Convective Surface Heat Flux Effects on Wind Turbine Power

Jordan Nielson* and Kiran Bhaganagar**
*University of Texas at San Antonio, San Antonio, TX, USA, jordantnielson@gmail.com
** University of Texas at San Antonio, San Antonio, TX, USA, Kiran.bhaganagar@utsa.edu

Abstract

Large Eddy Simulation was performed for single, double, and triple wind turbine arrays. The simulations used three different surface heat fluxes for a given geostrophic wind speed to generate inflow of different states of the convective ABL. The results showed that the change in surface heat flux significantly affected wake recovery rates and power production of downstream wind turbines for the same geostrophic wind speed. The results were used to estimate energy production from frequency data measured in the field.

Keywords: *Large Eddy Simulation, Convective Atmospheric Boundary Layer, Power Deficits, Surface Heat Flux*

Introduction

Full-scale wind turbines operate in the Atmospheric Boundary Layer (ABL). The Atmospheric stability is known to have an effect on recovery rates of wind turbine wakes[1]–[4]. Different wake recovery rates lead to differences in wind turbine power production[5]–[7]. Most of current studies analyze the effects of stability by separating stability classes into general stable, neutral, and convective regimes. The studies show large differences between the general regimes, but this creates other questions. Are there significant changes between different stabilities within each regime (stable, neutral, convective) and would these differences affect power prediction? How would one probabilistically implement different atmospheric states in power/energy forecasting?

Methods

The current work studies wind turbine recovery rates, turbulence, as well as power deficits. The study used two months of meteorological tower data from the NREL Colorado Site. The study created a Probability Density Function (PDF) of surface heat flux as an input into Large Eddy Simulations (only using the values at noon LT). The negative one standard deviation, mean, and positive one standard deviation surface heat flux were used as boundary conditions for three different LES cases where the geostrophic wind speed is held constant. These cases are then mapped to a single, double, and triple wind turbine simulations to study the effects of the change in surface heat flux on wind turbine characteristics. The current work uses the SOWFA tool with the methodologies proposed by Churchfield et. al[2], [10].

Equation 1 shows the recovery rate exponent that is calculated by fitting a power law. The exponent n is a measure of how fast the wake recovers to the inflow of the first wind turbine. The wake recovery rate is used to compare the wake recovery of different simulations performed.

$$\frac{U_{hub} - U_{min}}{U_{hub}} = A\left(\frac{x}{d}\right)^n \quad (1)$$

Results

The exponents, shown in Figure 1, calculated from the simulations fall within the expected range from previous experiments[11]. The exponents increase as the surface heat flux increases (faster wake recovery). The increase from negative one standard deviation to the mean is much larger than the increase from the mean to positive one standard deviation suggesting a maximum wake recovery. The power deficits for a second wind turbine aligned 4D downstream are shown in Figure 1 b). The power deficit decreases with increased surface flux and is directly related to faster wake recovery. The power deficit goes from 47% in the negative one standard deviation simulation to 28% in the positive one standard deviation simulation. The large difference in the power produced by the second wind turbine shows the importance of accounting for different convective ABL states.

The simulated data was also used to predict energy production based on frequency data for a different month of the NREL data set. At a hub height wind speed of 6.5-7.5 ms^{-1} (the average wind speed for the three simulations was 7.1 ms^{-1}), there were 132 1hour instances of surface heat flux between 0.0584 and 0.1735 kms^{-1}, 168 instances between 0.1735 and 0.2885 kms^{-1}, and 72 between 0.2885 and 0.405 kms^{-1} (corresponding to N1SD, Mean1, and P1SD). If one used the power curve to estimate the energy produced during these 372 hours without taking into account wake deficits, the total energy production would be 1.25GWh. If one used the power deficit of the Mean1 simulation, the total would be 1.04 GWh. If one used all three bins to estimate the power the total would be 1.02 GWh.

