Fully developed experimental wind turbine array boundary layer

John J. Turner V* and Martin M. Wosnik**
*University of New Hampshire, Durham, NH, USA, JohnJTurnerV@gmail.com
**University of New Hampshire, Durham, NH, USA, Martin.Wosnik@unh.edu

Abstract
Validation/benchmark data of a fully developed model wind farm are presented. A model wind turbine array consisting of 19 rows and 5 columns of turbines was deployed in a large boundary layer wind tunnel. The wind turbine array is comprised of 0.25 m porous disks, drag-matched to wind turbines, that act as momentum sinks in the flow. Porous disks were shown to have wakes similar to that of scaled rotating turbines. At the 1st row of the wind turbine array, the turbines are in the bottom third of the turbulent boundary layer. A coefficient of determination calculation is performed to determine row to row similarity and confirm the fully developed condition of the array. The data presented directly correspond to simulations that employ the actuator disk method.
Keywords: *Experimental model, Wind turbine array, boundary layer, Fully developed*

Introduction

There is no a priori configuration of large arrays of wind turbines that generates the maximum power output. Large, regularly spaced, wind farm arrays have historically had their power production overpredicted. Overlooked in some early predictions were the true physics of the wake effects of upstream turbines and the coupling of wakes with incoming boundary layer dynamics in an effort to ease calculations [1]. These combined physics create the wind turbine array boundary layer. When an array is sufficiently large, the wind turbine array boundary layer can reach a state known as the fully developed wind turbine array boundary layer. In this fully developed state, the flow statistics become consistent from one row of turbines to the next [2, 3].

Experimental studies have been performed with 2 or 3 columns and up to 10 rows of turbines. This current work is an extension of these experimental wind farm arrays [4, 5]. Uniquely, the farm constructed here is sufficiently large that it achieves the fully developed condition.

The phenomenon of a fully developed farm is primarily investigated using computer simulations. Numerically generated actuator disks models, rather than fully resolved turbines, are chosen to save computational cost [6, 7]. Experimental studies have shown the similarities of a wind turbine wake with that of a porous disk or circular mesh and justified the use of physical porous disks to simulate the numerical actuator disks which then more easily compare the wind tunnel experiment to CFD [8, 9]. Fully developed simulations can be achieved with periodic boundary conditions that allow the flow to have multiple passes over the turbines. Experimentally, this condition can only be achieved with a long development fetch, as shown here.

Methods

The turbine array studies were conducted in the University of New Hampshire (UNH) Flow Physics Facility (FPF). The UNH FPF is a large physics quality turbulent boundary layer wind tunnel. The test section measures 6 m (W) x 2.7 m (H) x 72 m (L). Details of the FPF and boundary layer measurements are reported in Vincenti et al., 2013. Figure 1 shows a top down view of the FPF (test section shortened in drawing, see break lines).

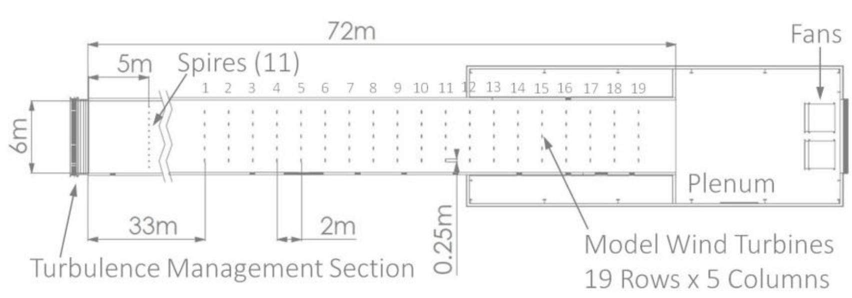

Fig 1. Top down view of the FPF

A 19 row and 5 column turbine array consisting of 0.25 m diameter (D) disks with 5 mm hole size and 7.5 mm center to center spacing, was constructed. The disks were drag matched to a scaled rotating model turbine used in a previous study. The array is positioned at 4D spacing in the spanwise and 8D spacing in the streamwise directions. A set of 11, 1 m tall Irwin spires were positioned at 5 m downstream of the tunnel turbulence management section [10]. The spires aid in boundary layer growth so that the entrance of the array at 33 m downstream has a boundary layer height of 0.8 m. With a turbine hub height of 0.75 D, the turbines are in the bottom 1/3rd of the incoming boundary layer. An experimental turbine array of this scale can provide other valuable insights such as studying a hole in a wind farm, determining impact of yaw configurations, or understanding atmospheric scale oscillations.

Pitot tube velocity data was obtained at 17 streamwise locations at an x/D = 6 behind the center column turbine. 24 vertical points were obtained per profile. Each time series provided 625 statistically independent samples corresponding to approximately 2.5% uncertainty. Density in the velocity calculation was corrected for temperature, barometric pressure and humidity.

Results

Following the work of George and Castillo 2001, the velocity deficit is normalized by the maximum velocity and the location is normalized by boundary layer height, δ. The profiles are shown collapsed in figure 2. Excellent agreement is seen in normalized variables beyond the initial transition which lasts until row 4. Further analysis is performed via a coefficient of determination (R^2) calculation comparing the entirety of the normalized profiles to the far downstream row 16. Also compared is the non-normalized velocity profiles and the equilibrium region. The equilibrium region exists from top tip height of the turbines to approximately 0.5D above top tip height. In this region, the turbulence intensity and shear stress exhibit a levelling off behavior, where turbine power extraction balances vertical kinetic energy entrainment [11]. The R^2 value for the equilibrium region is greater than 0.9 at row 12 indicating the fully developed condition. This data set should be useful to modelers using the actuator disk method.

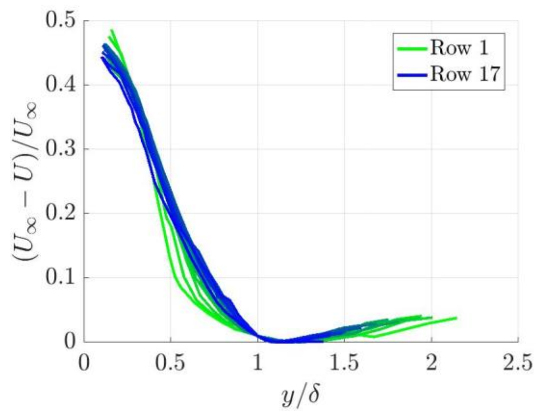

Fig 2. Velocity deficit normalized by max velocity and boundary layer height

Conclusions

A large model wind farm has been constructed in a boundary layer wind tunnel. A benchmark data set for validation of the actuator disk method has been obtained. The velocity deficit profiles appear similar past row 4. The array is sufficiently large that the fully developed condition presents itself through high R^2 value in the equilibrium region of the flow at row 12 and further.

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