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Wind tunnel tests applied to wind energy management: comparison of measurements in closed-circuit and open-circuit wind tunnels

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Abstract. Power loss, damages overestimation and environmental impacts are the main problems related to wind energy and its planning and management. One of the tools used to analyse and manage this problem is the aerodynamic wind tunnel. In this work wind tunnel tests were performed in two different facilities, an open-circuit wind tunnel and a close-circuit wind tunnel, in order to study the suitability of these features to optimize wind farms layout and power quality and its dependence of the type of tests facility. Experimental results in this work are reported as wind speed and turbulence intensity vertical profiles and flow fields with a simulated ABL with and without the presence of a three-bladed wind turbine model. Results show that mean wind velocity is similar in both tunnels, but turbulence intensity is higher for the open-circuit wind tunnel.

Key words. Wind tunnel, wind energy, optimization, power quality, management.

1. Introduction

As the interest and the need to implement renewable energy systems have increased, several works have analyzed the environmental impacts produced by wind farms, the infrastructure design optimization and the site selection; in order to obtain the best spatial location, maximizing the power extraction and the number of windmills needed to obtain the energy target.

Wind Farm Design and Optimization is a problem to be studied [1] ; as many scenarios have to be analysed, Wind Tunnel simulations jointly with Computational Fluid Dynamics simulations, on-site measurements and algorithm development have been carried out, being the most used tools for the study of wind energy systems [2,3] .

Aerodynamic tunnels or wind tunnels are tools used for studies in which wind flow and infrastructures interaction plays a fundamental role. They have usually been used in studies of vehicles aerodynamics, aeronautics and wind loads on structures. However, nowadays its use has been extended to the study of ecosystems [4] and the interaction between the ABL and renewable energy systems [5,6]. Because of the possibility of study a dynamic, complex and large system at reduced-scale, this facility improves the knowledge and allows the extrapolation of results to the full scale, being fundamental for systems assessment and management.

The main advantage of the use of wind tunnels compared to other practices is the ability to simulate the Atmospheric Boundary Layer (ABL) and the kinematic characteristics of wind flow at spatial scale. As well as balances and gradients derived from the turbulent nature of this layer and the interaction with other environmental variables [7].

An inadequate location of wind farms, the incorrect estimation of kinematic and environmental variables and the interaction between the atmosphere and the windmills, cause a reduction of the energy extracted by up to 50% [8]. So, it is essential to calibrate experimental results and compare them with similar ones from other systems or infrastructure.

The objective of this work is to study the potential of wind tunnels to be used as a tool for analysing renewable energies, in particular wind energy systems, and corroborate if the wind tunnel type influences the results obtained for the same experimental tests. This is very important for wind farms design and it can influence the optimization and the power supply that could be obtained by each wind turbine.

In order to analyze the influence of the type of facility, tests were carried out in two different types of wind tunnels, an open-circuit Boundary Layer Wind Tunnel and a closed-circuit Climatic Wind Tunnel.

This document is organized as follows: set up, facilities and data generation are presented in section 2. The results are discussed in section 3, and main conclusion are drawn in section 4.

2. Materials and Methods

There are two basics types of wind tunnel: open circuit and closed circuit. In the first one, air flows straight from the entrance to the test section around the objects and then exits to the exterior, and in the closed-circuit type, the air recirculates with almost no change of air with the exterior [9] .

Prior to this work, an analysis of flow homogeneity has been performed in both wind tunnels in the absence of roughness elements and energy dissipaters [10,11]. This work has shown that it is appropriate to work with scaled models and ABLs with a scale factor of 1:300. A hot-wire anemometry system has been used in both tunnels, to avoid errors related to the use of different instruments, and because of it is the most widely used instrument for wind fluctuation measurements in aerodynamic wind tunnels [12].

