically reduced. Urban wind energy is, therefore, meant to become a factor for the energy mix in the future smart cities, especially in windy regions with low solar irradiance (Grieser et al., 2015).

However, urban wind has several characteristics that makes its harvesting more complicated than in the open terrain. The conglomerate of buildings that shapes the cities increases the terrain roughness length, shifting the atmospheric boundary layer upwards. The main effect of this is that the mean wind speed found in city centres is significantly lower than in the countryside areas (Drew et al., 2013). These winds present very high values of turbulence (Janajreh et al., 2013) and in some locations the turbines would receive incident wind with considerable skew angles (Balduzzi et al., 2012b). Due to these complications, the true suitability of wind turbines for use in the urban environment is not yet proved. Most of the past urban wind installations failed to reach the expected energy yield (Bianchi et al., 2016; Bianchini et al., 2015), resulting in underperforming turbines and bad press for the technology. A careful analysis of urban wind conditions is therefore mandatory for this technology to reach its maturity and economic viability in an acceptable time horizon.

Among the various technologies considered for urban wind applications, small vertical-axis wind turbines (VAWTs) are probably the most promising solution (Cooper, 2010). Despite their lower intrinsic efficiency, some specific features like omnidirectionality, lower noise emissions and arguably a more pleasant aesthetic appearance (Paraschivoiu, 2002) have made them a valuable alternative to conventional horizontal-axis wind turbines (HAWTs) in urban applications (Balduzzi et al., 2012a; Drew et al., 2013). Among the variety of VAWT designs, H-Darrieus turbines have especially attracted the attention of researchers, due to their higher efficiency and simple geometry (Aslam Bhutta et al., 2012).
High turbulence is one of the preeminent characteristics of urban flows. The study of its effect on VAWTs is up to now generally limited to on-field data obtained by comparing the performance of the installed turbines and the on-site wind turbulence measured by a meteorological station. These studies often yield unreliable and contradictory conclusions, as the effect of turbulence is said to be positive (Bertényi et al., 2010; Möllerström et al., 2016), negative (Kooiman and Tullis, 2010; Pagnini et al., 2015) or velocity-dependent (Lee et al., 2018). The impossibility to control all external conditions and influences in a real urban environment suggests that wind tunnel measurements are needed in order to obtain precise and repeatable turbine power curves under the influence of different turbulence levels.

Nevertheless, replicating the urban flow characteristics inside the wind tunnel is not an easy task. Most of the experimental facilities are designed for aeronautic purposes and have a very low background turbulence intensity ($I_u < 1\%$). In contrast, turbulence intensity inside cities is typically higher than 10% (Janajreh et al., 2013), and also the typical integral length scales ($L_{00}$) are large compared with middle-sized wind tunnels, with values of $L_{00}$ in the order of 1 m (Dallman, 2013). These values are very difficult to replicate in a wind tunnel of limited dimensions. Another limitation is the blockage: when the turbine area is large with respect to the wind tunnel section, the walls create an interference that may deform the expected wind conditions during the turbine operation (Dossena et al., 2015).

The first extensive studies of VAWT in the wind tunnel date to the end of the 1970s in the SANDIA research project (Blackwell et al., 1976). The performance of a 2 m diameter Darrieus VAWT measured in a 4.6 x 6.1 m wind tunnel was successfully compared with field tests (Shepherd, 1981). No turbulence or blockage effects were considered in that study. More research was done on VAWT wind tunnel testing at the University of Montréal: there were conducted the first studies on the wake of a VAWT (Brocher et al., 1986) and the first attempt to model the influence of turbulence (Brahimi, 1992). During the 1990s little other wind tunnel research was carried out, one example being the study on VAWTs with variable pitching blades in Australia (Kirke and Lazauskas, 1993).

The 2000s saw the resurgence of VAWT technology for its applicability to urban environments. Delft University started testing the influence of skewed flows (Mertens et al., 2016), and soon researchers from all over the world followed (Battisti et al., 2011; Howell et al., 2010). Wind tunnel tests on the influence of turbulence on VAWT performance have only been done in the last years. Miau (2012) measured a slight increase of power coefficient $C_p$ for a 5-bladed Darrieus turbine. Peng and Lam (2016) and Hohman et al., (2018) measured the influence of turbulence in the wake of the VAWT. Ahmadi-baloutaki et al. (2015) performed a full set of experiments regarding the interaction between turbulent flows and a H-Darrieus, and though detecting a huge increase of power delivered, he could not retrieve the complete power curves.

Apart from turbulence, in small wind turbines also Reynolds number (Re) influence cannot be omitted. Studies have shown that this effect is evident in the range of operation of small VAWTs (Miller et al., 2018) and that it affects not only the turbine performance but also its optimal rotational speed (Bachant and Wosnik, 2016). CFD simulations have permitted to conduct parametric studies of those parameters, revealing a cross effect between Re and $I_u$, especially for low tip-speed ratios ($\lambda$), (Rezaeih et al., 2018a). From other CFD campaigns it was concluded that Re also defines the optimal aspect ratio of the turbine ($H/D$) (Zanforlin and Deluca, 2018) or that $\lambda$ and the turbine solidity ($\sigma$) are linked as an invariant parameter that defines the optimal performance of the turbine (Rezaeih et al., 2018b).

