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Parameter study of power production in wind farms - experimental investigation of interaction of two wind turbines in tandem array

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Master's Thesis
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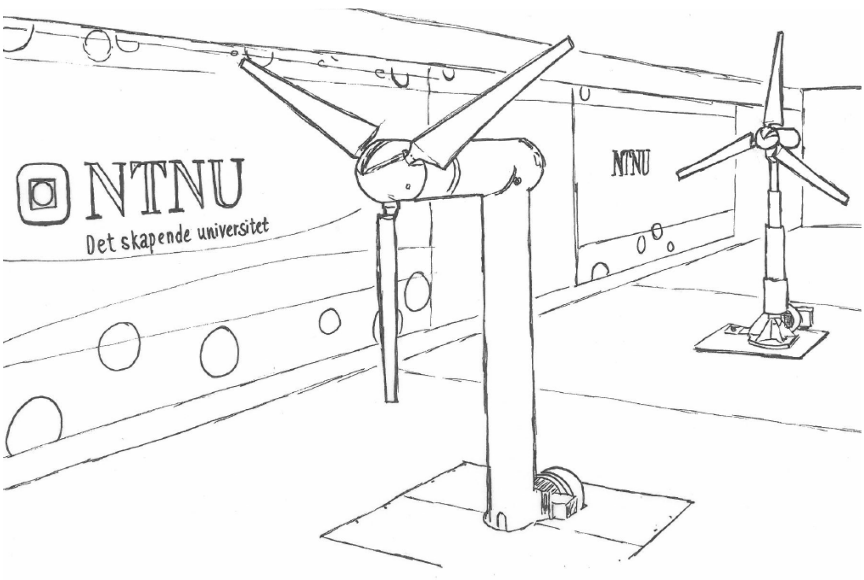

Master Thesis

Supervisor: Professor Lars Roar Sætran

Department of Energy and Process Engineering
NTNU Trondheim

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MASTER THESIS

for

Piotr Wiklak

Spring 2014

Parameter study of electric power production in wind farms –experiments using two model scale wind turbines

Parameterstudie av elektrisk effekt-produksjon i vindparker –eksperimenter hvor det benyttes to modellskala vindturbiner

Background and objective

The maximum power rating of wind turbines (WTs) is nowadays around 5 - 8 MW. The current value of rated power of individual WTs, along with the increase in the capacity of the wind power plants (especially in the case of offshore facilities) requires the installation of a large number of turbines in a relatively small area: a 1 GW wind farm (WF) would need 200 WTs of 5 MW. Under these circumstances, the wake effect plays a key role when evaluating the energy production of a WF, since the energy captured by a WT leads to a decrease of the wind speed downstream. As a result, WTs located downstream produce less energy than if they were in air free-flow. In the case of onshore WFs, the energy losses due to the wake effect constitute about 5 - 10% of the production [1], while in offshore WFs, the wake effect losses can reach higher values; approximately 15% [2]. This increase results from the higher degree of compactness (number of turbines per unit area) of offshore wind farms due to their high implementation costs. During the design stage of a wind farm, and in order to increase the WF production (by reducing wind speed deficits or wake effect losses), it would be desirable to separate the WTs as far as possible. However, due to constraints such as surface availability and cost of electrical connections and the total cost of electrical losses over the lifespan of the installation [3], [4], the maximum distance between WTs is limited. Consequently, the general rule when deciding the layout of WTs is to locate the WTs as far away from each other as possible according to the prevailing wind directions. However, not even in the case of prevailing wind directions it is possible to completely prevent wake-effect losses. Furthermore, these wake losses are higher for the remaining wind directions due to the shorter distance between WTs according to these directions. Although the power production of the wind farm for non-prevailing wind directions is less, its frequency means that the annual amount of energy generated for these wind directions remains significant.

The usual operating mode of each WT in a wind farm is to set the pitch angle and the tip speed ratio so that the WT strives to capture the maximum aerodynamic power available from the air inflow at the position of each WT. This means that every WT operates with the maximum power coefficient when the wind speed is lower than the rated wind speed, or operates at rated power for higher wind speeds. However, in a WT cluster, this operating mode is not optimum in terms of the overall production (aerodynamic efficiency) of the WF, because the energy captured by each WT decreases the aerodynamic power available to other downwind turbines due the wake effect. Therefore, it might be possible to find an optimal operation strategy by individually controlling the setup of each WT so that the overall wake effect losses (speed deficits) are minimized and, as a consequence, the power production of the plant is maximized.

The concept of individual control power of WTs was initially suggested by Steinbuch et al. [5] by selecting the tip speed ratio of each wind turbine by means of trial and error. However, according to the conclusion presented by the authors, the increase in the output power obtained by this method was insignificant. In 2004, Corten and Schaak [6] presented experimental results showing the possibility of increasing the power generated and of reducing the loads by individually selecting the tip speed ratio of each wind turbine. In early 2011, Larsen et al. [7] presented the technical report corresponding to the TOPFARM project which deals with optimal topology design and control of wind farms. That study showed that it is possible to increase the overall efficiency of a WF through the individual control of the generated power by each WT, however no further details are provided on how this control can be implemented or what the degree of the production improvement would be. In 2011, Madjidian and Rantzer [8] proposed the control of the power generated by the WTs in order to increase the overall efficiency corresponding to a row of wind turbines. With the purpose of evaluating the wake effect, the authors suggested a recursive model dependent on the thrust coefficient of the WTs. Through this wake model, the authors proposed a global control of the wind farm by using the same set point for all WTs. In 2012, Lee et al. [9] , presented a strategy of individual control of each of the WTs by optimizing the pitch angle of each turbine by means of a genetic algorithm, and used a wake model based on the eddy viscosity model. In that study, the authors considered the case of a row of wind turbines and achieved an improvement in the aerodynamic power of 4.5% with regard to the conventional operating strategy (COS).

The following tasks are to be considered:

For the development of theoretical simulation models for control of individual WTs in a WF it is necessary to calibrate the model with experimental results of good quality. For full-scale WFs there is difficult to find documented experimental cases where all necessary parameters are controlled and measured. Therefore, one can use model scale experiments as benchmark cases. For this work we propose to do experiments using the wind tunnel and the 2 model WTs at the EPT department. The main goal is to find criteria for optimum total power production for this "2-WT-WF". Parameters to be varied can be: Tip Speed Ratio for both WTs, separation distance between the WTs, turbulence level in the incoming wind, shear in the incoming wind, yaw angle of the WTs, pitch angle of the rotor blades, etc.

