International Conference on Renewable Energies and Power Quality (ICREPQ'16)
Madrid (Spain), 4th to 6th May, 2016
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.14 May 2016

Wind flow around a wind turbine system over hilly terrain and its environmental effects: wind tunnel tests

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Abstract. Wind tunnel tests were performed in order to study the wind flow field over hilly terrain and the effects of a wind turbine on a typical Mediterranean ecosystem. Cross-wire anemometry was used to measure wind speed and turbulence intensity, and Reynolds stress was estimated over the ground as well. The tests show changes in the wake behind the wind turbine, showing a decrease of wind speed and an increase of turbulence intensity caused by the system. Theoretical formulations allow to relate the measured disturbances in the Atmospheric Boundary Layer (ABL) to seed dispersion by wind and evaporation rate. Results are in concordance with previous studies.

Key words

Atmospheric boundary layer, wind turbine, wind tunnel, hilly terrain, environmental effects.

1. Introduction

Wind energy is a clean and renewable alternative to fossil fuels. However, windmills may also generate some environmental impacts due to the extraction of kinetic energy by their turbines [1]. Vertical and horizontal heterogeneity plays an important role on turbulence properties within the turbine wake [2]; this produces a decrease in the wind velocity and an increase in the turbulence intensity, which may cause several disturbances in ecosystems [3][4].

The influence of wind turbine infrastructures and their spatial configuration on the flow field has been widely studied [2]. Nevertheless, less attention has been paid to the joint effect of these structures with the topography. Wind tunnel tests are a good option to study terrain-induced turbulence [5].

Structure and physiology of plants are the main factors affected by changes in the wind field. When the wind velocity is low, some plants species have less structural elements, its growth is larger as well as its leaf area [6]. Moreover, there exist variations in evapotranspiration depending on changes in wind velocity [7]. Generally, higher evapotranspiration rates are related to stronger winds [8]. In addition, depending on the plant specie and its type of reproduction, wind can affect different features, like seed dispersal which is studied in this work [9].

In order to analyze the impact that wind farms cause on their environment, it is necessary to quantitatively assess the incident wind flow transformation due to the presence of the wind turbines [10]. This work deals with the characterization of the wind field around an isolated wind turbine located over hilly terrain in the atmospheric boundary layer. In this regard, an actual Mediterranean wind farm was selected to perform an experimental study consisting of:

- Characterization of mean and fluctuating properties of the incident wind profile.
- Analysis and characterization of kinematic variables that define the wind field.
- Study of the influence of the hilly terrain and the isolated wind turbine on the near wake.
- Qualitative analysis of the potential influence of near wake on the environment and the vegetation.

This document is organized as follows: section 2 describes the scope of the study and the methodology, section 3 shows the results of the tests, section 4 remarks the environmental effects of windmills and, finally, section 5 summarizes the main conclusions.

2. Materials and methods

Tests were performed in the Boundary Layer Wind Tunnel of the IISTA Fluid Dynamics Laboratory (University of Granada). The tunnel has a plan length of 40 meters with a test section of 2.15 x 1.80 meters and 15 meters of length.

A. Incident wind conditions

The selected wind farm is located in Granada (Southern Spain) over an agroforestry area. In order to reproduce its roughness characteristics in the wind tunnel, different dissipative devices have been tested. By means of thermal anemometry, which allows for sampling frequencies higher than 1kHz, mean velocity and turbulence intensity profiles were measured and compared to reference expressions. The final configuration consists of a wooden barrier located in the wind tunnel entrance and a surface covered by bolts. This zone extended 2.7 m along the wind tunnel axis where bolts were positioned in two subzones with different densities (Figure 1 bottom).