The effect of blockage is another topic that has been gaining attention in the last years. When the turbine model spins it “blocks” a large part of the wind tunnel section, the flow around it is accelerated due to the continuum mechanics. If not corrected, then the performance measured in small wind tunnels is not realistic, higher than in real open-air cases. Among others, Ross and Altman (2011) applied the available blockage corrections for bluff bodies on a Savonius drag-driven rotor. Its effect for Darrieus turbines is still being discussed within the scientific community; Dossena et al. (2015) defined an experimental correction that included thrust coefficient and tip-speed ratio, while other researchers (Bianchini et al., 2011; Jeong et al., 2014) opted for more simplified approaches. It is generally accepted that corrections must be applied for solid blockages ($\epsilon$) over 0.1 (Battisti et al., 2011).

The goal of this article is to evaluate, in wind tunnel-controlled conditions, the performance of VAWT under turbulent flows and study experimentally the crossed influence of Re, $I_u$ and $L_{00}$, these last two parameters rarely studied in the past. The testing in two wind tunnels of different sections allowed to
quantify the effect of blockage, while the use of different turbulent grids permitted to study the turbulence intensity and length scale effect on the turbine performance. Therefore, this study produces new experimental data that is compared with previous experimental and numerical studies, in order to expand the knowledge on the parameters that influence the operation of small VAWTs in urban environments.

The Methodology section describes the facilities and equipment used, as well as the data analysis and blockage corrections. Generation of turbulence relates the characteristics of passive grids to increase turbulence inside the wind tunnel, and how is this process carried out in the two wind tunnels. The Results section presents the measurements on the VAWT performance: the effects of blockage, Reynolds number, $I_u$ and $L_u$ are tested and compared. Summary and conclusions are exposed at the end of the article.

2. Methodology

2.1. The turbine

The rotor is a two-blade H-type Darrieus turbine with two NACA0018 blades with a 5 cm chord ($c$) and two inclined struts per blade (see Figure 1). Due to the small size of the rotor (diameter $D = 0.5$ m, frontal area $A_{VAWT} = 0.4$ m$^2$), angular speeds (and thus centrifugal loads) were high (around 1200 rpm) in order to achieve Reynolds numbers as high as possible. To ensure proper mechanical properties, the rotors were manufactured using carbon-epoxy composite. Figure 2 presents the dimensions of the rotor.

![Figure 1. H-Darrieus VAWT prototype in the VUB wind tunnel.](image1)

![Figure 2. Dimensions in m of the VAWT used in the experiments.](image2)

The operational characteristics of the turbine are presented in Table 1. In the tests, the turbine was operated at an approximate diameter-based Reynolds number of:

$$Re_D = \frac{\rho \bar{U} D}{\mu} = 300,000$$

(1)

Where $\bar{U}$ is the mean wind speed (9 m/s as a reference), $\rho$ is the air density, $D$ the turbine diameter and $\mu$ the air dynamic viscosity. These values are small compared with large scale VAWT (FloWind turbines had a $Re_D \approx 1.5 \cdot 10^7$) which are Reynolds number independent (Miller et al., 2018), but are of the same order of magnitude as small VAWTs and prototypes (SANDIA 2m VAWT presented values of $Re_D \approx 1.2 \cdot 10^6$, (Paraschivoiu, 2002)). The solidity and aspect ratio are adequate for this $Re_D$ range according to literature: Zanforlin and Deluca (2018) define the optimal $H/D$ for low Re as 1.9, while Rezaeiha et al., (2018b) calculated an optimal $\sigma = 0.24$ for $\lambda = 3$. 

Table 1. Operational characteristics of the VAWT prototype.

<table>
<thead>
<tr>
<th>Re₉ range</th>
<th>Rotational speed</th>
<th>Tip-speed ratio λ</th>
<th>Solidity σ = nc/D</th>
<th>Aspect ratio H/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6 to 3.3 \cdot 10⁵</td>
<td>800 to 1200 rpm</td>
<td>2.5 to 3.5</td>
<td>0.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.2. The facilities

The research has been carried out in two different facilities. The Vrije Universiteit Brussel low-speed wind tunnel is located in Brussels, Belgium (Figure 3). It is an open-circuit boundary layer wind tunnel with a blowing fan. The second laboratory is the CRIACIV one, located in Prato, Italy (Figure 4), an open circuit boundary layer wind tunnel with larger test section, a suction fan and a T-shaped diffuser.

Table 2 summarises the characteristics of both wind tunnels. In the CRIACIV one, due to its larger size, solid blockage ε is reduced by half, but in any case, it is still slightly higher than 0.1 and therefore non-negligible (see Section 2.4). This solid blockage is calculated with Eq. 2, where A_{VAWT} is the frontal area of the turbine and A_{ts} the size of the wind tunnel test chamber.

\[ \varepsilon = \frac{A_{VAWT}}{A_{ts}} \]  

2.3. Equipment

In both cases, the mean flow speed was monitored with a Pitot tube connected to a sensor Setra AccuSense model ASL. The free stream wind speed was determined by placing the Pitot tube in the test section before the turbine was switched on. The spectral properties of the induced turbulence were determined through measurements with a Dantec single-component hot-wire probe. The spatial homogeneity of the flow at the position of the model was verified prior to the tests. The turbulence intensity, that quantifies the fluctuations \( u \) in the wind speed, was calculated by using the rms of the velocity fluctuations and the mean incoming longitudinal flow speed \( \bar{U} \) (Eq. 3)

\[ I_u = \frac{\text{rms}}{\bar{U}} \]  

The longitudinal integral length scale \( L_u \) provides a measure of the sizes of the vortices in the flow direction. It was calculated through the autocorrelation function, that describes how much a measurement of a turbulence component \( u \) is related to the value of the same component at a consecutive time instant,
and assuming Taylor’s frozen-eddy hypothesis (Tavoularis, 2002). The results were confirmed by fitting the measured spectrum to a von Kármán spectrum, that offers a good representation of turbulence inside wind tunnels (Burton et al., 2001).