A. Closed section wind tunnel

Secondly, the same tests were performed in the Climatic Boundary Layer Wind Tunnel (CWT) of the Institute of Theoretical and Applied Mechanics (ITAM), Prague (Czech Republic), a Göttingen closed-circuit type wind tunnel. The tunnel has a 11 meters long aerodynamic test section with a 1.9 m wide x 1.8 m high cross section. A *Dantec Dynamics* cross hot-wire anemometry system was used to take measurements, with a sampling frequency of 1kHz, recording data during 120 seconds for each point. The data acquisition and analysis were performed using *StreamWare Pro Software.*

B. Open section wind tunnel

Firstly, tests were performed in the Boundary Layer Wind Tunnel (BLWT) of the Fluid Dynamics Laboratory from the Andalusian Institute for Earth System Research (IISTA, University of Granada), an open-circuit type wind tunnel. The tunnel has a plan length of 40 meters with a test section with 15 m of length and a 2.15 m wide x 1.80 m high cross section. A *TSI IFA-300®* cross hot-wire anemometry system was used to take velocity measurements, with a sampling frequency of 1 kHz in this work, recording data during 131 seconds for each point. The data acquisition and analysis were performed using *Thermal Pro Software*.

C. Experimental set up and data generation

To generate the required ABL model, in order to reproduce an open field area, different roughness elements have been tested modifying the spatial distribution, height and density of the elements. In this work, the final configuration selected consists of a wooden barrier with height *B* (*B*=15 cm) located in the entrance of the test section, and two sizes dissipation elements made of wood cylinders (two sizes: 15x10 mm and 10x10 mm) and arranged in staggered a 15 x 15 cm layout along 2.7 meters, shown in Figure 2. The ABL simulated in both tunnels is showed in the Figure 1.

The same reduced-scaled model was used in both experiments, showed in Figure 3. It was a 3-blades free rotation wind turbine with a hub height of 30 cm and a rotor diameter of 35 cm, and it was built with a scale factor of 1:300, this model was made based on the wind turbines currently located in Mediterranean wind farms. In both tunnels, neutral stability of the atmosphere has been considered, without any change in temperature or humidity, with a reference speed of 3 m/s for both cases.

Thirty profiles arranged in a lattice of 6x5 were measured up to 1 m high. The distance between profiles was D/2, where D is the rotor diameter. Each profile consisted of 12 measurement points (Figure 2). In both tunnels, the hot wire anemometry was placed on a 3D positioning system, which allows position it to take data at all points of the study section. This section was selected to take measurements in the area where the turbulent wake behind the wind turbine appears and it expands.

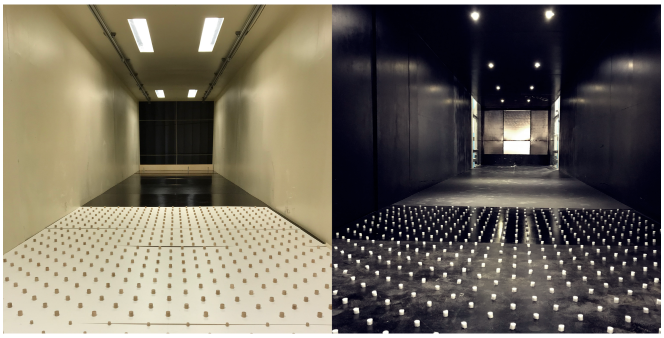

Fig. 1. ABL simulated with roughness generation elements inside the CWT (left) and the BLWT (right).

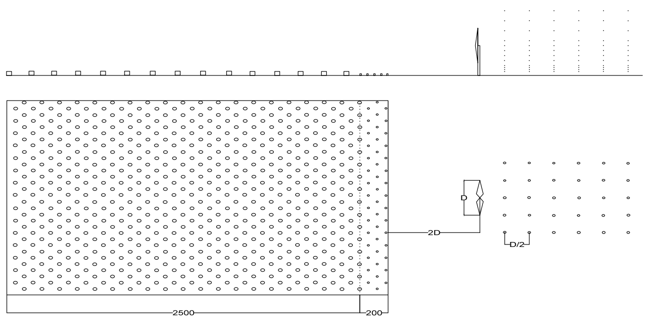

Fig.2. Set up, profiles and points of measurements. This configuration was used in both wind tunnels.