This is an ongoing research program at our department [10], [11], [12], and the student is supposed to both work in a team with other students and to do individual experiments. The experimental results obtained will be part of a data bank, and the student will choose parameters and results that shall be analyzed in detail.

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[12] Krogstad P-Å., Sætran L.R. and Adaramola S. J Fluids and Structure 2014 (accepted)

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

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☑ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. August 2014

Olav Bolland	Lars Sætran
Department Head	Academic Supervisor

Research Advisor: Jan Bartl

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- **Pål Egil Eriksen** – PhD candidate at Norwegian University of Science and Technology,
- **Andrea Spiga** – Master student at Universitá Politecnica delle Marche in Ancona (Italy),
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Preface

All this effort was possible thanks to the **Norway Grants** the scholarship and training fund entitles: *Mobility projects in higher education*.

Following master thesis has been performed at Department of Energy and Process Engineering, the Faculty of Engineering Science and Technology at Norwegian University of Science and Technology (NTNU) in Trondheim.

Presented data was made as the 4th part of an on-going research program at Department of Energy and Process Engineering called "the Blind Test". This research program was created to verify the accuracy and causing development of the existing algorithms designed to predicted the performance and wake development for operating turbines

Abstract

During the last decades, given rapid growth wind turbines and wind farms increase in numbers, becoming one of the most promising renewable energy technologies to supply the greenhouse-gas-free electricity. Currently, the main task is to get the highest power value for a single wind turbine and to achieve the highest efficiency of entire wind farm.

Computer simulations has become one of the most important tools in the planning of wind farms, but still with imperfect algorithms require continuous improvements and verifications.

This paper includes the documentation from wind tunnel investigations carried out to create the experimental data as a reference against numerical calculations in the approaching 4th Blind Test challenge: NTNU's ongoing program focused on benchmark of calculating models for wind turbine wake and efficiency prediction.

The main goal of this experimental study was to find criteria for optimum total power productions of a tandem array of turbines in a "small" wind farm. Experiment included testing of two models of wind turbines (HAWT) in scale, each one with 0.9 m of rotor diameter. During tests turbine models were coaxial and were tested with 3 different relative distances, separating them denoted as 3D, 5D, and 9D, where D is rotor diameter. Working conditions also were varied by changing the Tip Speed Ratio (TSR) of both turbines and the turbulence intensity of the incoming wind. A hot wire probe was used to scan the velocity field between the model turbines in a defined positions to characterize velocity deficit and the level of the turbulence in disturbed flow.

Keywords: HAWT, wind turbine, tandem array, wake, blind test

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Nomenclature

Symbols

A	Rotor Swept Area [m^2]
C_p	Power Coefficient [-]
C_t	Thrust Coefficient [-]
D	Rotor Diameter [mm]
M	Mesh size (sidewall single square)[m]
R	Rotor radius [mm]
T	Torque [Nm]
T_1	First (upstream) model wind turbine
T_2	Second (downstream) model wind turbine
T_I	Turbulence Intensity [%]
U_{ref}	Reference velocity [m/s]
u	Local velocity [m/s]

Greek letters:

ω	Angular Velocity [rad/s]
ρ	Density [kg/m^3]

Abbreviations:

Max	Maximum
Min	Minimum
RPM	Revolutions Per Minute [-]
S/D	Separation distance/ rotor Diameter [-]
TSR	Tip Speed Ratio [-]
Z/R	Z axis position (vertical)/ rotor Radius [-]
HAWT	Horizontal Axis Wind Turbine
NTNU	Norges Teknisk-Naturvitenskapelige Universitet

1 Introduction

1.1 Sustainable development - wind power

Diversification of energy sources and increasing participation of renewables in the energy sector is nowadays one of the biggest and most important challenges of the developed countries. As experience of recent years has shown it is not an easy task. Along with the development of technologies to maximise the fostering of the available wind energy, there appears numerous problems: technical, environmental and economic, which were absent in conventional power plants.

Currently, a visible increase of interest in wind turbines is due to the fact that the development of technology already allows to achieve power from 5 to 8 MW from a single turbine, wherein the investment costs each year are becoming lower. This is why the energy is believed to be the biggest alternative to conventional sources.

Despite numerous tests and centuries of excavation of energy from wind, some phenomena of flow around wind turbines are not clarified. Related issues are intricate, knowledge of parameters such as velocity distribution, trace excitation and turbulence intensity distribution for the turbine rotor is of crucial importance in the design of wind farms. Additional difficulties when modellers are trying to imitate the volatility real working conditions turbines and axial displacement between the rows of turbines. In the near future, there will be a need of vital deeper understanding of these processes in order to improve the efficiency of turbine systems.

The world today (2013) totally produces 23 127 TWh of electricity per year, of which slightly more than 2.7% comes from wind farms [1]. Maybe now, it is not very much, but estimates of global technical potential range from 85 EJ/yr (23 400 TWh/yr) to a level of 580 EJ/yr (162,000 TWh/yr) [2] shows, it could cover entire present global demand and even more. That is why in the last ten years, the installed wind power capacity increased by 800 percent and reached the level of 318 106 MW [3](fig. 1) while it still continues to develop rapidly.

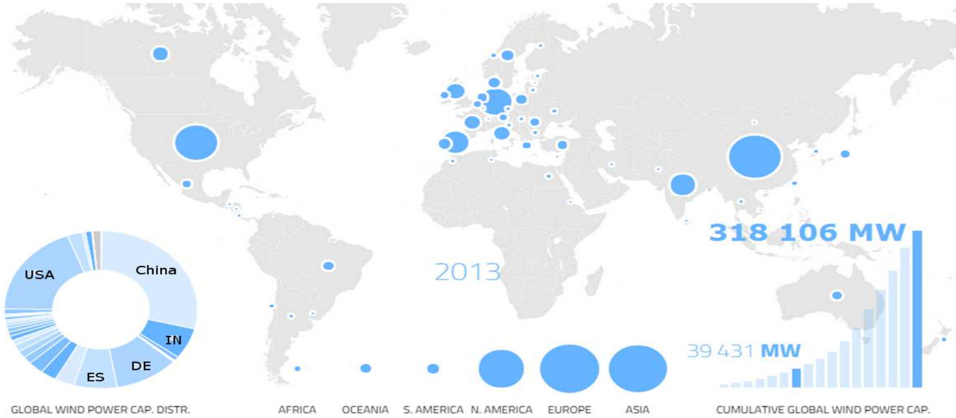


Fig. 1. The distribution and location of global installed wind energy capacity [3].

