Experimental Study of Turbulence Influence on Wind Turbine Performance

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ABSTRACT

Regarding the issue of unmatched Reynolds numbers for downscaled wind turbine tests in wind tunnels, a study of the performance characteristics of a model wind turbine operating in the wake of another turbine of the same model under laminar and turbulent inflow was performed. The distance between the two turbines was set at 5, 10, and 15 turbine diameters. In the laminar inflow case, the wake of the front turbine reduced the efficiency of the rare turbine greatly even when the distance was 15 diameters. This was due to slow velocity recovery in the low Reynolds number wake. To solve this issue, turbulent inflow is created using an active grid system installed between the contraction and test-section of the wind tunnel; the maximum turbulence intensity can reach 20%. Velocity fields upstream and in the wake of the turbine were measured using a 2D-PIV system; 1000 pairs of images were acquired for each location to achieve statistical convergence. It was found that by using turbulent inflow the efficiency of both the upstream and the downstream turbine was highly improved. Flow separation in the suction side the wind turbine blade was studied using PIV under laminar and turbulent flow for a single turbine, and it was found that the wind turbine efficiency was directly related to this phenomena since the laminar case presented more flow separation. It was also found that the efficiency of both turbines is highly related to the turbulence intensity in the inflow. At a constant tip speed ratio for the upstream turbine, the efficiency for the downstream turbine was 4.1 times higher than in laminar case when two turbines are separated by 5 diameters; for 10 and 15 diameters with the same conditions it was 2.71, and 2.48 times higher respectively. The maximum efficiencies reached for the downstream turbine were 38.5%, 34.5%, and 24.6% for 15, 10, and 5 diameters of distance respectively, this results is close to the design power coefficient. Therefore, despite the low Reynolds number a realistic flow similar to the field can be reached using turbulent flow created by an active grid system.

INTRODUCTION

Wind tunnel tests of wind turbines are still preferred to field tests where the incoming flow is much more difficult to describe in sufficient detail and simulations are very time-consuming as a result of the characteristics of the wind [1]. But, as mentioned by Giacomo [2] the use of downscaled models represent a limitation due to discrepancies with respect to real wind turbine flows. The major reason is that the lower Reynolds number, due to downscaled model, creates differences in the boundary layer flows over the suction side of the blades and generates laminar separation bubbles on the blades [3]. The Laminar separation bubble is a phenomenon associated with low Reynolds numbers. Laminar flow separates from the blade before it can transition to turbulent flow as a result of an adverse pressure gradient. This leads to an increased the boundary layer thickness,causes excessive increase in pressure drag, loss in aerodynamic lift,performance, and noise [1]. Despite a considerable number of research activities, there are still issues involving the lower Reynolds numbers reproduced in wind tunnel tests, as well as uncertainties associated with turbulence in turbine simulations. For instance, Alfredsson [4] reported a lower power coefficient for downscaled wind turbine models.

In this research, influences of inflow turbulence intensity to the wind turbine performances and wake recovery were evaluated. An experimental study of the performance characteristics of a model wind turbine operating in the wake of another turbine of the same model using both laminar and turbulent flow was performed. The distance between the two turbines was set at 5, 10, and 15 turbine diameters. The effect of turbulence intensity on the performance of the downstream turbine, the wake, and the flow separation on the wind turbine blades was studied. It was found that the reduction in the maximum power coefficient of the downstream turbine is strongly dependent on the turbulence intensity, distance between the turbines, and the tip speed ratio of the upstream turbine. These findings agree with the studies of Krogstad [5], Souma [6], and Measa [7]. In addition, at a given distance, the amount of area overlap between the upstream and downstream turbine will also affect the performance of the downstream turbine (Medici and Alfredsson [8], Kotb and Soliman [9], B. Sanderse [10], and Sittichoke Pookpunt and Weerakorn Ongsakul [11]). Also, the minimum of the downstream turbine was obtained when the upstream turbine was operated at its peak efficiency, due to lower kinetic energy in the wake of the upstream turbine (Adaramola [5]). However, among this research it was found that there is a much bigger factor that influence the performance of the downstream turbine, which is the type of flow: turbulent or laminar. Significant increments in efficiency were found while using turbulent inflow created by an active grid system.

EXPERIMENT SET UP

Wind tunnel

All the experiments for this research were performed in a low-speed wind tunnel shown in figure 1. The wind tunnel has an intake section if 4m by 4m, and a testing section o1.4m (W) x 1.4m (H) x 14.6m (L) long; maximum speed in the test section can reach 45m/s. For turbulent flow case, wind turbines were installed in the last test section, which is approximately 11.5m from the contraction; and the wind turbines were installed immediately downstream the contraction for laminar flow cases.

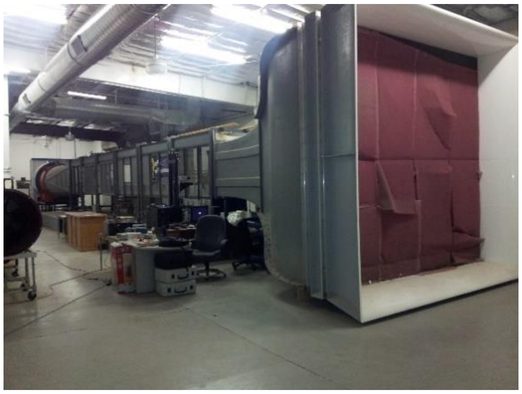

Figure 1. Wind tunnel of the college of engineering of New Mexico State University.