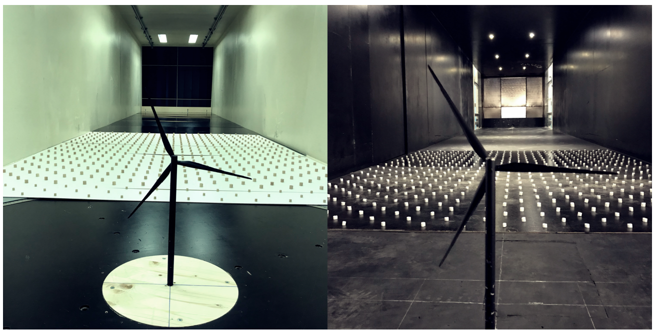

Fig.3. Set up and wind turbine model used for tests in both wind tunnels.

3. Results and discussion

Variables have been represented in dimensionless form. The wind velocity was normalized by *Uref* which is the measured velocity at *zref*=0.5 m (half of the total height measured) for ABL graphs, being *zref*=*d*=D/2 for graphs with wind turbine models.

A. ABL calibration

Figure 4 shows the theoretical and measured vertical profiles for mean wind speed and turbulence intensity with roughness elements. The theoretical profile has been calculated based on the usual features of wind farms in the South of Europe. The aerodynamic length used to obtain the theoretical mean velocity profile is z_o=0.07 m, in concordance with the roughness length from an open field considered as the reference.

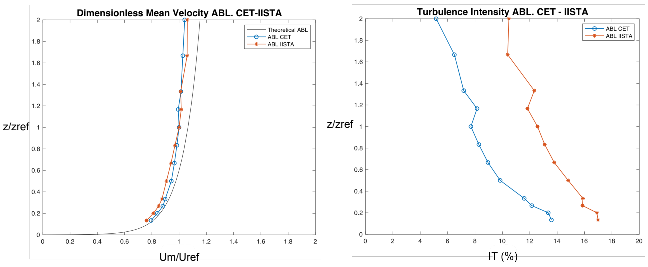

Fig.4. Comparison of Theoretical ABL and ABL simulated inside CWL and BLWT. Mean wind speed (left) and Turbulence Intensity (Right).

The left in Figure 4 shows the comparison of velocity profiles measured in both wind tunnels. Differences are almost non-exist, however, the right in Figure 4 shows a 2% increase in IT in the BLWT, maintaining the vertical shape of the profile. Probably this difference is due to the characteristic of the tunnel shape or the flow recirculation around external objects.

B. Wind tunnel tests with wind turbine model

Figures 5 to 8 show central longitudinal section of measurements in central profiles for both test sections (CWT and BLWT), behind the wind turbine in the flow direction, and its distribution of dimensionless variables. Wind flow was measured until a distance of two times the rotor diameter, the rotor height is marked in the graphs with a yellow line.

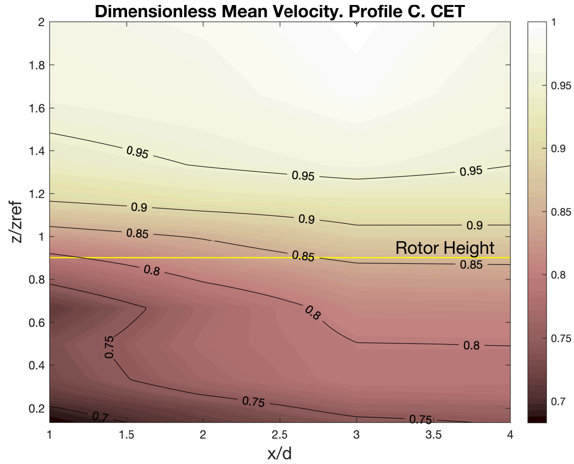

Fig.5. Dimensionless mean wind speed downwind of the windmill in CWT

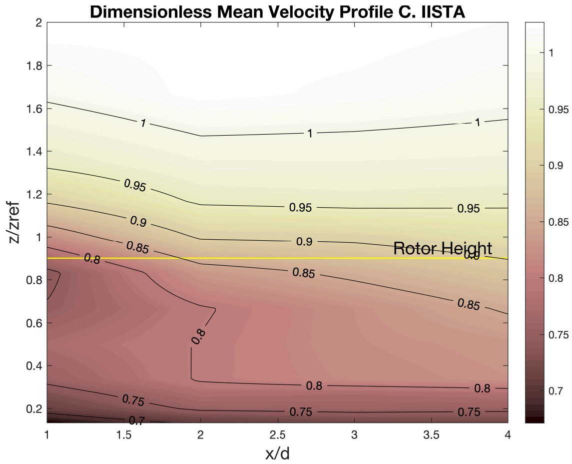

Fig 6. Dimensionless mean wind speed downwind of the windmill in BLWT.