1.2 Current problems

Given this rapid growth, wind turbines and wind farms increase in numbers. It manifesting in some of the research challenges to interpret and reduce bad influence of interactions between the single turbines and the atmosphere or neighbouring turbines to accurately predict and improve power output before wind farm construction and efficient control of existing structures.

Inside wind farms, turbines can be located with some limited distances to reduce investment costs like expenditures for electrical connections and land possession, but also to avoid higher grid losses [4],[5]. Additionally, each upstream turbine during conversion of wind energy, reduces the available stream velocity and generates vortices, what contributes to a wake effect losses and results in lower efficiency of subsequent downstream turbines (fig. 2). Performance degradation is increasing with shrinking distance between the turbines. Due this, onshore wind farms energy production may be lower from 5 to 10 % [6], while for offshore wind farms, loss could rise even up to 15% [7].

Main problem in proper predictions of wake development and wake-turbine interaction is very little data on these phenomena available at reasonable scale. Full scale experiment is very expensive, time consuming and very hard in implementation. That is why planners more often applying computer simulations, which allow to reduce costs and necessary time.

Fig 2. Natural visualisation of Wake turbulence behind wind turbines – (photo of Horns Rev offshore wind farm in Denmark) [8]

However, modelling of turbulent flows and other phenomena associated with the 3D aerodynamics is challenging. It requires the use of advanced computational algorithms, which still are based on the simplifications and assumptions, in the end providing only approximate results.

To be more accurate and sure of computational results, all algorithms should be calibrated and validated with well executed physical experiments. This brings confidence that the model will better reflect the reality [6].

Some of modellers instead of full scale experiment, trying to calibrate these numerical models, by using wind tunnel testing, where the boundary conditions are easier to control, which makes them more suitable for benchmarking purposes. But in that case, the most problematic are scaling issues, to refer simulation results, when wind tunnel key factors (Reynolds number, tip speed ratio, geometry) usually are not comparable with full scale conditions [7].

All this makes the task of creating a very a theoretical model or high accuracy simulation method to predict the turbine performances and the wake development downstream still an open question.

2 Objectives

The goal was to create trustworthy documentation of the performances for wind turbines working in a tandem array. This database will serve as the reference data against numerical calculations in the approaching 4th Blind Test challenge.

Conducted measurements were made to localize points of optimum total power production of each wind turbine and characterize the surrounding flow conditions.

The objectives of the present paper are the experimental investigation of:

- power and thrust coefficients for both wind turbine models, achieved by the scanning of the entire Tip Speed Ratio (TSR) range with finding of maximum points,
- the influence of the inlet turbulence on the functioning of the turbines,
- the operation of the turbines when distance between them is increased,
- the wake propagation, turbulence intensity and velocity deficit along the tunnel, between working turbines.

3 Experimental setup

The experiments were carried out in the large closed-loop wind tunnel facility at NTNU. The dimensions of the test section are L=11.15 m, W=2.72 m, H=1.80m. The roof of the tunnel is set up to produce zero pressure gradient in the whole test section.

The research was divided into two main parts. The first part of the measurements was conducted with uniform low level of turbulence intensity T_I=0.23% in 2D from inlet (placement of T_1). For the second part uniform high background turbulence over T_I=10 % was used. It was done in order to reflect realistic conditions more often occurring in the atmosphere. High turbulence was generated by large scale bi-planar mesh, with the size of M=0.24 m and the solidity of around 35%.

Reference velocity was always set to U_{ref}=11.5 m/s. The reference velocity for low turbulence was measured by a Pitot probe installed between inlet and the upstream turbine in a place not disrupting the flow. For high turbulence reference velocity was measured by a contraction nozzle (placed in the inlet to the test section) and corrected by a empirical factor.

Model turbines used in the test are 3 bladed HAWTs. Turbines were arranged coaxially (tandem array), the downstream turbine (T_2) was fully submerged in the wake of the upstream machine. This manifested in the reduction of the efficiency T_2 and introduced loads, which are fatiguing for the structure.

Upstream turbine (T_1) was fixed at 2D (diameter) from inlet, but obstructed turbine was tested at 3 different distances away. The hubs of the turbines were located almost in the centre of the test section, 0.826 m above the floor, about 1 m under ceilings and almost 1.4 m from both sides to the nearest wall. Placed in that order turbines with rotor swept area took about 12 % of the wind tunnel cross section. Thus specified blockage is sufficient for benchmarking purpose, even if this value is slightly more than the commonly accepted in wind tunnel testings.

The blades of both turbines are based on the NREL S826 airfoil along the entire span (Fig. 3). This profile was designed as high lift coefficient, low sensitivity to roughness, and soft stall characteristic, suitable for the tip of low solidity blades. More details about its construction are available at Tangler and Somers [11].

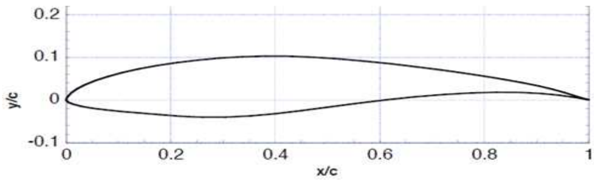


Fig. 3. Shape of the airfoil NREL S826

The turbines were designed to operate at TSR=6 which is typical for a full scale turbine. The turbines have the same blade geometry but T_1 rotor diameter (D_1=0.944m) is slightly bigger then T_2 rotor size (D_2=0.894m) this is dictated by differences in the construction of the nacelle and the hub size (Fig. 4). This also affects the maximum C_p level, which for T_1 is about 0.47 and for T_2 it is slightly lower and equal to about 0.45.