Active grid system

Active grid system (AGS), first introduced by Makita and Sassa [12], is capable of generating turbulent flow with high turbulence intensity in relatively small facilities. Following the same concept a similar system was built and installed in the low speed wind tunnel between the contraction and test section. The system allows the wind tunnel to create arbitrary velocity profile with controllable turbulence intensity. This system was built to generate turbulent inflow conditions similar to the atmospheric boundary layer. The purpose of the AGS is to find a solution for the wind turbine scaling issues, e.g. Reynolds number scaling, since the Reynolds number in a wind tunnel test is 2-3 orders of magnitude lower than that in the field.

The AGS was installed in the wind tunnel between the contraction and the test section. It had 6 vertical and 6 horizontal shafts with flaps mounted onto them; all the shafts were driven by programmable stepper motors. A Matlab program was developed to control the motors. In this manner, a variety of turbulent flows were generated to resemble the flow in atmospheric boundary layer.

Figure 2. Active Grid System

In order to create the desired velocity profile the first three horizontal shafts were set at 18°, 36°, and 54°, respectively as shown in figure 3 from a side view perpendicular to the flow. The vertical shafts were at 0° with respect the flow. The detailed velocity profile is presented in *Turbulent Boundary Layer.*

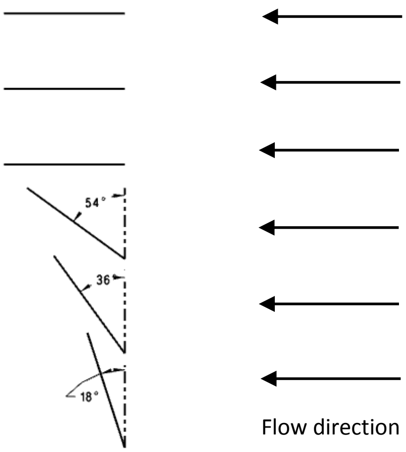

Figure 3. Active grid system setup to create the desired boundary layer. The first three rows of flaps were angled at 18°, 36°, and 54° respectively.

Wind Turbines

The scaled two-blade wind turbines used in this experiment had a diameter of 8 inches. Each turbine was mounted on a 480 DD motor of 8.4 volts utilized as a generator. The experiments were conducted using two scaled wind turbines aligned with the flow, as shown in figure 4. The purpose of this was to investigate the influence of a wind turbine operating in the wake of another turbine operating at various distances between them. Also, different types of flow were used, laminar flow, and turbulent flow.

Figure 4. Wind Turbines in array with 10 diameters of distance between them.

For the laminar inflow case, wind turbines were installed in the first section of the wind tunnel with the AGS removed. At this section, because it was immediately following the contraction, the flow was uniform and had a very low turbulence intensity. On the other hand, for the turbulent cases, the measurements were performed at the last section of the wind tunnel, over ten meters away from the AGS to allow big flow structures generated by the AGS to dissipate. A turbulent boundary was designed in order to mimic the wind turbine-atmospheric boundary layer relationship in the field, details are explained below.

PIV System

A 2D particle image velocimetry (PIV) system was used to experimentally obtain the velocity profile in the boundary layer and downstream the wind turbines. This system is composed of a Quantel dual-cavity Nd-YAG laser (532 nm wavelength); a high sensitivity CCD camera (Sensicam QE, PCO images, Germany); a computer to acquire particle images and process the data, and a timing box (IDT, Inc.) to synchronize the camera, laser, and the computer. The laser sheet was generated using a spherical lens and a cylindrical lens; a mirror inclined at 45° was used direct the laser sheet to the region of interest. The integrated experimental system is illustrated in figure 5.

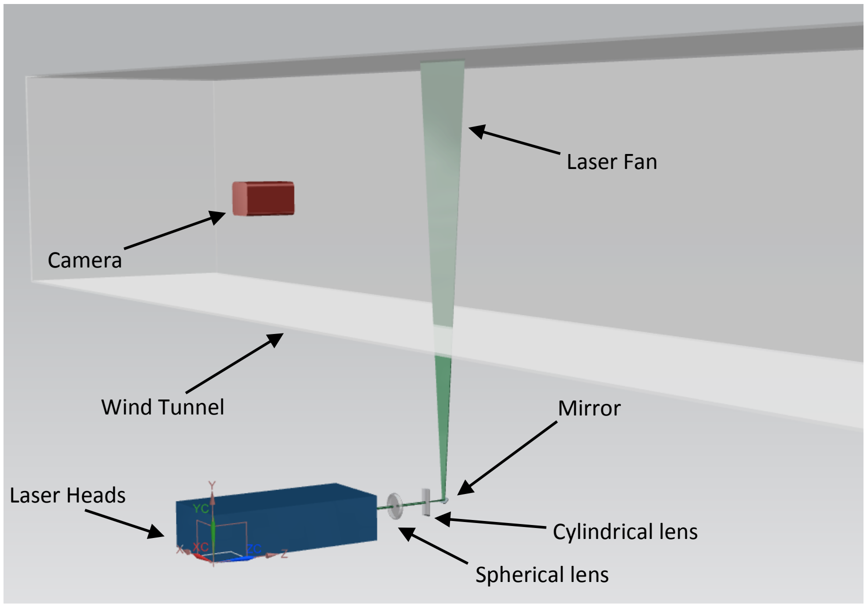

Figure 5. PIV experiment setup

The flow was seeded using olive oil droplets generated by Laskin nozzles. The mean diameter of these particles was approximately 1 µm. 1000 pairs of images were acquired at each region of interest to achieve statistical convergence. tThe bottom and side walls of the tunnel were transparent to allow optical access.