In the Figures 5 and 6, dark colors mean a lower speed with respect to the reference speed, due to the presence and blades rotation of the wind turbine, as the work of [6] shows. The average speed is stabilized and homogenized earlier in the BLWT, both in height and downwind direction.

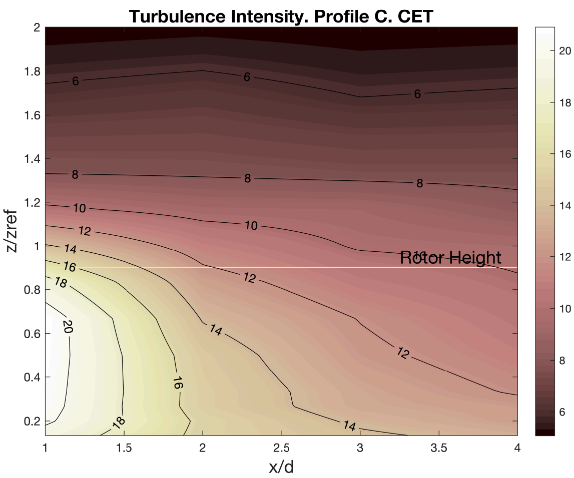

Fig.7. Turbulence Intensity in % downwind of the windmill in CWT.

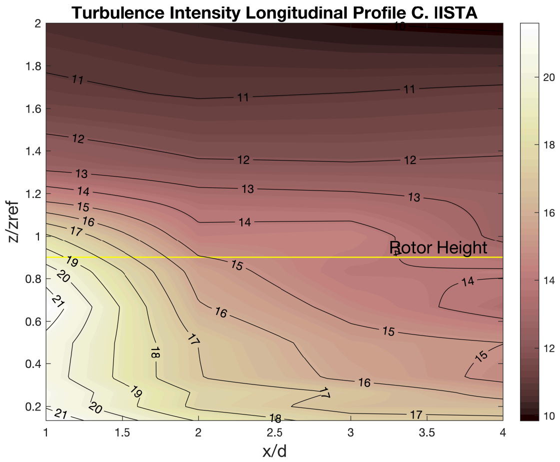

Fig.8. Turbulence Intensity in % downwind of the windmill in BLWT.

In the Figures 7 and 8 the lighter colors are translated into a greater intensity of turbulence. An increase of IT is noticed in the area near the wind turbine, generated by its operation and size. For the BLWT, the IT is higher compared to the CWT, especially as we move to leeward. At a height of approximately *1.6* z/z_{ref} these differences are higher, reaching almost the double in the case of the BLWT, according to the vertical profiles obtained just with the simulated ABL.

4. Conclusions

The aim of this article is to compare wind tunnel tests from two different facilities applied to the analysis of a wind energy system, simulating the same ABL and using the same windmill model and corroborate if the simulation of energy extracted by a wind farm is dependent of the wind tunnel where tests are carried out.

The replication of tests with the same set up and scaled models had not been done before, so this work can serve as reference for future tests and comparison and the study of wind farms management.

Wind flow is less turbulent inside the close-section wind tunnel and the shape of the vertical profile is conserved in both tunnels. This difference may be due to specific characteristics of the open-section wind tunnel or the air flow recirculation around external objects.

Regarding the results of this work, the type of wind tunnel will influence the estimation of turbulence development due to the wind turbine presence and blades rotation, but the initial velocity deficit due to shielding between wind turbines will be the same because of wind speed is similar in both facilities.

It is concluded that the characteristics of the facility can affect the results. While it will not change, the power estimated, but it can overestimate the variables related to the turbulence intensity and the damage from wind over the wind turbine.

Several wind-turbines models, configurations and topographical changes have been tested inside both wind tunnels and will be analyzed jointly with the influence of temperature changes. Temperature influence has been tested in the CWT comparing the differences taking into account neutral stability conditions and unstable stability conditions.

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