Field measurements in the wake of a model wind turbine

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Abstract. As a first step to study the dynamics of a wind farm, we experimentally explored the flow field behind a single wind turbine of diameter 1.17 m at a hub height of 6.25 m. A 10 m tower upstream of the wind farm characterizes the atmospheric conditions and its influence on the wake evolution. A vertical rake of sonic anemometers is clustered around the hub height on a second tower, 6D downstream of the turbine. We present preliminary observations from a 1-hour block of data recorded in near-neutral atmospheric conditions. The ratio of the standard deviation of power to the inflow velocity is greater than three, revealing adverse effects of inflow turbulence on the power and load fluctuations. Furthermore, the wake defect and Reynolds stress and its gradient are pronounced at 6D. The flux of energy due to Reynolds stresses is similar to that reported in wind tunnel studies. The swirl and mixing produces a constant temperature wake which results in a density jump across the wake interface. Further field measurements will explore the dynamics of a model wind farm, including the effects of atmospheric variability.

1. Introduction
The model wind farm facility of the National Wind Resource Center (NWRC) of Texas Tech University (TTU) is focused on energy production of the entire farm, rather than on making single turbines more efficient. The question naturally arises as to whether such a study should be performed in a controlled wind tunnel or in the atmosphere that has realistic turbulence structure and density stratification, both of which produce atmospheric variability. In a wind tunnel, it is difficult to replicate the effects of stratification, roughness and Reynolds number [1, 2], and there are blockage effects to be considered for wind turbine arrays [3]. For simulations, experimental data is

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generally required to create an inlet profile for wind turbine arrays and to validate the solutions generated. The role of stratification, as well as the requirement to impose periodic boundary conditions, makes it difficult for simulations to reproduce real field conditions [4]. Consequently, physical mechanisms are poorly understood due to the unavailability of representative simulations and wind tunnel experiments [5,6]. The primary motive of constructing the subscale wind farm is to conduct cost effective tests on wind turbines with modified designs in short amount of time. Although, the dynamic similarity between the full and model scale will not be achieved dominant effect of atmospheric variables on turbine performance can be studied. Significant differences are expected in the near wake structure; however the far-wake flow is regarded to be similar to the full scale. These field studies compliment the wind tunnel and simulation studies since varying nature of atmospheric inflow and effect of stratification can be observed.

We will study the effects of varying inflow atmospheric conditions on wake characteristics and power output of successive rows of turbines. A major emphasis will be to explain the role of coherent structures on these.

Atmospheric stratification has an important effect on the output of wind farm and is particularly targeted here. Specifically, for stable stratification the loss in output has been attributed to the wakes defect being preserved for longer distances as compared to the neutral case [7]. The wake persistence during these conditions is explained by reduced momentum transport due to lower turbulence intensity. In addition to the effect of turbulence intensity, we emphasise that the buoyancy differences at the wake interface should be considered since they could have favourable or adverse effect on momentum transport depending on the stratification. As shown in Figure 1 for stable boundary layer inflow, buoyancy differences are created at interfaces of mixed layers formed by tip vortex, hub vortex and the swirl in the wake that has an adverse effect on transport across interfaces. It can be shown by mass balance that the interfacial buoyancy difference is proportional to the depth of the mixed layer, thus effecting momentum transport at the interface. Our goal is to quantify the effect of buoyancy differences on wake characteristics. In the case reported below abrupt changes in the temperature across the wake are observed, suggesting buoyancy differences at the wake interface.

In the subsequent section, a brief description of the experimental setup is presented for measurements of a single turbine wake. In the results section, observations regarding the wake defect, energy flux due to Reynolds stress, velocity-power correlations, and buoyancy differences (due to temperature) variations are presented.

Figure 1. Schematic showing the variations of density profiles (green) at three locations: upstream of the turbine, in the near wake, and in the far wake (wake illustration from [1]).
2. Site setup
The field site is located near level farmland with no significant structures obstructing the flow. The predominant wind direction to the site is from the south allowing the alignment of the wind farm in south-north direction (Figure 2). Meteorological towers instrumented with Campbell Scientific CSAT 3D sonic anemometers are placed at the inlet (south end) and the outlet (north end) of the site. A vertical rake of six evenly distributed anemometers was installed on the inlet tower to characterise the inflow boundary layer (heights given in Figure 3). At the downstream tower, a rake of five evenly spaced anemometers was installed at the location where the wake was expected. In addition, an anemometer was placed lower on the tower to capture the wind speed below the wake (Figure 3).