When measuring flow separation in the suction side of the blade, the laser sheet cuts through the cross-section of the blade while the wind turbine was spinning, as shown in figure 6. Using a photoelectric laser sensor (42EF Laser Sight) and a diode laser beam passing through the wind turbine, a trigger signal was created every time one of the blades touched the laser beam. This signal was used to trigger the PIV system and calculate the angular speed of the wind turbine. 1000 particle image pairs were acquired with the blade located at the same angular position. The wind turbine can spin as fast as 300 RPS, an Arduino uno was programed to divide the triggering signal to a few Hz to accommodate the PIV acquisition rate. In all PIV measurements, the time intervals between the two laser pulses were adjusted so that the maximum displacement was close to but less than 6 pixels.

PIVPROC software (Provided by NASA) was used to process the particle images and acquire the velocity data. FFT bases cross-correlation method was used to calculate the velocity. For the flow separation measurement, the interrogation was 16x32 pixels with 50% overlap. The background image was subtracted from the particle images to remove the effect of boundary glare. Interrogation windows were 32x32 pixels for the experiments on the wind turbine's wake.

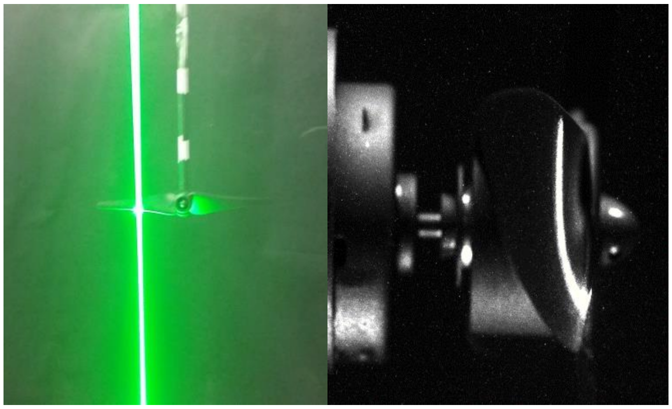
(a) (b)

Figure 6. PIV setup to measure flow separation on the suction side of wind turbine blade a) front view of the fan laser and wind turbine, b) PIV picture of a side view of the cross sectional wind turbine test area.

There were three main sources of error which could bring uncertainty to the velocity results, calibration uncertainty for pixel magnification, uncertainty due to the cross-correlation algorithm, and the calculation of the mean velocity from the turbulent velocity fields (convergence). Based on PIV uncertainty analysis provided by Shu [20], the total uncertainty of velocity was less than 2.5% and the uncertainty of the measured turbulence intensity was less than 4.5% of the maximum turbulence intensity.

Turbulent Boundary Layer

Wind turbines in wind farms always operate in the Atmospheric Boundary Layer (ABL) which is the lowest part of the atmosphere. Since it is very close to the Earth's surface, it is directly affected by the frictional and viscous effects of the ground. It is important to know how a turbine interacts with the atmospheric boundary layer [13]. According to Salih et al. [14], mechanical and electrical performances of wind turbines are highly affected by wind characteristics. These affects have to be considered during the analysis of wind turbine performance.

According to Anderson [19], the atmospheric boundary layer at sea level is around 300 m; that means all the wind turbines are influenced by the ABL. By programming the AGS, a turbulent boundary layer flow was generated to mimic the ABL. In this experiment, a turbulent boundary layer was scaled down to a boundary layer thickness of approximately 0.6 m (figure 7), according to scaling ratio of the model wind turbine. The velocity profile is also shown in the same figure. This thickness was considerably larger than the fully developed boundary layer experimented by Klebanoff [15], and larger than the atmospheric boundary layer thickness in a wind tunnel experiment by Makita and Sekishita [16] that used a turbulent active grid as well, having a value of 0.4 m. The inflow turbulence intensity was approximately 17.4% at the center of turbine. This boundary layer was used only for the influence of turbulence intensity to wind turbine array experiment explained below.

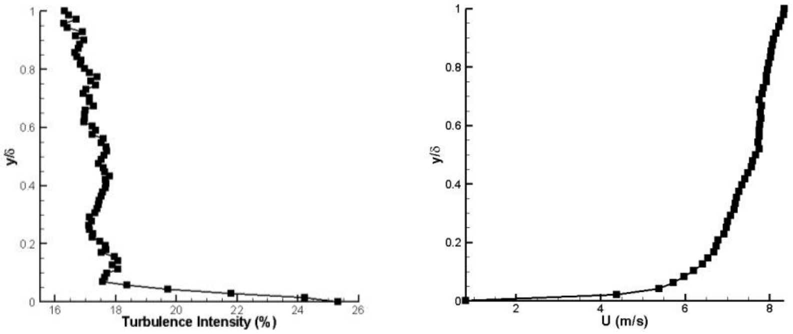

Figure 7. Designed boundary layer properties. Turbulence intensity and velocity profile with respect height.

Power Coefficient Measurements

Power generation of the turbine was calculated as a product of the shaft torque and angular speed. Torque measurements were conducted to study the wind turbines efficiency and determine the optimal tip speed ratio (λ). In this study, a torque sensor (NANO 7 IP68) adapted to the wind turbine (Figure 8) was used to measure the torque and consequently the power coefficient of the wind turbine using equation 1.