B. Experimental set-up and flow field measurements

The reduce-scaled model was a 3-blade wind turbine and it was built with a scale factor of 1:300. Its rotor had a diameter of 35 cm. Furthermore, a hill model of 15 cm high was used to simulate the topography effects.
Figure 1 depicts the experimental set-up and Figure 2 shows the set-up inside the wind tunnel. Forty profiles arranged in a lattice of 8x5 were measured up to 0.8 m high. The distance between profiles was D/2, where D is the rotor diameter. Each profile consisted of 16 measurement points in which wind velocity was recorded with a sampling frequency of 1 kHz. To evaluate the turbine effects, tests were performed with and without the windmill.

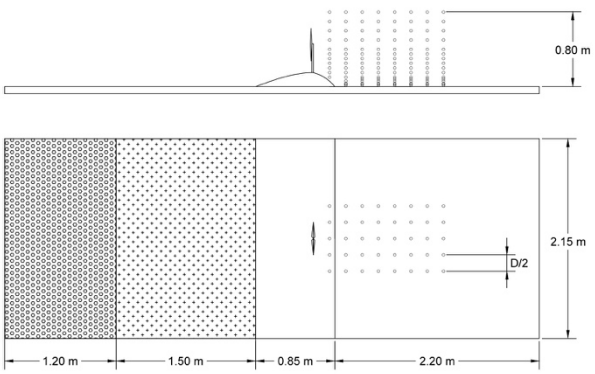

Fig. 1. Experimental set-up.

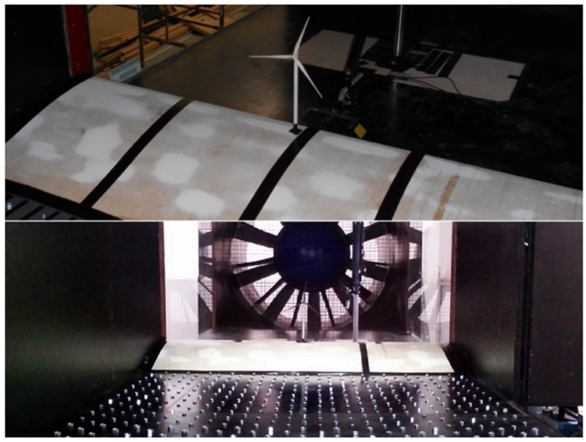

Fig. 2. Hill and wind turbine model placed inside the wind tunnel.

3. Results

A. Theoretical and measured Atmospheric Boundary Layer.

Figure 3 shows the theoretical and measured profiles for incident mean velocity and turbulence intensity. The theoretical ABL has been calculated based on a reference spectrum and by taking into account the characteristics of the study area.

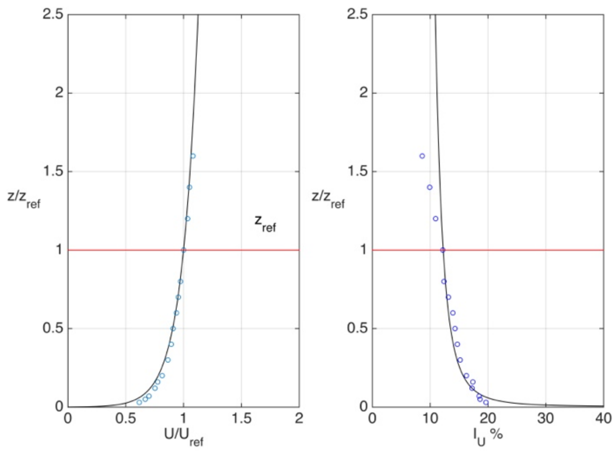

Fig. 3. Theoretical ABL profile (black line) and measured ABL profile (blue circles) for mean velocity (left) and turbulence intensity (right).

B. Mean velocity and turbulence intensity

Figure 4 and 5 show the central longitudinal section of the measurement region and its distribution of mean velocity dimensionless with the reference velocity (Uref) measured at the reference height (zref) and turbulence intensity with the isolated hill and with the wind turbine, respectively. Along wind flux, that is to say, horizontal and vertical directions changing mean velocity and turbulence intensity, there are many changes (Figure 5). Main disturbances occur under hill height in both cases, which agree with other studies [11]. The area under the influence of the wind turbine shows a decrease of the mean velocity and an increase of the cross-section wind flux for conservation of mass.