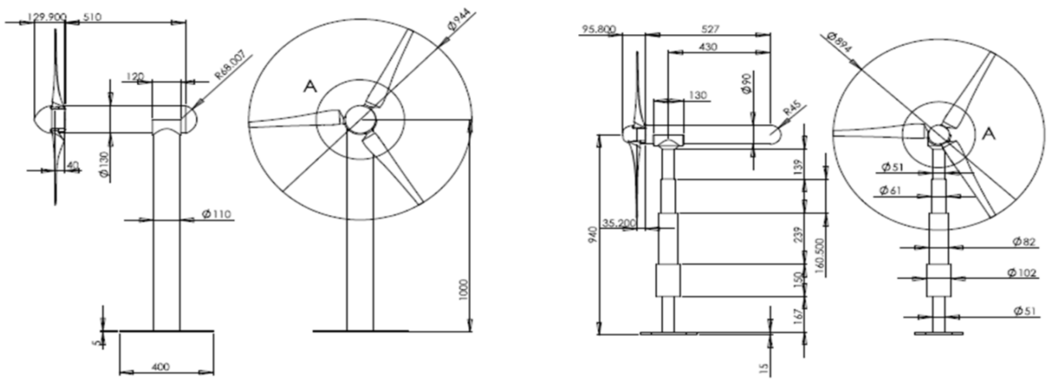


Fig. 4. Blueprints of the upstream turbine-T1 (Left) and downstream turbine - T2 (Right).

3.1 Power and thrust measurements

The rotational speed (RPM) of both turbines are driven by electric engine and can be controlled by a Siemens Micromaster 440 frequency inverter. This allows for the recording of the stable power characteristics. All the key parameters (RPM, Torque, Thrust), generated by the turbines and actual tunnel conditions (velocity, temperature) can be measured simultaneously.

The required output was represented by the thrust and power coefficient for the upstream and downstream turbines, defined as:

$$C_p = \frac{T \cdot \omega}{\frac{1}{2}\rho \cdot A \cdot U_{ref}^3} \quad (1) \qquad\qquad C_T = \frac{Thrust}{\frac{1}{2}\rho \cdot A \cdot U_{ref}^2} \quad (2)$$

C_p is ratio of the turbine generated power to power contained in the wind inflow, specifying turbine's efficiency .

Below are presented arrangements of the performance investigations:

- Inlet turbulence: 0.23% (Low) and ~10% (High).
- Tip-speed ratio of T_1: 3 – 10 with step of 0.5.
- Tip-speed ratio of T_2: 1 – 9 with step of 0.5.
- Distance of T_2 behind T_1 (S/D)= 3, 5, 9.

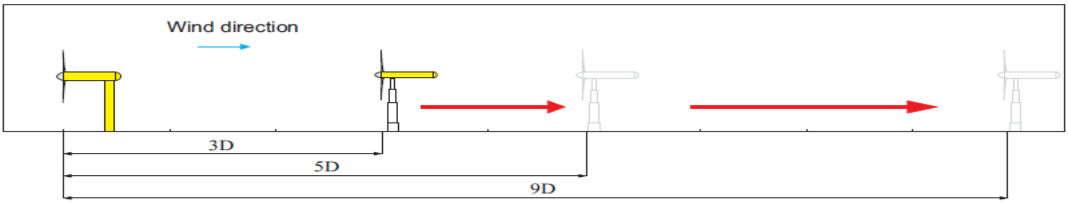


Fig. 5. Arrangement of turbines for the purpose of tests

3.2 Wake measurements between two model turbines - vertical

Third part of investigations was focused on characterization of the wake development between operating turbines. Tests were performed using hot-wire anemometry. For achieving full picture of overall phenomena at all planned positions, a manual traverse of the probe was necessary. This gives actually lower obstruction of the wind flow, but also allows to test speeds and turbulence only in a vertical plane. Measurements of wake impact were performed for the best efficiency operating points of both turbines.

The following parameters were established for this test:

- Inlet turbulence: 0.23% (Low) and ~10% (High).
- Distance of T_2 behind T_1 (X/D)= 9
- Wake measurement distance behind T_1: 3D, 5D, 8D, (9D without T_2)
- Tip-speed ratio of T_1: 6
- Tip-speed ratio of T_2: 5

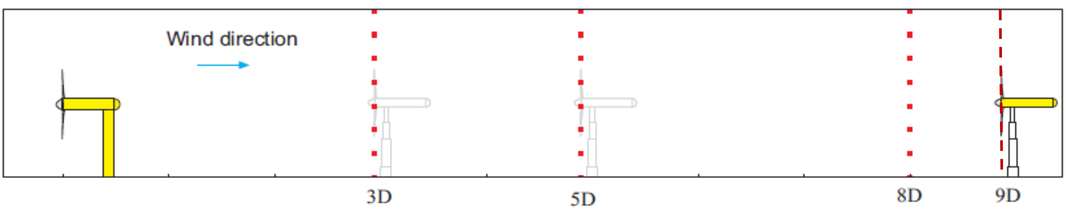


Fig. 6. Arrangement of the vertical wake measurements

4 Results and discussion

4.1 The Grid (inlet turbulence)

The difference in using the grid compared to undisturbed flow is higher maximum power coefficient for T_1 and the changed shape of the Cp curve. For single turbines operating with low turbulence, maximum C_p is about 0.47 for T_1 and about 0.45 for T_2, but with higher turbulence those values are slightly bigger: 0.48 for T_1 and 0.46 for T_2. The shape of averaged Cp curve for turbine T1 is presented in figure 7.

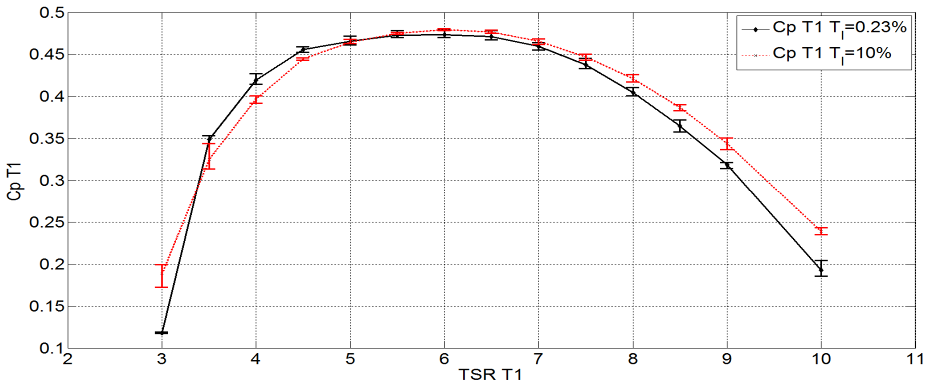


Fig. 7. Power coefficient of T_1 for low (black) and high (red) inlet turbulence intensity

Despite early start of the curve growth for the case with the grid (red), it is also characterized by smoother course of the chart, without significant fold and flattening of the upper part of the graph that can be observed for the case with lower turbulence intensity. Applied different level of the turbulence has a similar pattern, but much greater impact on turbine located downstream, it will be described in detail in the later section of this paper.