Equation 1

Where,

= Power coefficient

= Shaft torque ( )

= Angular speed of the turbine ( )

= Radius of the wind turbine ( )

= Density of the air ( )

= Free stream speed ( )

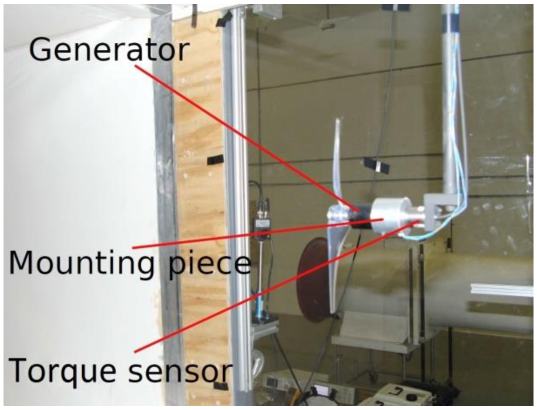

Figure 8. Torque sensor mounted onto the winter turbine

The tip speed ratio (λ) is the speed of the blade at its tip divided by the speed of the wind as shown in equation 2, where is the radius. The optimal tip speed ratio, where the maximum efficiency is found, is provided by the equation 3 [18], where is the number of blades the wind turbine has. For this experiment the optimal tip speed ratio should be around 2 .

Equation 2

Equation 3

In this experiment, the turbine speed was controlled by using an adjustable load resistance connected to the generator. When the load resistance decreases, greater torque is required to rotate the generator, i.e. the turbine speed becomes slower with decreasing resistance. When the circuit is open, the motor rotates with the minimum torque, thus maximum speed.

RESULTS

Turbulence intensity influence to of a single turbine.

Using a torque sensor mounted onto the wind turbine the total power harvested from the flow was measured. This power was non-dimensionalized as (coefficient of power), which was used to determine the wind turbine's performance. Laminar and turbulent inflow, with a turbulence of 10% for the turbulent case, were used to make a comparison on the performance. In figure 9 the results for the vs. the tip speed ratio are shown having a performance 3 times bigger using turbulent inflow.

One of the reasons the wind turbine performance decreases under laminar inflow is the flow separation around the wind turbine blades from the suction side of it. Therefore an experiment was performed to study this phenomenon using the same PIV technique used before. The same inflow characteristics as the previous experiment were used. Using a trigger signal, 1000 pictures were taken on the blade side view as shown in figure 6 where the flow around the blade can be observed. The experiment was performed using a single wind turbine at a tip speed ratio of 5.4 for both cases. It was found that the flow separation on the blades is directly related to the wind turbine performance, the more flow separation the bigger drop in the performance. It was found that using laminar inflow the flow separation was enhanced, this was the reason for lower in laminar inflow conditions. As shown in figure 10, in the laminar case the over 50% percent of the blade was covered by the separation bubble, while for the turbulent case it was approximately 25%.

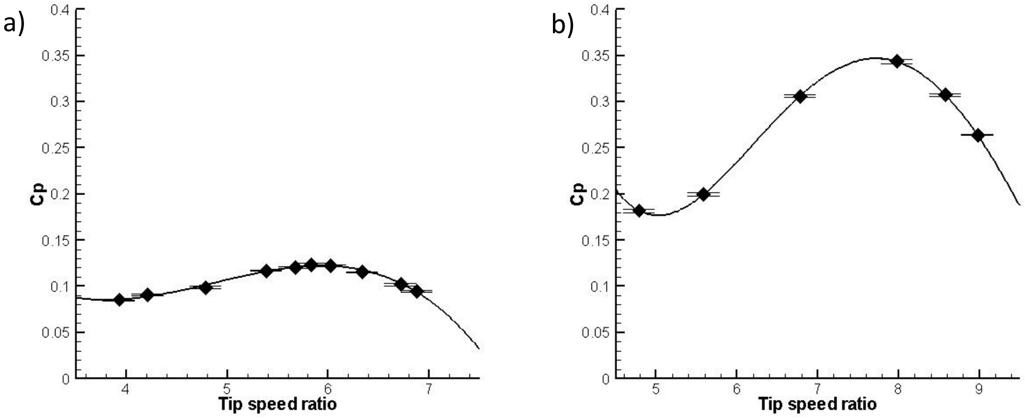

Figure 9. C_p vs. tip speed ratio for (a) laminar and (b) turbulent case for a single turbine.

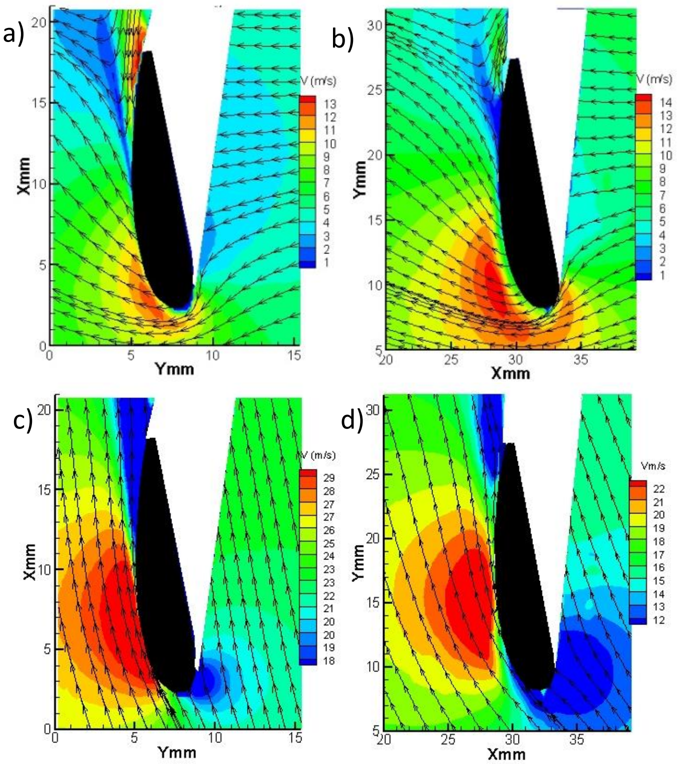

Figure 10. Flow separation around the wind turbine blade. (a) and (b) show the shown the velocity field in global coordinate system for laminar and turbulent inflow cases, respectively. (c) and (d) represent the velocity field relative to the blade for laminar and turbulent inflow cases. The tip speed ratios were 5.4 for both cases.