Figure 6 depicts the ratios between the case with wind turbine and the measurements with the isolated hill. In general, the wind turbine decelerates the wind flow and generates turbulence. The velocity disturbance is larger at the bottom, within the hill wake, while, on the contrary, the effects on turbulent intensity are more notorious near the turbine.

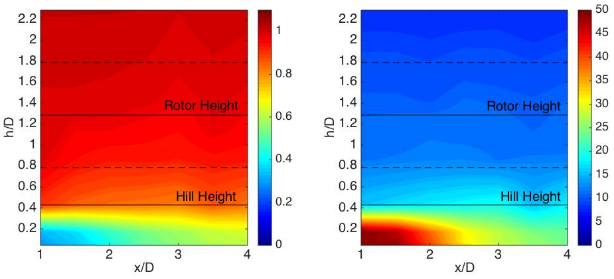

Fig. 4. Mean velocity (left) and turbulence intensity (right) around an isolated hill.

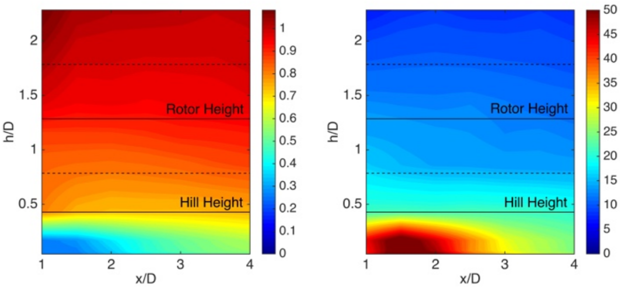

Fig. 5. Mean velocity (left) and turbulence intensity (right) around wind turbine system placed over a hill.

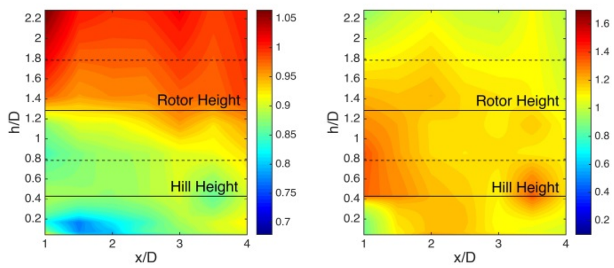

Fig. 6. Mean velocity ratio (left) and turbulence intensity ratio (right).

C. *Reynolds stress at surface*

Reynolds stress characterizes the wind turbulent shear stress. As a result, it affects mass and momentum transport phenomena and the structural stability of plants. This magnitude is analysed at the bottom to quantify the mean turbulence effect on the vegetation cover, and its potential physiological and structural modifications.

Figure 7 shows that Reynolds stress varies with the space position respect to the windmill, being higher near the hill. It also exhibits a central area with slower value under the influence of the wind turbine system.

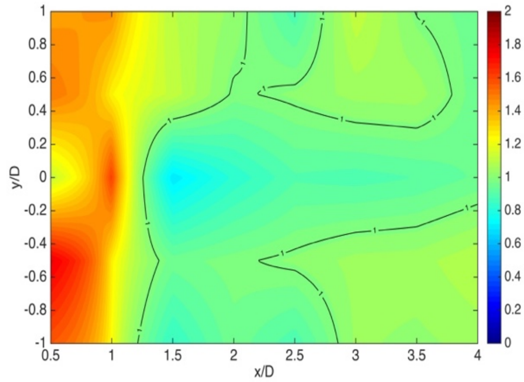

Fig 7. Reynolds stress at surface.

4. Environmental effects

Figure 8 shows the spatial gradients of wind velocity and turbulence intensity due to the presence of the wind turbine (results from the hill scenario minus results from the hill and windmill one). It depicts a decrease of the mean wind speed and an increase of the turbulence intensity near the model, where the flow field is under the influence the wind turbine. The same situation exists on the wind flux direction, but the effects over the mean velocity and the turbulence intensity are lower due to the spatial dissipation of disturbances. These changes are correlated with seed dispersal and evapotranspiration rate [12] as shown bellow.