The VAWT rotor was connected via a torque sensor and a drive belt to a brushed-DC motor. This motor was used to drive the VAWT rotor during start-up, while it acted as a generator in normal operation. The electrical output of the motor was fed to a circuit of variable resistance for angular speed control. A torque sensor was used to measure the mechanical torque and angular speed (and thus mechanical power) of the VAWT. The torque sensor, drive belt, DC motor, and measurement equipment were housed inside an aluminium frame. The torque sensor was a Lorenz Messtechnik DR-3000 sensor with accuracy of $\pm 2 \times 10^{-3}$ Nm. It was fitted between two torsionally-stiff couplings to allow for possible misalignments.

2.4. Blockage correction

As both wind tunnels present levels of $\varepsilon > 0.1$, blockage corrections must be applied in order to obtain realistic and comparable ratings. From the literature on the subject reviewed in the introduction, Dossena et al. (2015) had the most thorough approach to VAWT blockage. However, their calculations include the thrust coefficient, which was not measured during the present experiments. The correction proposed by Jeong et al. (2014) was also inapplicable because it was highly dependent on the configuration of the setup, with the local velocity measured in a particular position.

For the present study the work of Ross and Altman (2011), who studied the blockage effect but for a Savonius rotor, has been taken as a reference. Using three scaled models in the same wind tunnel concluded that Maskell (1987) provides the best windspeed correction $U_c$ for this type of turbines. However, Maskell’s formula (Eq. 4) contains the experimental parameter $m$ specific for Savonius turbines, so its applicability to H-Darrieus (less solid) was compromised.

$$ \frac{U_c^2}{U^2} = \frac{1}{1-m\varepsilon} $$

On the other hand, the correction proposed by Pope for wind tunnel models of “unusual shapes” (Pope and Harper, 1966), that was considered invalid for a Savonius (Ross and Altman, 2011), is often used in Darrieus studies (Bianchini et al., 2011) due to its simplicity (Eq. 5):

$$ U_c = U\left(1 + \frac{1}{4} \varepsilon\right) $$

Among those two formulas, the Pope correction (Eq. 5) provided the most acceptable results for the present study, as it will be detailed in Chapter 4.

3. Generation of turbulence

3.1. Passive grids to generate turbulence

Squared turbulence grids have been used for decades to generate artificial levels of homogenic turbulence inside wind tunnels. They have been known to provide quasi-isotropic, Reynolds number independent profiles, and allow to reach levels of $I_u > 15\%$ (Roach, 1986). The turbulence intensity depends on the bar width $b$ and decreases with the distance $x$ downstream from the grid (turbulence decay). The empirical law proposed by Laneville (1973) has been found to describe accurately the $I_u$ levels found downstream of the grid (Eq. 6).

$$ I_u = 2.58 \left(\frac{x}{b}\right)^{-8/9} $$

The other characteristic property of turbulent flow is its integral length scale, an indicator of the size of its most energetic eddies. According to a study of Dallman (2013), in urban environments this value is of...
the order of $L_{ux} \sim 1$ m. From an empirical study of Roach (1986), those turbulent structures increase in length downstream of the grid following the law presented in Eq. 7.

$$L_{ux} = 0.2b\left(\frac{x}{b}\right)^{1/2}$$  \hfill (7)

As it can be seen, the size of the eddies is proportional to the grid bars width $b$, which limits the maximum $L_{ux}$ that can be obtained in medium-sized wind tunnels as the ones used in this study. It is true that those turbulent structures increase in length downstream, but then there is a limitation due to the decay of turbulence intensity. After a careful study of literature and previous studies at the University of Florence (Bearman and Morel, 1983; Mannini et al., 2015; Vita et al., 2018), it became clear that the largest scales that could be generated would be in the order of $L_{ux} \sim 0.2$ m. According to Bearman and Morel (1983), when $L_{ux} >> c$, the gross effect of turbulence can be estimated using a quasi-steady assumption. Though not exact ($c = 0.05$ m), this assumption was considered as valid in this case.

The creation of a uniform profile of wind speed and turbulence was also pursued, in order to compare the results accurately against the free stream conditions. According to previous literature, the flow will be fully developed after a distance 5 times the mesh size of the grid $M$ (Baines and Peterson, 1951). However, when using mesh sizes larger than 10% of the wind tunnel dimension, the wind profile is unstable (Bearman and Morel, 1983), and small changes of geometry can lead to significant modifications in the flow. This was a condition that could not be fulfilled and at the same time maintain the high values of $L_{ux}$. Therefore, a careful parametric study was done to define the optimal grid geometry to obtain the desired uniform profiles.

### 3.2. Optimization of grids

Figure 5 presents the parameters to optimize in this study. $M$ is the mesh size (observe that the mesh is squared), $b$ is the width of the bars (both horizontal and vertical bars), and $d$ is the distance from the top and bottom bars to the ceiling (or floor) of the wind tunnel.

![Schematic representation of the parameters used in the optimization of the grid.](image)

The starting point was a regular mesh of $M = 0.33$ m, with 6 cells horizontally and 3 vertically. The width of the bars was limited to 7 cm as the grid drag increases drastically for values of $b/M > 0.25$ creating too much disturbance in the flow (Laneville, 1973). But as said in the previous subsection, with $M$ of one third of the wind tunnel height ($H$), the wind profile with this initial grid was not uniform at all. The challenge was, in fact, to find an optimised distance from the wall to the closest grid bar; leave enough space to prevent blockage of the flow, but not too much to avoid flow acceleration next to the walls.