![Figure 2. Wind rose for site location from: a) West Texas Mesonet historical wind data close to the site, and b) measurements at the upstream tower, using three days of data.](image)

The sonic anemometers collected 3-component velocity and temperature data at 10 Hz. This sampling rate reasonably resolves the turbulence of the inflow. The measurement resolution of the sonic anemometers for velocity is 0.001 m/s for each component and temperature resolution is 0.025°C.

The initial setup had an Airbreeze model turbine of 1.17 m at 6.25 m hub height, aligned between the two met towers, as shown in Figure 3. The turbine is rated for 160 W (at 12.5 m/s), and has a typical angular velocity of 600 RPM, though it can go as fast as 1200 RPM. The tip speed ratio ($\lambda$) is 7 with a coefficient of power ($C_p$) of 0.25.

The turbine has been modified to collect instantaneous power and RPM data at 20 Hz. The data is transmitted via radio to a receiver connected to the data-logging computer. The Airbreeze turbine contains a 3-phase alternator with a permanent magnet rotor. A controlled 3-phase rectifier converts the 3-phase output voltage to DC and regulates the DC output current of the turbine, which is designed to charge a deep discharge rated lead acid battery. This controlled rectifier board provides no significant energy storage such that the instantaneous output power on the DC side is equal to the instantaneous mechanical drive power. In order to measure the electrical output power, an additional custom PCB with resistor divider circuit and a Hall Effect sensor were installed to measure the voltage and the current, respectively. The board also contains an optical sensor which is used to measure the angular velocity. In addition, the board holds a micro-controller for power and speed computation and data management as well as a GPS module for accurate time-stamping of the data. The data are conditionally sampled for winds aligned with the turbine and tower ($\pm 5^\circ$) and further classified for various atmospheric stability conditions from the measurements at the inflow tower. The data reported comprises of four 15 minute average periods taken between 16:45-17:45 Local Standard Time (LST).
The atmosphere in this case was neutrally stable, the flux Richardson number being close to 0 having values of -.037, -0.016, 0.094 and 0.28 for the 15 minute average periods.

3. Results

3.1. Wake defect and Reynolds stresses

Wind tunnel studies have shown that the velocity deficit at 6D is usually 0.6 times the original free stream velocity [8, 9]. However, our data (Figure 4a) indicates this value varies between 0.75 and 0.95. This is higher value is perhaps due to high momentum transport in the turbulent freestream. Additionally, a log-law profile using the velocity and the height of the hub as a reference is shown in Figure 4a. The normalization collapses the inflow data indicating typical atmospheric boundary layer inflow. Turbulence is observed to increase at the blade tips because of the shear layer created by the rotating blades, which in turn increases downward transport of momentum. This observation is consistent with the results presented by [10]. Figure 4(b) indicates that there is an enhanced turbulent transport of momentum, since Reynolds stress values are elevated compared to that of the inflow. The maximum value is nearly 1.5 at the outflow compared to 0.25 for the inflow. Figure 5 indicates the normalized energy flux produced by the Reynolds stress, \( \frac{\overline{U'u'w'}}{U_h^3} \). The higher flux at the top tip height as compared to the bottom tip indicates accumulation of downward transported mean kinetic energy into the wake region. This follows from the integral form of mean kinetic energy equation (MKE) where the flux values at top tip (lower limit) and bottom tip (upper limit) are limits for integration [10], a positive difference shown in this case indicates the accumulation of MKE. The flux is nearly equal to that reported by [11] (\( O(10^{-3}) \) at top tip and \( O(10^{-3}) \) at bottom) for downstream spacing of 5D. It was found in [4, 10, 11] that this energy flux contributes a significant portion of the power generated by the downstream turbine. Since the fluxes observed are similar to the earlier studies, a similar observation for power generated at the downstream turbine is expected at the field site.
Figure 4. Normalized values for a) inflow and outflow wind speed w.r.t. probe height, and b) Reynolds Stress w.r.t. probe height for both inflow and outflow. Symbols denote 15 min. average.