4.2 Power efficiency of wind turbine in tandem array

Measurements were conducted based on maintaining constant work parameters of the first turbine (T_1) while collecting the consecutive data by variation of TSR of the second turbine (T_2). In result it gives spatial graph. All collected data is shown in Table 1. The most visible relation for all the cases is the fact that with the achievement of the highest efficiency by T_1, the second turbine reached the lowest efficiency and it is working also in opposite way. It is easily explainable taking into account the principle of conservation of energy.

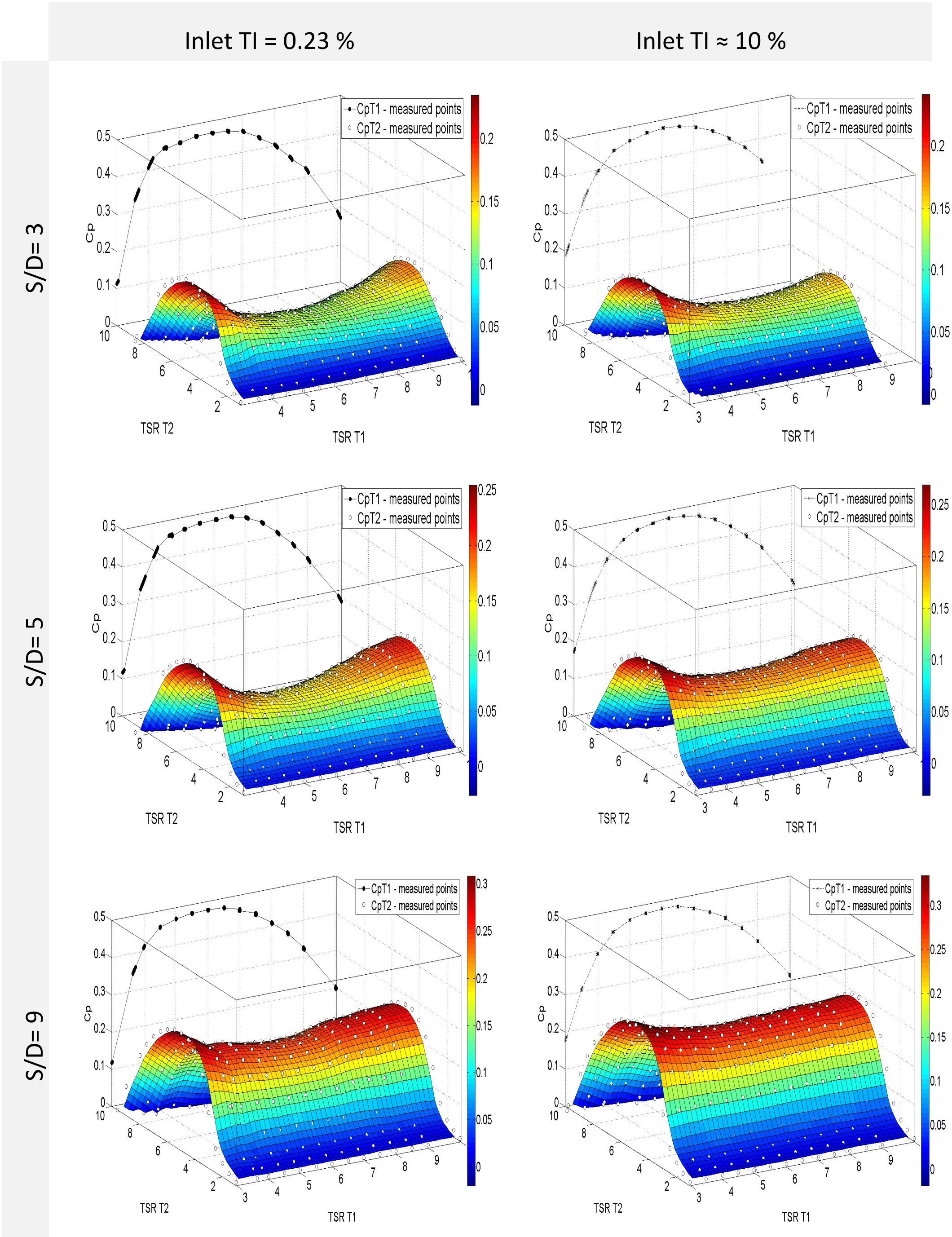


Table. 1. Matrix of power coefficients of T_1 (background) and T_2 (spatial) in function of TSR.

The overall remaining energy available to T_2 rises with increasing separation distance between the turbines. Shrinking of the deflection on T_2 curve can also be seen, caused by progressive reduction of T_1 wake effect influence. The deflection is even lower when turbines are operating under higher turbulence intensity. To visualize the situation better, Fig. 8 presents the comparison of the maximum C_p values along the cross section through the charts of maximum points in function of T_1 TSR). Additionally, the total C_{p_sum} (Cp_{T1}+Cp_{T2}) of both operating turbines in all combination of the TSR has been shown.