A trial-and-error process was then performed by changing grid mesh size and distribution and evaluating the standard deviation of the $U$, $I_u$ and $L_{ux}$ profiles obtained in the vertical direction of the wind tunnel. The process, detailed in Carbó Molina et al. (2018), produced a versatile grid (VUB1, Figure 6.a) that allowed to generate the desired turbulence and length scale profiles at various distances from the grid. Moreover, as predicted by literature, the turbulence generated by squared-bars grids is not speed dependent.
A similar grid was designed for the CRIACIV wind tunnel (CRI for simplicity) to generate the most similar turbulent conditions possible (Figure 6.b). A third grid of smaller mesh size was also used in order to compare the results with turbulent flows of smaller integral length scale. This grid was built in CRIACIV for previous experiments (Mannini et al., 2015) and can be seen in Figure 6.c. The geometrical characteristics of each grid can be compared in Table 3. As it can be seen, in grid CRI 2 no optimization of the wall distance is needed as $M/H < 0.1$ (Bearman and Morel, 1983).

![Turbulence grids](image)

**Figure 6.** Turbulence grids used in the study at VUB wind tunnel (a) and CRIACIV (b, c).

<table>
<thead>
<tr>
<th>Grid</th>
<th>Mesh size $M$</th>
<th>Bar width $b$</th>
<th>$b/M$</th>
<th>Distance from bar to wall $d$</th>
<th>$M/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VUB 1</td>
<td>35 cm</td>
<td>7.2 cm</td>
<td>0.21</td>
<td>12.5 cm</td>
<td>0.34</td>
</tr>
<tr>
<td>CRI 1</td>
<td>32.5 cm</td>
<td>7 cm</td>
<td>0.22</td>
<td>12.5 cm</td>
<td>0.20</td>
</tr>
<tr>
<td>CRI 2</td>
<td>10 cm</td>
<td>2.5 cm</td>
<td>0.25</td>
<td>0 cm</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### 3.3. Turbulence conditions in the tests

A wind speed of 9 m/s was chosen as a benchmark as it allowed the widest range of rotational speeds in the turbine prototype available. As explained in previous sections, moving the aforementioned grids upstream and downstream along the wind tunnel, different values of $I_u$ and $L_{ux}$ could be obtained. Figure 7 shows the vertical profiles of wind speed, turbulence and length scales obtained at the VUB wind tunnel at different distances $x$ downstream of the grid, being $y$ the distance from the floor. Closer to the grid the flow is more turbulent, $L_{ux}$ is smaller and the profiles are less uniform. However, all the conditions depicted in Figure 7 are considered stable enough and within the desired range of the experiment. In order to preserve flow uniformity, the minimum distance at which the grid could be placed was $x = 3$ m. Also, as it was impossible to generate a clear turbulence spectrum at low turbulence flows, $L_{ux}$ is not calculated for smooth flow conditions.
Figure 7. Vertical wind profiles obtained with grid VUB 1 measured at three distances downstream of the grid.

Figure 8 presents the wind profiles obtained with grid CRI 1. Here it was possible to place the grid closer to the test section ($x = 2.1$ m), and it can be seen how $I_u$ levels reached were higher, but at the cost of a less uniform wind profile. Being a larger wind tunnel, it was also possible to place the grid farther away reaching lower $I_u$ and higher $L_{ux}$. However, for larger distances ($x > 7.6$ m), the wind profile did not vary much with further distance increase. It is worth mentioning that as the grid gets further, the $L_{ux}$ profile is more irregular, a fact specially visible in this figure but also appreciated in Figure 7 and Figure 9.

Figure 8. Vertical wind profiles obtained with grid CRI 1 measured at three distances downstream of the grid.

However, when using grids of different mesh and bar size (grid CRI 2), turbulence characteristics change. Figure 9 presents the wind profiles obtained with grid CRI 2 at the CRIACIV wind tunnel. As it can be seen, the use of a smaller mesh creates very uniform profiles even at short distances ($x = 2.1$), but does not allow to achieve high values of $L_u$ and $L_{ux}$. That precise profile will allow to evaluate the effect of $L_{ux}$, as it provides similar values as $I_u$ as grid CRI 1 at $x = 7.6$ m ($\approx 5\%$), while the values of $L_{ux}$ are much smaller ($\approx c$ in this case).
Figure 9. Vertical wind profiles obtained with grid CRI 2 measured at two distances downstream of the grid.

Figure 10 presents the average values of \( I_u \) (top) and \( L_{ux} \) (bottom) obtained with the different grid positions shown in the previous figures. The values are compared with the empirical laws presented in section 3.1: equations 6 (Laneville, 1973) and 7 (Roach, 1986). It can be seen how the trends were accurately predicted by the literature, especially in the \( I_u \) case, and that the laws only tend to underestimate \( I_u \) and \( L_{ux} \) for high values. This is understandable seen that both empirical relations were developed in wind tunnels smaller than the ones used in this study, therefore also the size of the grids was smaller (only comparable with grid CRI 2, which is the most accurately predicted).

Figure 10. Comparison of the average \( I_u \) (top) and \( L_{ux} \) (bottom) values obtained with the different grids with the values predicted by literature (Laneville, 1973; Roach, 1986).