Figure 5. Normalized energy flux produced by Reynolds stresses at the downstream tower. Symbols denote 15 min. average.

3.2. Power-velocity correlation

As argued by [12, 13], coherent structures exist in the turbulent boundary layer that dominate the turbulent momentum transport process. Analysis of wind tunnel data by [14] showed that scales larger than 1D produce significant energy for the wind farm. They also showed that large-scale motions are highly inhomogeneous and more energetic than the small scales. Figure 6 demonstrates that there is strong correlation between turbine power output and the inflow, compared to the power output and the outflow. This observation motivates future analysis to verify if this correlation is indeed due to the presence of coherent structures having dimensions similar to that of a wind farm.

Figure 7 indicates that the ratio of rms fluctuations of power to the turbulence intensity is greater than 3. Since power is proportional to the cube of the wind speed, for very low turbulence intensity the higher order terms can be neglected which leads to the quantity shown in figure 7 to be equal to 3. However, the slightly greater numbers indicate that higher order terms may need consideration for turbines located in real atmosphere given the higher turbulence intensity.
3.3. Buoyancy effects

As discussed earlier, it is expected that the flow in the wake – consisting of the tip vortices, hub vortices, and swirl – will enhance mixing, leading to a mixed wake of constant density with buoyancy jump at its boundary. In the case of full-size turbines, it is expected that the mixing occurs at the tip and hub vortices, but the swirl does not contribute to the mixing. However, for model turbines such as the one at this site, the turbine RPM is high enough to produce significant swirl-dominated mixing, causing the density to be constant in the entire wake region.

Figure 8 depicts the normalized temperature field at the inflow and the outflow, which can be assumed to be a surrogate for density (assuming negligible pressure changes over the diameter of the turbine). The temperature close at both tips (outer dotted lines) is nearly equal, whereas the temperature at the hub and outside the wake follows the same trend as that of the inflow. Moreover, the temperature at the hub location is unaltered since the swirling effect in the wake is not experienced at the hub location due to the nearly stagnant fluid behind the large nacelle (~0.1D); the long-arm tail boom (~0.8D) further suppresses the rotation of nacelle wake. This leads to the reasonable conclusion that this fluid has the same temperature as that of the inflow fluid at the hub height. The difference between tip (top and bottom) and hub velocity direction in Figure 9, indicates tangential velocity of opposite direction at the top and bottom tip which is result of the wake swirl. The difference between hub height velocity direction and that outside of the wake is negligible, as expected.

Figure 6. Correlation between inflow velocity and power; also outflow velocity and power. Symbols denote 15 min. average.

Figure 7. Ratio of rms fluctuation of power to the inflow turbulence intensity. Symbols denote 15 min. average.

Figure 8. Inflow and outflow temperatures at hub height. Dotted lines indicate upper and lower tip. Symbols denote 15 min. average.

Figure 9. Difference between the tip and hub velocity directions at the outflow tower. Dotted lines indicate upper and lower tip. Symbols denote 15 min. average.
Conclusion
Field measurements in the wake of a model wind turbine at 6D are reported for neutral atmospheric stability conditions. For the inflow winds aligned with the streamwise direction of the apparatus, it is shown that there is an average velocity deficit of 25%. This wake defect (at 6D) is lower compared to previous studies, possibly due to the turbulence in the freestream. The Reynolds stress profiles for the same period show an increase in magnitude and gradient at the wake location, indicating substantial increase in turbulent transport of momentum in the downward direction, as compared to the undisturbed inflow boundary layer. This field observation is indeed consistent with those of the wind tunnel studies by [10, 11]. Additionally, ratio of power fluctuation to the inflow turbulence intensity is greater than 3.

Further, the effect of the turbine on the temperature field is observed. The swirl in the wake causes mixing of the inflow leading to a constant density profile in the wake. This phenomenon leads to density jumps at the wake interfaces for stratified inflow. During stable conditions, it will prevent momentum transport when compared to neutral cases. In unstable conditions, this would cause an enhancement of downward momentum transport, increasing the rate of wake defect recovery. In the case of the field site, the wake swirl is identified as the primary mechanism of mixing. In continuing experiments, a columnar array (3x1) will be performed to look at turbine interactions and the effects of atmospheric stratification.

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