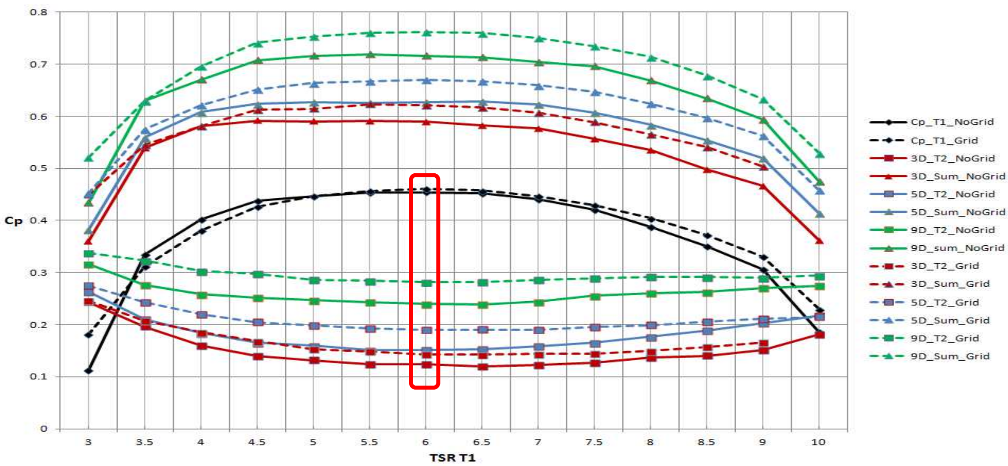


Fig. 8. Comparison of all the power coefficients: T_1 (black), T_2 (lower part), total sum (upper part).

The power coefficient values of turbine T_2 are rising with the increasing separation distance. For all cases when higher flow turbulence occurs the power coefficients Cp for T_2 are bigger than those for lower inlet turbulence. The lowest Cp belongs to characteristics obtained for 3D distance without the grid and the highest Cp to the characteristics obtained for the 9D with a grid installed.

The looped red area presents the highest C_p of first turbine (T_1=TSR6) and the minima of all other Cp characteristics recorded for T_2. This confirms the earlier statement that highest efficiency of the T1 automatically resulted in the lowest efficiency of the T_2. It seems necessary to illustrate how does it looks, in step by step progress of T_2 turbine C_p curve. Figure 9 and Figure 10 show dependences, which part of maximum efficiency is equivalent for considered separation distance and applied inlet turbulence. There is also a prediction of a minimum separation distance when the upstream turbine will not have any influence on power production of the second downstream turbine.

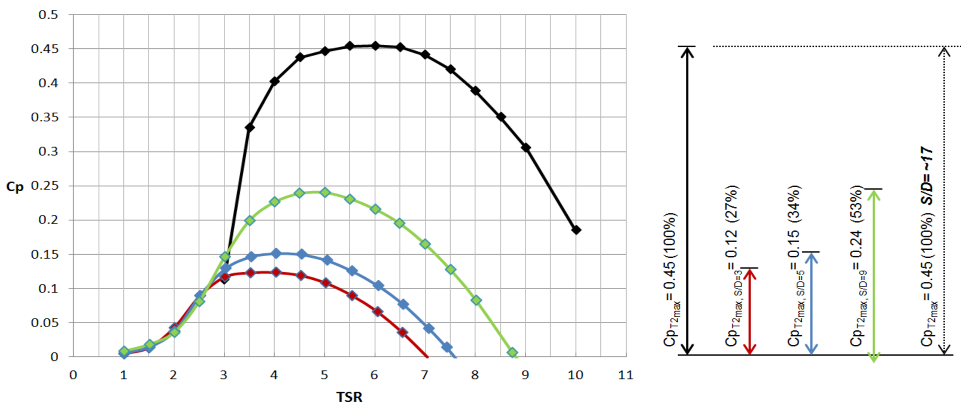


Fig. 9. Power curves of T_2 wind turbine operated with low inlet turbulence and different separation distance at optimal T_1 TSR=6 in order 3D (red), 5D (blue), 9D (green), optimal T_2 curve (black).

For 3D and 5D cases with low inlet turbulence, the best operating points are at TSR around 4, but for 9D, TSR is equal 5. Estimated on this data, distance without wake influence is approximately 17D. Other researchers report this distance to be equal from 20D to even over 30D [12][13].

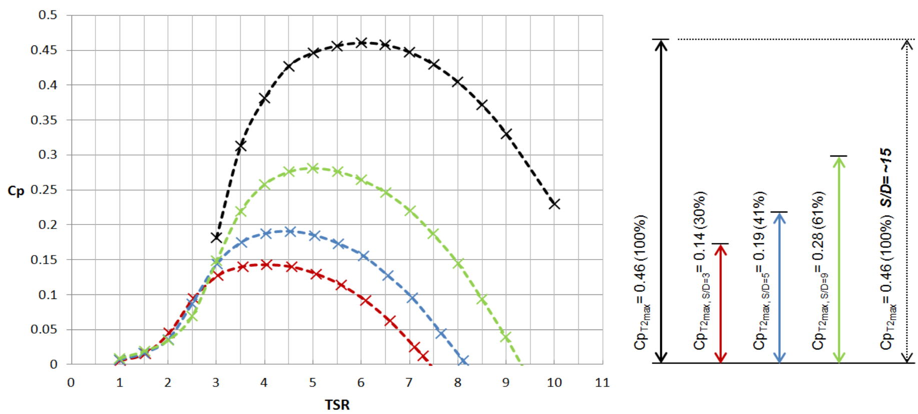


Fig. 10. Power curves of T_2 wind turbine operated in high inlet turbulence and different separation distance at optimal T_1 TSR=6 in order 3D (red), 5D (blue), 9D (green), optimal T_2 curve (black).

For cases with higher inlet turbulence best operating point for 3D case is at TSR=4, for 5D is at TSR=4.5 and for 9D TSR is equal to 5. Estimated minimal distance ensuring most optimal efficiency of the T2 turbine in this case is around 15D.

Next, Table 2 presents spatial graphs of the total sum of the power coefficient C_{p_sum} (Cp_{T1}+Cp_{T2}) in all tested combinations of turbines TSR.