4. Results

4.1. Calculation of power curves

The parameter to represent the performance of the turbine was the mechanical power coefficient:
\[ C_P = \frac{P_{\text{turbine}}}{P_{\text{wind}}} = \frac{Q \omega}{\frac{1}{2} \rho A V_{\text{AWT}} U^3} \]  

(8)

Where \( Q \) is the mechanical torque delivered by the rotor and \( \omega \) the rotational speed. The conventional way to represent \( C_P \) in wind turbine studies is plotting it against the tip-speed ratio (\( \lambda \)) of the turbine, a non-dimensional number that relates the speed of the blade tip with the incident wind:

\[ \lambda = \frac{\omega R}{U} \]  

(9)

Being \( R \) the turbine radius. To obtain the points in the power curves, time histories of \( P \) and \( \omega \) obtained were analysed. Each measurement was taken only when the turbine \( \omega \) remained stable within a range of \( \pm 2 \) rad/s during 60 s to avoid transient effects and reduce the random error. It is also worth noting that rotational speed was controlled manually by means of a variable resistor.

The uncertainties were calculated for those sampling periods using the error propagation method proposed in Dénos (2005) and, similarly, in ITTC (2008). In the following sections the effect of the different parameters under study (wind speed-Re, turbulence intensity and length scale) on the turbine \( C_P - \lambda \) curves are analysed.

4.2. Reynolds effect

To evaluate the effect of Reynolds number only the measurements in smooth flow (no grid) were considered. Apart from the benchmark speed, power curves were also measured at \( \bar{U} = 8 \) m/s (\( \text{Re}_D = 267,000 \)) and \( \bar{U} = 10 \) m/s (\( \text{Re}_D = 333,000 \)) to provide an indication of the Reynolds number effect. Those values are calculated with \( D \) as a reference length (Equation 1). For studies focusing on the aerofoil aerodynamics, Reynolds number is often referred to the chord of the blades \( c \). In this case, the effective \( \bar{U} \) is the one perceived by the blades and it changes on the blade position and the rotational speed. For simplicity and according to references (Bachant and Wosnik, 2016; Zanforlin and Deluca, 2018), \( \text{Re}_c \) is calculated as in Eq. 10. As the rotational speed (and therefore \( \lambda \)) changes in order to obtain all the point of the curves, the values of \( \text{Re}_c \) would be different within each experiment. To have an indication of this parameter for the present measurements, Table 4 shows the values of \( \text{Re}_c \) for each flow condition, at \( \lambda = 2.5 \) (low \( \omega \)), \( \lambda = 3.5 \) (high \( \omega \)) and \( \lambda = 3 \) (around the maximum efficiency point).

\[ \text{Re}_c = \frac{\rho \bar{U} c}{\mu} \]  

(10)

Table 4. Values of chord Reynolds numbers at different \( \lambda \) for each condition of \( \bar{U} \) in the measurements.

<table>
<thead>
<tr>
<th>( \bar{U} )</th>
<th>( \text{Re}_D )</th>
<th>( \text{Re}_c ) (( \lambda = 2.5 ))</th>
<th>( \text{Re}_c ) (( \lambda = 3 ))</th>
<th>( \text{Re}_c ) (( \lambda = 3.5 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 m/s</td>
<td>267,000</td>
<td>66,667</td>
<td>80,000</td>
<td>93,333</td>
</tr>
<tr>
<td>9 m/s</td>
<td>300,000</td>
<td>75,000</td>
<td>90,000</td>
<td>105,000</td>
</tr>
<tr>
<td>10 m/s</td>
<td>333,000</td>
<td>83,333</td>
<td>100,000</td>
<td>116,667</td>
</tr>
</tbody>
</table>

Previous experiments on H-Darrieus (Howell et al., 2010; Miu, 2012; Paraschivoiu, 2002) already showed a considerable rise of performance due to the wind speed increase, a fact that according to literature would occur for \( \text{Re}_c < 10^6 \) (Miller et al., 2018; Rezaeiha et al., 2018a). This increase is also shown in Figure 11 as the powers curve are shifted upwards when increasing Reynolds number.

Figure 11.a shows the uncorrected power curves measured in both wind tunnels, for 3 different Reynolds numbers. As explained in previous sections, high blockage modifies the incident wind speed condition, altering turbine ratings. This can be observed in Figure 11.a as values of \( C_P \) and \( \lambda \) at VUB wind tunnel (where the blockage ratio \( c \) is larger) are significantly higher. Due to that effect (acceleration of the flow due to blockage) power curves at \( \text{Re}_D = 267,000 \) could be only retrieved at VUB but not at CRIACIV.
In Figure 11.b Pope’s blockage correction (Pope and Harper, 1966) is applied, and it can be seen how the curves coming from both wind tunnels look much more similar. The only remarkable difference is the values at high $\lambda$ at $Re_D = 300,000$, but overall it is shown that Pope’s correction can be applied to H-Darrieus reasonably. Paying special attention to the optimal operational conditions, the maximum $C_P$ from both wind tunnels converge accurately, while the optimal $\lambda$ coincides for $Re_D = 333,000$ but not so much for $Re_D = 300,000$. If we put these optimal values in context with literature, $C_P$ max is rather low due to the reduced size of the rotor (SANDIA’s prototype tests reached $C_P > 0.3$) but still higher than other small wind tunnel studies (Jeong et al., 2014; Kirke and Lazauskas, 1993). The optimal $\lambda$ is correctly predicted by the most recent studies for this solidity values: according to Rezaeiha et al. (2018b), $\lambda_{opt}(\sigma=0.2) = 2.97$.