Influence of turbulence intensity to wind turbine array

Using a torque sensor mounted onto the wind turbine as in the last subsection the total power harvested from the flow was measured.

These experiments were conducted with one turbine in the wake of another turbine under laminar and turbulent inflow conditions. In the turbulent inflow case, the turbulence intensity was 10%. A constant inflow velocity was used, 15 m/s for the laminar case, and 8 m/s for the turbulent case. The uncertainty for this experiment on each data point taken is not bigger than 3%.Two variables were controlled in the experiment: the tip-speed-ratio and the distance between the two turbines, e.g. 5, 10 and 15 diameters (for both laminar and turbulent cases). For the laminar case, tip speed ratios range from 5.6 to 8.9; and for the turbulent case it ranges from 4.7 to 10.9. For both laminar and turbulent inflow cases, the upstream turbine was operated at various tip-speed-ratios with a range of 4-10, and torque measurements were performed at the downstream wind turbine. A vs. tip speed ratio was presented for the downstream wind turbine for each one of the upstream wind turbine velocities. In figure 11, some results for the downstream wind turbine are shown for laminar and turbulent flow, using 5, 10 and 15 diameters between turbine and turbine. The upstream wind turbine tip speed ratio was set at 6.78 for turbulent flow, and 5.6 for laminar flow.

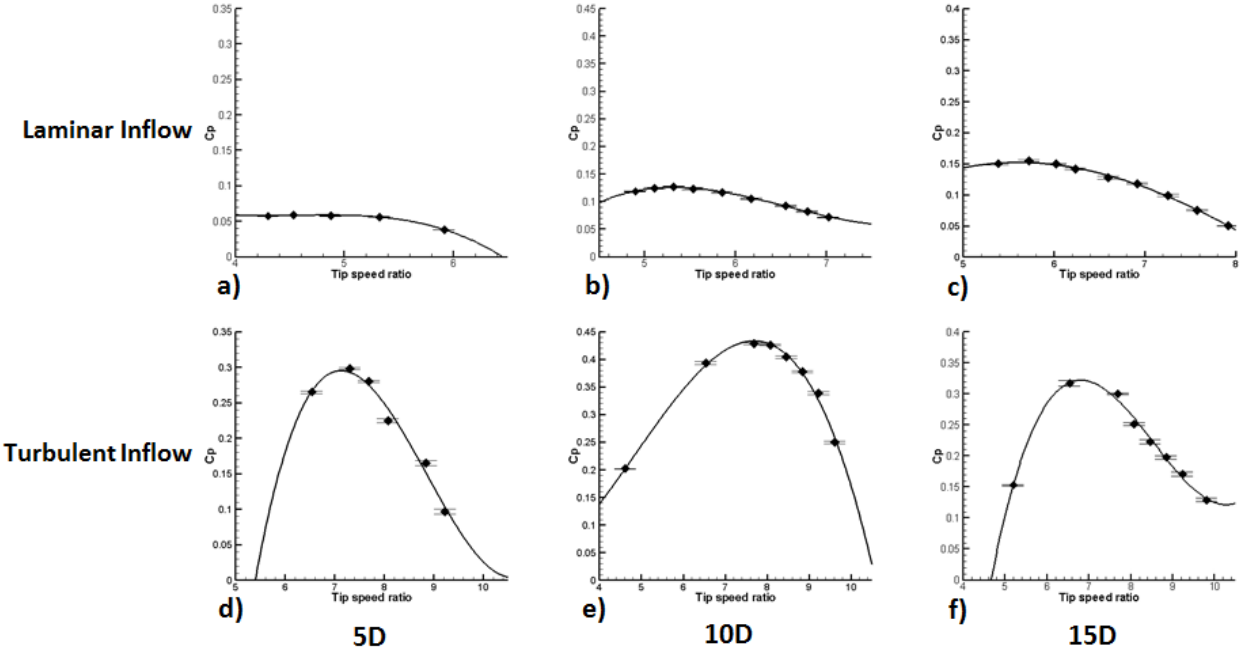

Figure 11. Downstream wind turbine coefficient of power versus tip speed ratio relationship for a) 5 diameters, laminar flow, b) 5 diameters, turbulent flow, c) 10 diameters, laminar flow, d) 10 diameters, turbulent flow, e) 15 diameters, laminar flow, f) 15 diameters, turbulent flow. Upstream turbine's TSR is 5.6 for laminar inflow, and 6.78 for turbulent inflow.

A large difference in the efficiency can be seen under laminar and turbulent flow. For the 5 diameters case the maximum efficiency was 5 times higher under turbulent flow. For 10 and 15 diameters it was 3.3 and 2 times higher respectively. The maximum efficiencies reached for the downstream turbine were 30%, 42.8%, and 31.6% for 15D, 10D, and 5D cases, respectively. It was apparent that the reduction in the maximum power coefficient of the downstream turbine was strongly dependent on the distance between the turbines.