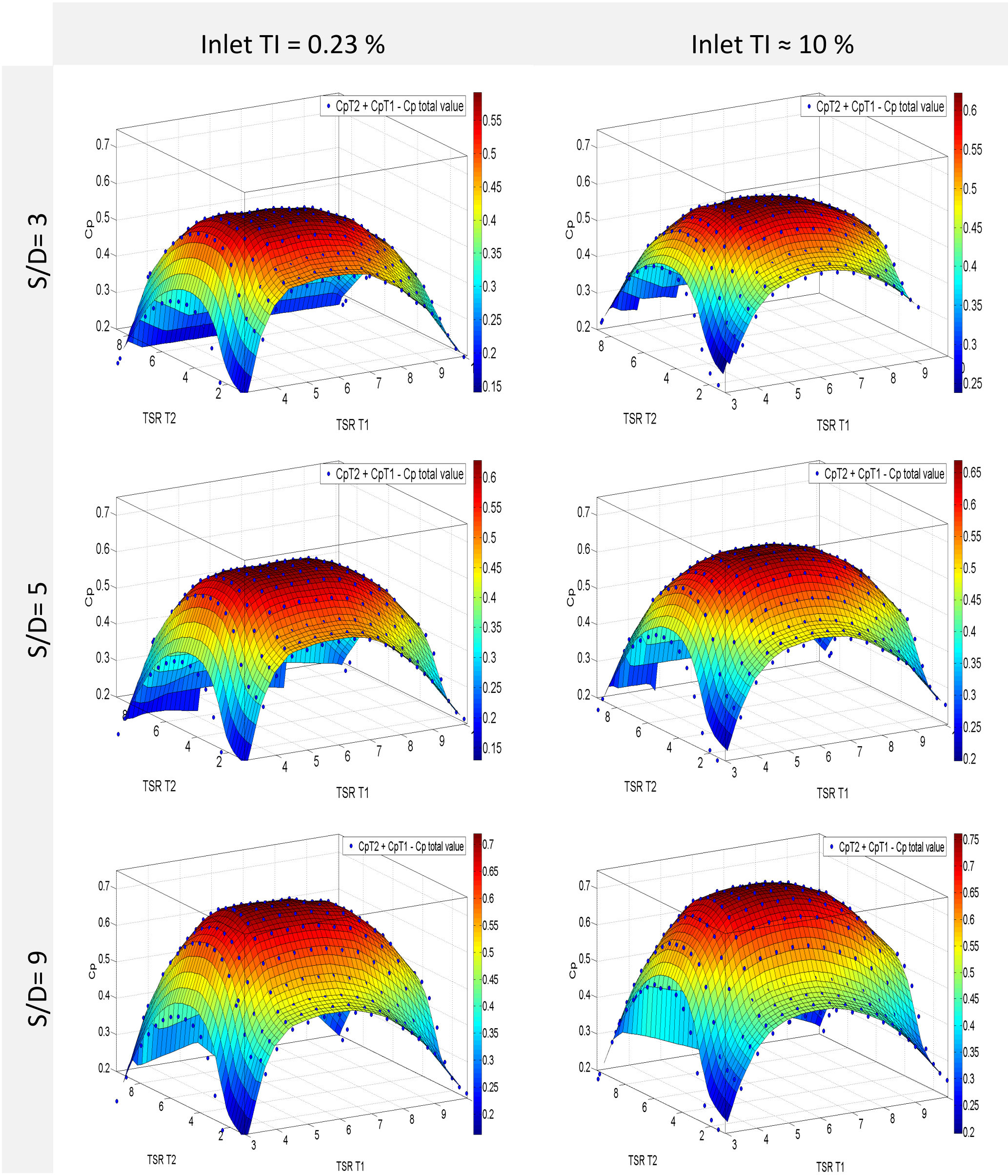


Table. 2. Total sum of power coefficient for T_1 and T_2 in function of TSR.

Table 3 contains the plots for the Table 2 (view from the top) and recalculated percentage efficiency of tandem wind farm, defined by the equation 3:

$$\eta = \frac{_{\max} Cp\_T1_{Tandem} + _{\max} Cp\_T2_{Tandem}}{_{\max} Cp\_T1_{Single} + _{\max} Cp\_T2_{Single}} [\%] \qquad (3)$$