The comparison between Figure 11.a and b also allows to appreciate the effect of blockage in turbine ratings: for example, in the reference case ($Re_D = 300,000$) maximum $C_P$ was overestimated by approximately 0.01 at CRIACIV and 0.02 in VUB. Those differences are not negligible at all, and therefore Pope’s blockage correction is applied to all further data.

Finally, it is also interesting to point out how, apart from the predicted effect of Reynolds number in increasing $C_P$, the peak of the curve is slightly displaced to the left as $Re_D$ increase. This effect, although small (from $\lambda = 3.2$ to $\lambda = 3.05$) is linked to the higher angles of attack experienced by the blades at lower $\lambda$, which causes dynamic stall (Hohman et al., 2018). And at high $Re_D$, the aerofoil is better equipped to cope with stall angles as aerodynamic lift is higher (Amandolèse and Széchényi, 2004).

### 4.3. Turbulence Intensity effect

To compare the power curves obtained under various turbulent conditions, only the measurements obtained with similar grids (VUB 1 and CRI 1) are plotted. Figure 12 presents the values obtained at CRIACIV wind tunnel at $Re_D = 300,000$ (a) and $Re_D = 333,000$ (b). Figure 13 shows the results from the VUB wind tunnel.

The main effect of $I_a$, which can be observed in all 4 graphs is a performance increase, resulting the power curves shifted upwards as turbulence rises. The difference between smooth and turbulent flow is larger for low $\lambda$, which suggests that it can be related with aerofoil performance. In fact, for low $\lambda$ the flow incidence angle on the blades is larger (Paraschivoiu, 2002), so the blade can suffer stall in some part of the rotation. And it has been reported in several studies (Ahmadi-baloutaki et al., 2015; Amandolèse and Széchényi, 2004; Hohman et al., 2018) that turbulent flow improves the static and dynamic stall conditions of the aerofoils.

Another contribution to this performance increase is that turbulent flow is more energetic than smooth flow, as the available power depends directly from $U^3$. With the same mean wind speed, turbulent flow will have slightly higher power derived from instantaneous higher speeds. However, this effect only accounts
for a small part of the $C_P$ increase. The interest of this study, and the main room for improvement, resides more in the turbine aerodynamics than in the power available.

Comparing the curves under different Reynolds numbers it is clear that the difference between low and high turbulence is lower when the Reynolds number increases. In fact, there are some points in Figure 12.b and Figure 13.b where the $C_P$ under smooth flow is similar to some of the low turbulence cases. That could suggest that the effect of turbulence is more evident for low $Re_D$. As in the case of $Re_D$ effect, also in this case when $C_P$ increases the optimal $\lambda$ shifts slightly to the left. This effect is also small but could also be related with the stall behaviour of the blades, as under turbulence the blade improves its performance under the high angles of attack present at lower $\lambda$ (Amandolès and Széchényi, 2004; Rezaeiha et al., 2018a). In that case, it can be concluded that the effect of turbulence can be equivalent to the $Re_D$ effect, energizing the boundary layer to cope better with high angles of attack.

Finally, it is interesting to explain why the error bars are larger for high turbulence cases, especially in the CRIACIV case (Figure 12). The main contribution to the error is the uncertainty of the incoming wind speed, as $\overline{U}$ plays a key role in the calculation of $C_P$. As it can be seen in the wind profiles obtained with the different grids (Figure 7 and Figure 8), the uniformity of the wind profiles at high turbulence is lower than in the cases with low $I_u$, meaning more uncertainty in the incoming $\overline{U}$ (calculated from the standard deviation of the wind profile). Nonetheless, even considering the error bars, the trends indicated in previous
paragraphs are still clear. This is applicable also to the results presented in Figures 14.

4.4. Length scales effect

The effect of $L_w$, is evaluated by plotting the power curves from 4 experiments done at CRIACIV wind tunnel using the 2 different grids (see Figure 14) at $Re_D = 300,000$ (a) and $Re = 333,000$ (b). The curves in smooth flow ($I_u = 0.7$%) are compared with one pair of measurements with similar turbulence level ($I_u \approx 5\%$) and different $L_w$ (0.18 m and 0.05 m), and one pair with similar $L_w$ (0.08-0.09 m) and very different $I_u$ (14.8% and 2.5%).

![Figure 14. Power curves obtained under different turbulence and integral length scale levels at the CRIACIV wind at a $Re_D = 300,000$ (a), and $Re_D = 333,000$ (b).]

The interpretation of the previous results is different from one figure to another, suggesting $Re_D$ may to have an important influence. Studying the curves obtained under $I_u \approx 5\%$ in Figure 14.a ($Re = 300,000$) the effect of $L_w$ appears only for high $\lambda$; for low $\lambda$ the curves coincide. The curve with $I_u = 2.5\%$ shows that already with low turbulence, its effects (increase of $C_P$ and decrease of optimal $\lambda$) can be appreciated.

However, when $Re_D$ is increased (Figure 14.b, $Re = 333,000$) those effects disappear, as the curves of $I_u \approx 5\%$ present a behaviour similar to smooth flow for medium and high $\lambda$, and the one with $I_u = 2.5\%$ has a maximum $C_P$ lower than the smooth flow case. In this case, the beforementioned effects of turbulence are only evident for large $I_u$. Above all, in general it is quite clear that the effect of $L_w$ in the power curves is not very relevant compared to that of turbulence seen in the previous section.