The efficiency of the downstream turbine was much higher in the turbulent inflow case mainly because of two reasons. First, wind turbines have greater efficiency under turbulent inflow due to suppressed flow separation in the suction side of the blade, which has been discussed in the previous subsection. Another reason is that the wake recovers faster for turbulent shear flow compared to laminar shear flow. Adaramola and Krogstad [6] found out the importance of the turbulent mixing mechanism in the wake of the upstream turbine in order to increase the rate of wake recovery.

Influence of turbulence intensity to wake recovery

For a better understanding of the wind turbine performance increment with turbulent flow, PIV measurement were taken upstream and in the wake of the wind turbines. Only the results for the 10 diameter cases were presented for brevity purpose. Four sections in the center plan of the two turbines were measured with 2D PIV system, for each section 1000 pairs of images were acquired to achieve statistical convergence. The locations of the four sections are shown in figure 12. These locations were chosen to study the flow recovery downstream the turbines.

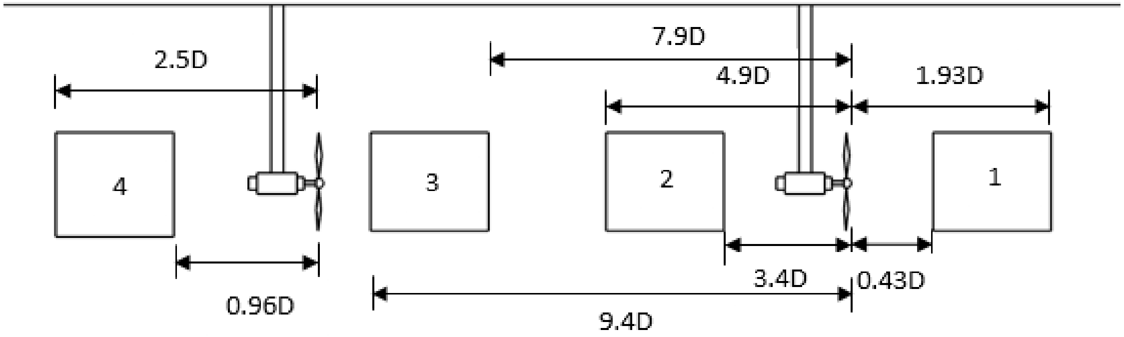

Figure 12. Schematics of PIV measurement windows.

To investigate the influence of turbulence intensity, the PIV measurements were performed using a high turbulence intensity (10%) and a low turbulence intensity (3%). The low turbulence intensity was created by fixing all the flaps parallel to the flow, where even though the grid did not spin, the shafts created some disturbance to the flow and the turbulence intensity was approximately 3% upstream the first turbine (Section 1) as shown in figure 15b. The high turbulence intensity was created by setting the flaps parallel to the flow but in this case they were oscillating at a constant angle with a frequency of 2 Hz and an amplitude of 30°, creating more disturbance in the flow and reaching approximately 10% of turbulence intensity upstream the first turbine as shown in figure 15a.

In figure 14, the velocity contour in the four sections for both turbulence intensities were presented. These velocity contours were normalized using the free stream velocity measured at section 1. For the high and low turbulence intensities cases the maximum free stream velocity was 13m/s and 13.8m/s respectively. As shown in figure 14(a) and (b), the velocity was approximately constant upstream the first turbine, in figure 13(a) the same velocity is represented at a constant x distance (x/d=0.93 from first turbine). In section 2, the turbulence intensities were elevated for both initial conditions after flow passed though the turbine (figures 15c and 15d). In section 3, the turbulence intensities decreased due to dissipation (figures 15e and 15f). When comparing the velocity profile in sections 2 and 3, it was clear that the flow recovered much faster for the higher turbulence intensity case (Figure 13(b) and (c)). With incoming turbulence intensity of 10%, flow in the wake of the upstream turbine almost fully recovered within 10 diameters. Results in section 4 indicated that turbulence intensity was similar for both cases which was around 30% as shown in figures 15(g) and (h). The velocity profiles are similar as well as shown in figures 14(g), (h), and 12(d). This was because high turbulence intensity had helped the wake to recover fast for both cases. Hence, the turbulence intensity of the inflow (initial turbulence intensity) does not affect the flow downstream the second turbine as great as it does for the flow downstream of the first turbine.