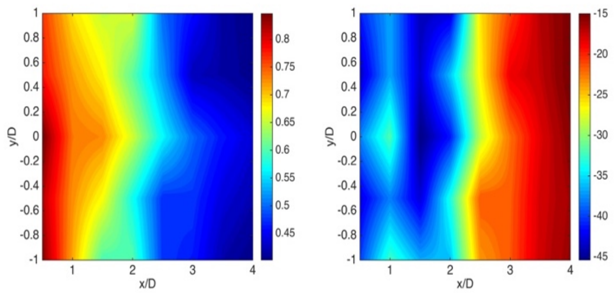

Fig. 8. Top view of mean velocity (left) and turbulence intensity (right) measured at the bottom.

A. *Seed dispersal variations*

Seed dispersal by wind is the main mechanism by which plants move and expand in space. Several models have been developed incorporating horizontal and vertical wind velocity and turbulent variations [13]. R. Nathan et al. [14] proposed an equation to estimate seeds dispersal distance (S) and its relationship with the logarithmic wind profile (1).

$$S = \frac{u_*}{K(F-W)}\left((H-d)\ln\left(\frac{H-d}{e\cdot z_0}\right)+z_0\right) \quad (1)$$

where u_* is the friction velocity; κ is the von Karman constant; F is the terminal velocity of a seed falling in still air; W is the mean vertical wind speed during flight; H is the height of seed release and d and z_0 are roughness parameters.
In the study area, the main vegetable specie is *Stipa tenacissima* L, whose reproduction is based on its seeds dispersal by wind, so wind speed distortions are considerably important over native ecosystems. By means of previous models and experimental studies, it is possible to estimate some seed dispersal parameters [15] and therefore spatial distribution patterns can be derived from Figure 8. Gentle winds produce shorter dispersal distances along wind flux direction and near the model. That effect is larger near the model and it is dissipated along wind flux direction.

B. Evapotranspiration rate disturbances

Evaporation rate is one of the most important parameters that affects the life of a plant. This rate depends on many factors: wind speed, air temperature, irradiance relative humidity and, for plants of small size, also turbulence [16]. Several works [8][17] have developed experimental studies and models in order to explore the relationship between wind speed and evaporation rate, usually by means of the Penman-Monteith equation [18]. They conclude that larger wind speed implies an increase in potential evaporation and a reduction of leaf transpiration.
Based on these studies and on the performed tests, a decrease in the evaporation rate can be deduced near the hill, in the area under the influence of the movement of the blades, this effect is notable around the measured area, but it is dissipated along flux direction. In dry climate, such as Mediterranean, this is an important fact since moisture retention improves plant growth.

5. Conclusions

The aim of this article is the study of the wind flow around a wind turbine system and its environmental effects over a Mediterranean ecosystem. The presence of a wind turbine involves a decrease in the mean velocity and an increase in the turbulence intensity with distance as the wake expand horizontally and vertically respect to the incident flow field. This system modifies the wind field and, consequently, produces a significant influence on the environment.
Regarding the Reynolds stress tensor, the presence of the wind turbine modifies the wind shear field. Changes in the wind efforts on the vegetation may have potential effects on its structure and growth patterns. Also, it changes the evaporation rate due to the temperature disturbances produced by wind shear field over leaves surface.
In order to estimate the long-distance seed dispersal, evaporation rate and its importance in ecology it is necessary to evaluate wind variations around the study model.
Future work will consider the presence of multiple turbines with different pitch angle ranging and wind farm configurations. On the other hand, the use of Particle Image Velocimetry (PIV) techniques to obtain the spatial distribution of the instantaneous velocity around around the wind turbine will be considered.

Acknowledgment

This research was funded by the Andalusian Regional Government (research project, Estudio Integral de los Efectos Ambientales de los Campos de Generación de Energía Eólica en Tierra, REF: PI/11-57055).

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