4.5. Analysis of maximum $C_P$

The previous chapters analysed the influence of $Re_D$, $I_u$ and $L_w$ independently in the power curves. To study the mutual influence among the three parameters only the peak $C_P$ of each curve is represented ($C_P\_\text{max}$). In this section, $\lambda$ is not anymore a variable because each point is selected at its $\lambda_{\text{opt}}$ (generally around 3). In order to double-check the accuracy of Pope's blockage correction the values are benchmarked with the max $C_P$ measured during another campaign with the same prototype in the large Politecnico di Milano (PoliMi) wind tunnel, where the blockage ratio was only of 0.9% (Vergaerde et al., 2018), and therefore, according to literature no correction is needed (Battisti et al., 2011).

Figure 15 shows the maximum $C_P$ of all the curves previously presented, applying the aforementioned correction, plotted against the turbulence intensity at each measurement. The values appear to be distributed among three groups, each depending of a Reynolds number, with no remarkable difference between the data coming from both wind tunnels. Also, the value from PoliMi wind tunnel seems to fit in the trends observed for the similar $Re_D$. Data suggest a linear increase of $C_P\_\text{max}$ with $I_u$, therefore these trendlines can be defined by Equation 11, where $C_P\_\text{max}$ represents the $C_P$ value at $I_u = 0\%$ and $S$ the slope of the function.

$$C_P(I_u) = C_P\_\text{max} + S \cdot I_u \quad (11)$$
This graph reveals that the influence of turbulence is definitely positive for the turbine peak performance, as there is a positive quasi-linear dependency between $\bar{C}_p$ and $I_u$, at least in the range studied. This is exposed in Table 5, where the parameters of each line are presented, as well as the coefficient of determination $R^2$ of this linear fit. It is clearly visible how the slope $S$ of the line decreases significantly as Re rises, meaning that the rotor is less sensitive to turbulence as $Re_D$ increases. At the same time, the data also tells that the difference of performance between the three $Re_D$ levels is lower as $I_u$ increases. This effect is observed at all turbulence levels for the lower $Re_D$ (267,000 and 300,000) while at $Re_D = 333,000$ the effect is only clear when $I_u > 5\%$ and at lower levels of turbulence the linear trend seems to flatter. This fact is expressed in the lower coefficient of determination $R^2$ obtained for that $Re_D$ case.

![Graph showing $\bar{C}_p$ vs. $I_u$]  

Figure 15. $\bar{C}_p$ obtained in the different experiments, applying in all cases the Pope’s correction. The trendlines show the linear fit for the experiments done at each Reynolds number.

Table 5. Parameters of the trendlines obtained for the relation $\bar{C}_p - I_u$ at each Reynolds number.

<table>
<thead>
<tr>
<th>$Re_D$</th>
<th>$\bar{C}_p$</th>
<th>Slope $S$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>267,000</td>
<td>0.113</td>
<td>0.0036</td>
<td>0.986</td>
</tr>
<tr>
<td>300,000</td>
<td>0.146</td>
<td>0.0027</td>
<td>0.960</td>
</tr>
<tr>
<td>333,000</td>
<td>0.167</td>
<td>0.0022</td>
<td>0.869</td>
</tr>
</tbody>
</table>

A similar reasoning can be done with the influence of $Re_D$ in the turbine performance. Figure 16 shows the maximum $C_p$ of all the curves previously presented, applying the aforementioned correction, plotted against the Reynolds number of the incoming flow at each measurement. The values are grouped among the measurement with similar values of turbulence ($I_u \pm 1\%$), as in the previous figure it was seen that there was no remarkable difference between the data coming from both wind tunnels. As in the $I_u$ case, the trendlines can be defined by the linear equation Equation 12, where $S_{Re}$ is the slope of the function and $\bar{C}_D$ a constant.

$$\bar{C}_p(Re) = \bar{C}_D + S_{Re} \cdot Re_D$$  \hspace{1cm} (12)$$

In this case, trendlines are only calculated for the $I_u$ groups with more than three measurement for statistical accuracy, which are $I_u = 0\%$, 5% and 9%. As for turbulence, the effect of Reynolds number is also positive for the turbine peak performance, as there is a positive quasi-linear dependency between $\bar{C}_p$ and $Re_D$, at least in the range studied. This is exposed in Table 6, where the parameters of each line are presented, as well as the coefficient of determination $R^2$ of this linear fit. Parallelly to Figure 15, here it can be seen how the effects of $Re_D$ and $I_u$ are reduced as both factors increase, which is clear as the slope $S_{Re}$ is lower for the higher $I_u$. The main difference between the two figures, is that in Figure 15 the three trends seemed to continue after the range studied ($I_u > 15\%$), while in Figure 16 the trends seem to converge just
after the maximum $\text{Re}_D$ studied ($\text{Re}_D = 400,000$). This fact is relevant, and it means that, even turbulence and $\text{Re}_D$ have both a positive effect in $\overline{C}_p$, while $\text{Re}_D$ still increases $\overline{C}_p$ for values of $I_u > 15\%$, when $\text{Re}_D > 400,000$, turbulence does not seem to affect the $\overline{C}_p$ values anymore. Assuming an optimal $\lambda = 3$, this would be translated to a $\text{Re}_c > 120,000$.

Figure 16. $\overline{C}_p$ obtained in the different experiments in function of $\text{Re}_D$, applying in all cases the Pope’s correction. The trendlines show the linear fit for the experiments done at similar turbulence numbers.