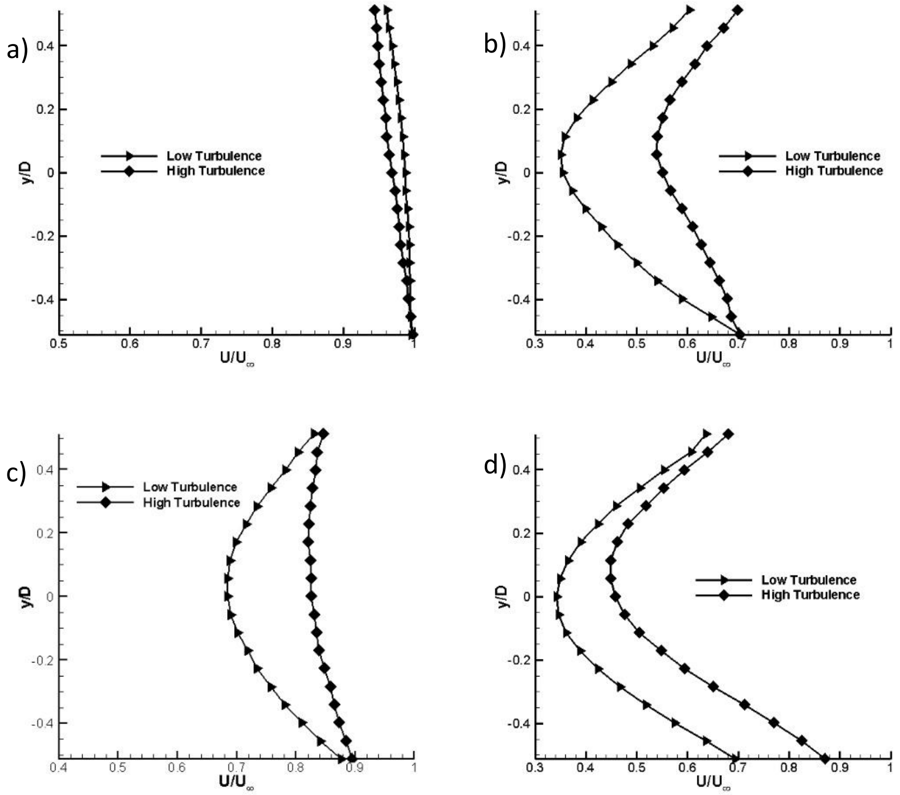

Figure 13. Normalized velocity profile for a constant distance x at: a) Section 1 (x/d=0.93 from first turbine), b) Section 2 (x/d=3.65 from first turbine), c) Section 3 (x/d=8.4 from first turbine), d) Section 4 (x/d=1.46 from second turbine)

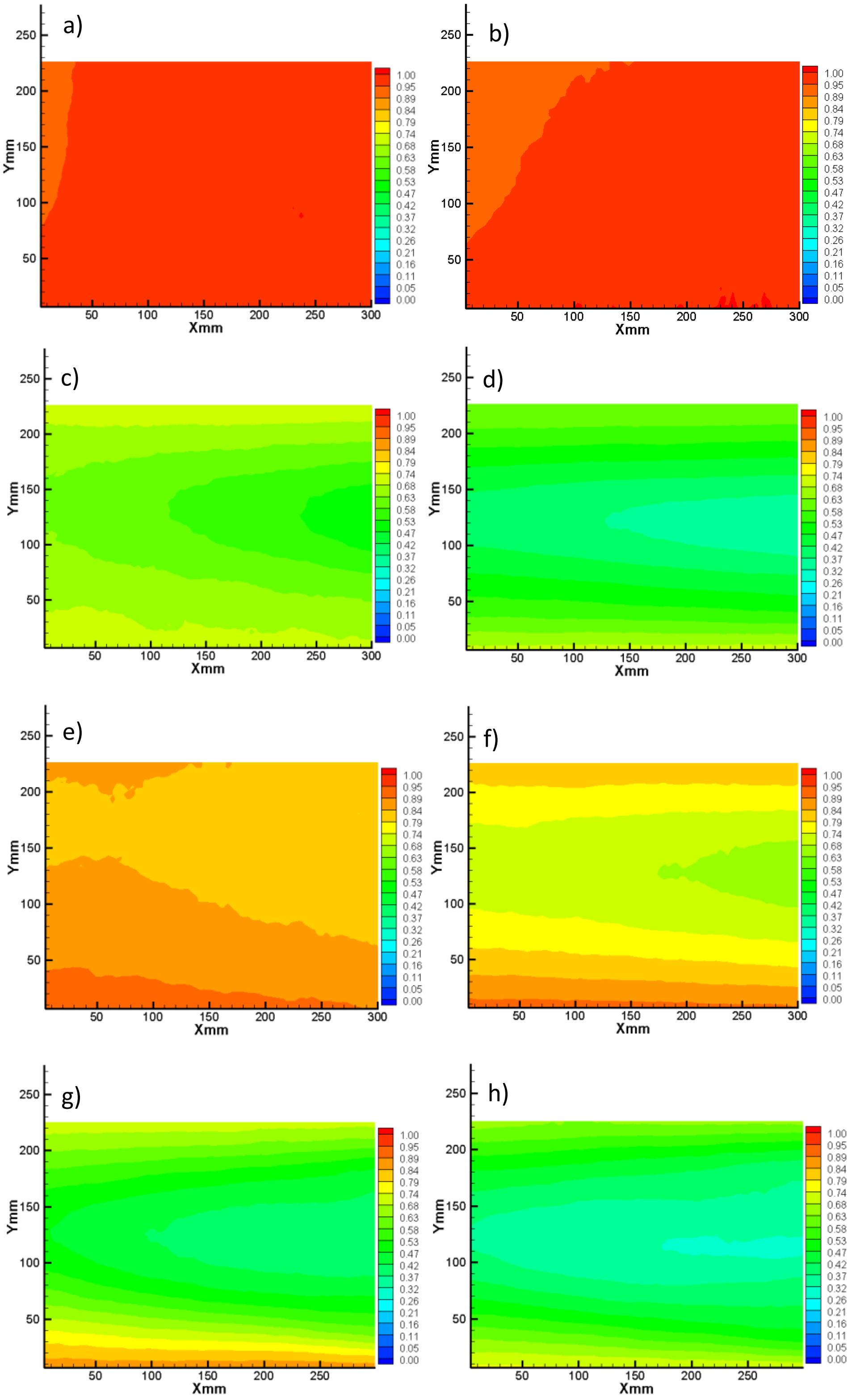

Figure 14. Normalized velocity contour for the following cases: a) Section 1 high turbulence, b) Section 1 low turbulence, c) Section 2 high turbulence, d) Section 2 low turbulence Section 2, e) Section 3 high turbulence, f) Section 3 low turbulence, g) Section 4 high turbulence, h) Section 4 low turbulence