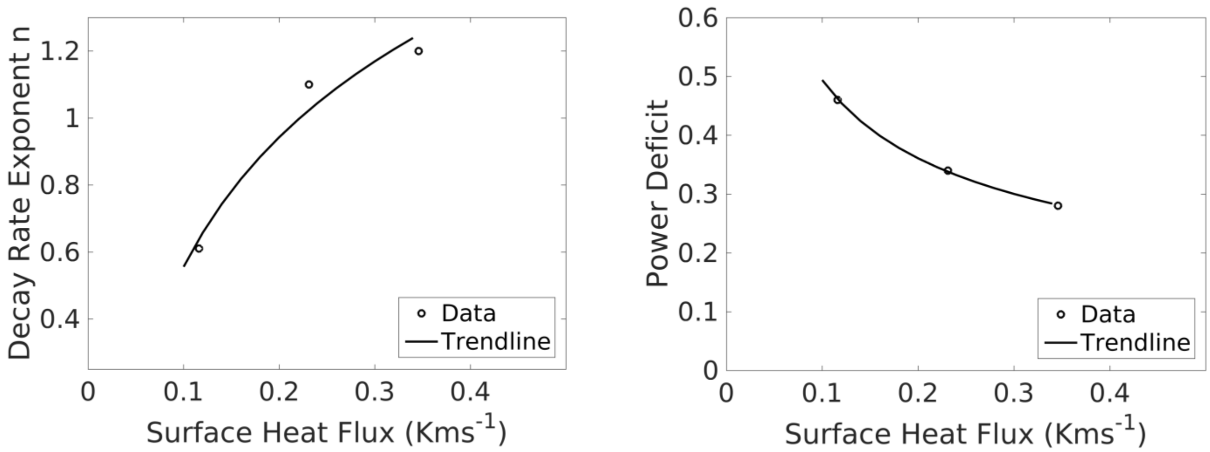

Figure 1: a) Decay Rate Exponent for single wind turbine wakes. b) Power Deficts for Aligned Wind Turbine 4D downstream. c) Decay Rate Exponent for Downstream Wind Turbine Wakes Aligned 4D downstream.

Conclusions

This study begins to quantify the effects of different convective ABL states on the characteristics of wind turbines. The results show that changes in surface heat flux in convective ABL have significant impacts on wake recovery rates and power production of downstream wind turbines. The results show the importance of classifying stability when predicting power outputs of wind farms and give a methodology to probabilistically estimate power for a downstream wind turbine.

References

[1] M. Abkar and F. Porté-Agel, “Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study,” *Phys. Fluids*, vol. 27, no. 3, p. 035104, 2015.

[2] M. J. Churchfield, S. Lee, J. Michalakes, and P. J. Moriarty, “A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics,” *J. Turbul.*, no. 13, p. N14, 2012.

[3] Y.-T. Wu and F. Porté-Agel, “Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study,” *Energies*, vol. 5, no. 12, pp. 5340–5362, Dec. 2012.

[4] N. S. Ghaisas, C. L. Archer, S. Xie, S. Wu, and E. Maguire, “Evaluation of layout and atmospheric stability effects in wind farms using large-eddy simulation,” *Wind Energy*, 2017.

[5] S. Wharton and J. K. Lundquist, “Atmospheric stability impacts on power curves of Tall wind turbines-an Analysis of a West Coast North American wind farm,” *Rep. Lawrence Livermore Natl. Lab. LLNL-TR-424425*, 2010.

[6] S. Wharton and J. K. Lundquist, “Atmospheric stability affects wind turbine power collection,” *Environ. Res. Lett.*, vol. 7, no. 1, p. 014005, 2012.

[7] B. J. Vanderwende and J. K. Lundquist, “The modification of wind turbine performance by statistically distinct atmospheric regimes,” *Environ. Res. Lett.*, vol. 7, no. 3, p. 034035, 2012.

[8] K. Bhaganagar and M. Debnath, “Implications of stably stratified atmospheric boundary layer turbulence on the near-wake structure of wind turbines,” *Energies*, vol. 7, no. 9, pp. 5740–5763, 2014.

[9] K. Bhaganagar and M. Debnath, “The effects of mean atmospheric forcings of the stable atmospheric boundary layer on wind turbine wake,” *J. Renew. Sustain. Energy*, vol. 7, no. 1, p. 013124, 2015.

[10] M. J. Churchfield, P. J. Moriarty, G. Vijayakumar, and J. G. Brasseur, “Wind Energy-Related Atmospheric Boundary-Layer Large-Eddy Simulation Using OpenFOAM,” *Natl. Renew. Energy Lab. Gold. CO Rep. No NRELCP-500-48905*, 2010.

[11] G. V. Iungo and F. Porté-Agel, “Volumetric lidar scanning of wind turbine wakes under convective and neutral atmospheric stability regimes,” *J. Atmospheric Ocean. Technol.*, vol. 31, no. 10, pp. 2035–2048, 2014.