<table>
<thead>
<tr>
<th>$I_u$ (±1%)</th>
<th>$\overline{C}_0$</th>
<th>Slope $S_{\overline{C}_0}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>-0.111</td>
<td>8.62·10^{-7}</td>
<td>0.993</td>
</tr>
<tr>
<td>5 %</td>
<td>-0.021</td>
<td>5.94·10^{-7}</td>
<td>0.980</td>
</tr>
<tr>
<td>9 %</td>
<td>0.133</td>
<td>5.29·10^{-7}</td>
<td>0.937</td>
</tr>
</tbody>
</table>

This is not presented for $L_{uu}$ as no clear trends were observed; as seen in Figure 14, the curves with higher $\overline{C}_p$ are all related with high $\text{Re}_D$ and high $I_u$, and no apparent effect of $L_{uu}$ is observed. Therefore, no linear trends or whatsoever are calculated for this case.

Overall, the results show a clear, linear increase of the performance with turbulence intensity $I_u$. This effect has been proved upon the same turbine in two different wind tunnels. This fact can be attributed to several reasons:

- Stall of the blades: turbulence delays significantly the stall in blades, which could be an important advantage in H-Darrieus, where the blade is stalled in an important part of the rotation, especially for low $\lambda$ (Amandolèse and Széchényi, 2004; Paraschivoiu, 2002).
- Lower losses due to the shaft: at low $\text{Re}_D$, increased turbulence entails a drag reduction of cylindrical cross-sections, which in this case will cause less losses due to the turbine shaft for the downstream blade. This fact has recently been shown both experimentally (Carbó Molina et al., 2018b) and numerically (Rezaeiha et al., 2017).
- Faster wake recovery: turbulent flow also might enhance wake recovery, decreasing the influence of the upstream blade in the downstream one. This fact, suggested by Dabiri (2011) has been also measured in this same prototype (Carbó Molina et al., 2018b), and it has been linked by Hohman et al., (2018) to the strength of the dynamic stall.

5. Summary and conclusions

Urban wind energy is still not viable, among others due to the lack of understanding of the complex flows. High turbulence is one of the main characteristics of this flows, but its effect on VAWTs is unclear.
Understanding this effect would allow to improve the design of future urban VAWTs, and for that, wind tunnel studies with controlled conditions are demanded.

Knowledge on turbulence generation using passive grids is used to artificially enhance the turbulence inside the wind tunnel to obtain similar turbulence characteristics as in urban environments. The process is repeated in two different wind tunnels (VUB and CRIACIV), and it is found that empirical relations found in literature predict reliably the average levels of turbulence intensity and length scales generated downstream of the grids. Three different grids are used to generate a range of values of $I_o$ and $L_{ux}$. Special attention must be given to the uniformity of the flow in order to improve the accuracy of the measurements.

A measurement campaign was performed in two wind tunnels using the same H-Darrieus VAWT prototype. The measurements were repeated for three different Reynolds numbers ($Re_D$ from 267,000 to 333,000). In agreement with literature, higher $Re_D$ proved to increase the power coefficient of the turbine, as well as reduce slightly the optimal tip-speed ratio.

The blockage was quite considerable in the wind tunnels tested ($c: 0.1$ and $0.19$), resulting in overestimations of $\bar{C}_p$ of more than $10\%$ in the most critical case. Pope’s correction proved to provide satisfactory corrections both regarding $C_p$ and $\lambda$, and when applied to the measurements from both wind tunnels the effect of blockage disappeared. This correction showed to be adequate also when dealing with turbulent flows.

In the Reynolds numbers range studied, turbulence intensity has a positive effect on VAWT performance, registering power coefficient increases up to $20\%$ from smooth ($I_o=0.5\%$) to turbulent ($I_o=15\%$) flows. This effect is more evident for lower $Re_D$ and lower $\lambda$, and as well as in the case of $Re_D$, increasing $I_o$ causes a slight drop in optimal $\lambda$. This effect can be linked to the fact that turbulence improves the stall characteristics of the blades for high angles of attack (present at low Re and $\lambda$).

Those results are consistent in the experiments done in the two wind tunnels. The data set obtained, benchmarked with a campaign with the same rotor done in a low-blockage wind tunnel, suggested a linear relation between the peaks of the power coefficient curves and the turbulence level $I_o$. The coefficients extracted from the linear regression of the results show that the $\bar{C}_p/I_o$ slope is more pronounced for low Re, and at the same time increasing turbulence ($I_o > 15\%$) makes the rotor less sensitive to Reynolds number. At the same time, results suggest that if $Re_D$ is sufficiently high ($Re_D > 400,000$) the turbine becomes much less affected by external turbulence.

With the use of two different grids at the CRIACIV wind tunnel, the effect of Integral length scales $L_{ux}$ on VAWT performance was also studied. This feature, however, did not prove to have a significant effect in the range studied ($c < L_{ux} < 3c$). The curves obtained under the different $L_{ux}$ condition appeared to be much more influenced by the values of Re and $I_o$, and therefore no further conclusions could be extracted regarding $L_{ux}$.

This study sets a reference by which to evaluate the performance of wind turbines under turbulent flows in a controlled and repeatable manner. The same set-up would also allow to study other effects of turbulence into VAWTs, as its influence on wake development or structural vibrations. The results open an interesting possibility to improve urban turbines efficiency, but need to be expanded with other VAWT designs, higher levels of turbulence and length scales, and especially higher Reynolds numbers in order to extrapolate these results to medium to large-scale VAWTs of higher efficiency.

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