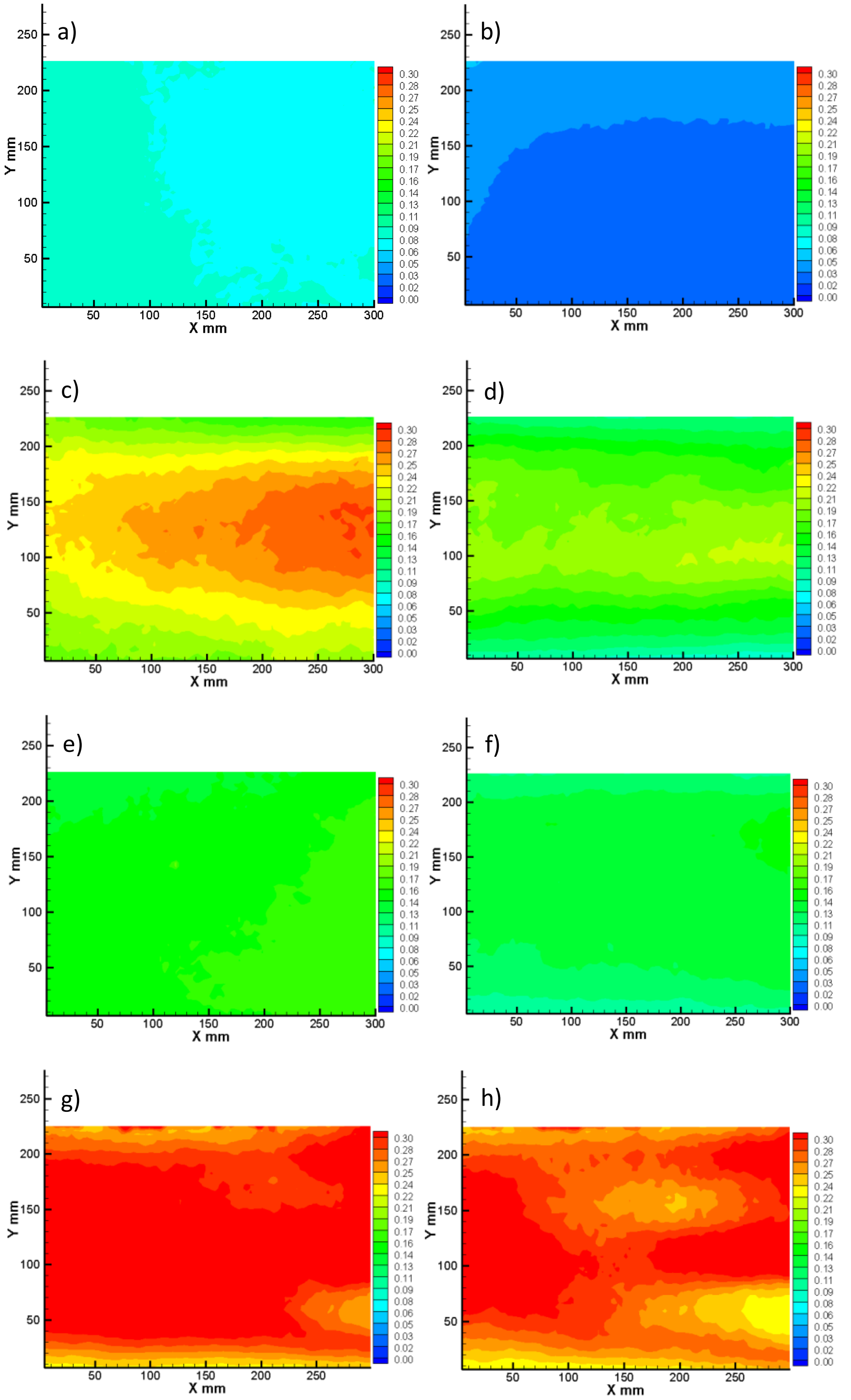

Figure 15. Turbulence intensity for the following cases: a) Section 1 high turbulence, b) Section 1 low turbulence, c) Section 2 high turbulence, d) Section 2 low turbulence Section 2, e) Section 3 high turbulence, f) Section 3 low turbulence, g) Section 4 high turbulence, h) Section 4 low turbulence

CONCLUSIONS

An experimental investigation was performed in order to find a solution regarding the issue of unmatched Reynolds numbers for downscaled wind turbine tests in wind tunnels. A wind turbine was tested operating in the wake of another turbine under laminar and turbulent inflow with various separation distances. In this study, turbulent inflow was generated with an active grid system. It was found that the efficiency of both turbines were highly dependent on inflow turbulence intensity. More realistic power coefficient efficiency was obtained under turbulent inflow in a wind tunnel. PIV results confirmed flow separation in the suction side of the blade when the inflow was laminar. Also PIV measurements were taken in the wake of both wind turbines and it was concluded that the flow recovery in the wake downstream the first wind turbine highly depends on the turbulence intensity in the inflow. For a higher turbulence intensity, a faster velocity recovery was detected. It was also found that the flow downstream of the second turbine was almost independent of the initial turbulence intensity. At this section the flow had a high turbulence intensity therefore, the initial turbulence intensity was not very important. As a conclusion, when testing wind turbines in wind tunnel, turbulence intensity of the inflow should be carefully controlled to counteract the influence of unmatched Reynolds numbers. Using of AGS could be an effective way to generate controllable turbulence intensity and get realistic wind turbine test results in wind tunnels.

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