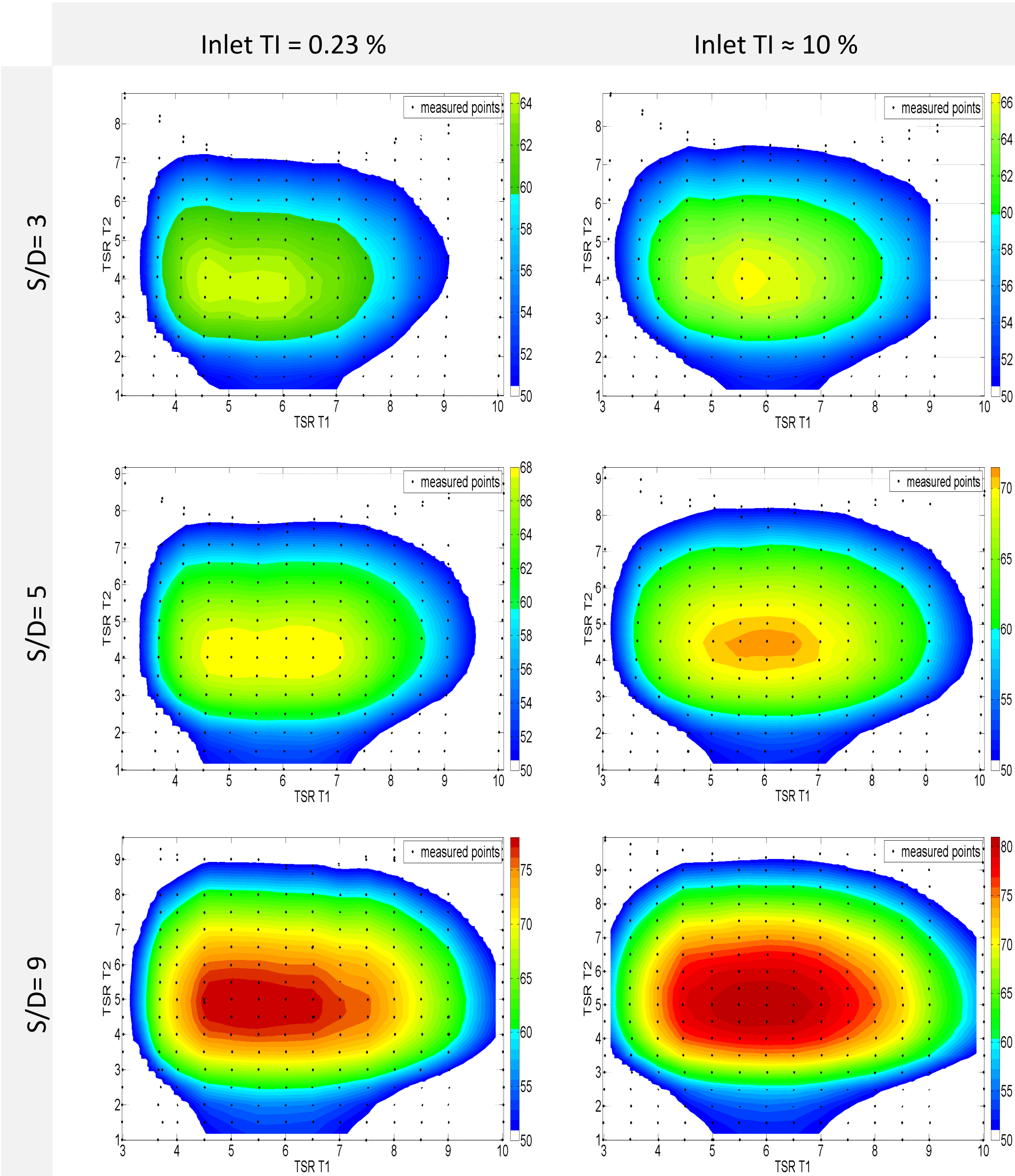


Table. 3. Percentage efficiency for wind turbines working in a tandem array.

Guided by the same dependencies as C_p the highest efficiency can be observed for 9D case especially when wind farm is operating under higher turbulence intensity. Also for the applied grid cases, very characteristic are the distinct peaks showing the optimum operating points in high turbulence field, when for low inlet turbulence, the optimum operating areas are broader.

Efficiency charts start with the value of 50%, because this value is the basis of work for the entire wind farm. Any value under that level (white area) means that a single turbine can generate this power by itself.

After reviewing the scientific articles most researchers investigating full scale wind farms observe efficiency rise of the wind farm with the increasing of turbine separating distance. However, little amount of field study data does not allow to clearly diagnose how far away from upstream turbine the wake will not have any influence on the rows of the downstream turbines. Especially, in the case where two wind farms with turbine separation between 7D and 10.3D do not make any significant differences (fig 11) [9][10].

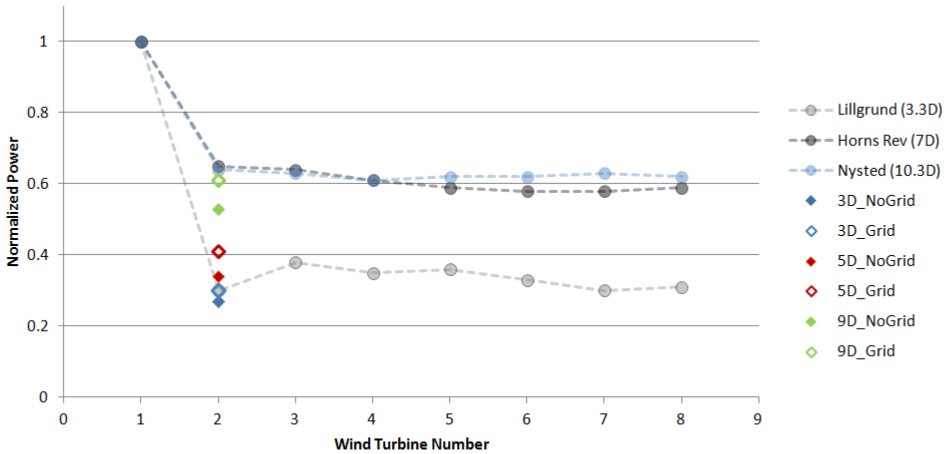


Fig. 11. Comparison of normalised power from measurement and full scale experiments.

4.3 Thrust

Because of some technical problems with weight balance under turbine T_1, only one thrust curve(C_t for T_1) was achieved, for the case: 3D without grid, all the others are lacking. To have a reference point to case with higher turbulence intensity this paper will use the Ct T_1 curve from the Blind Test 3.

Blind test 3 (BT3) [15] was using two turbines, similarity arranged in-line with separation distance equal to 3D and it should correspond well with the data recorded in this session. Unfortunately, in the Blind Test 3 an offset to simulate situation where only half of T_2 swept area is in wake impact of T1 was introduced. As it is shown in Figure 12, the Ct results from actual measurements are a little bit higher then these from BT3. The reason for that could be other setup, but more probably is that in BT3 the drag force was corrected by subtracting tower and nacelle influence. For this reason it is impossible to compare this cases directly.

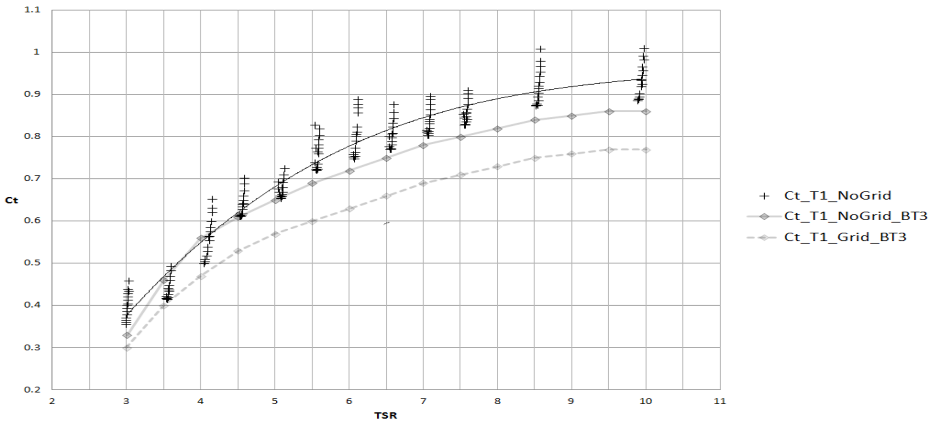


Fig. 12. Thrust (Ct T_1) curves from measurements of T_1 and from "Blind Test 3"[15].

The cases of T_1 C_t Blind Test 3 can be very valuable to comparison C_t T_1 data in further time, because irrespective of separation distance changes in all T_1 curves should be very little. The most important information is that the inlet turbulence is resulting in decreasing of general level of C_t T_1 curve, as has been shown in above Figure. Opposite situation is observed in Figure 13, where with the increasing inlet turbulence level of the T_2 C_t curve is rising. The least negative impact is registered for the case with 3D distance and without grid installed while the highest load is measured when 9D is used and with the grid installed. The charts in Fig. 13 are plotted for optimum upstream turbine operating point T_1 TSR=6.

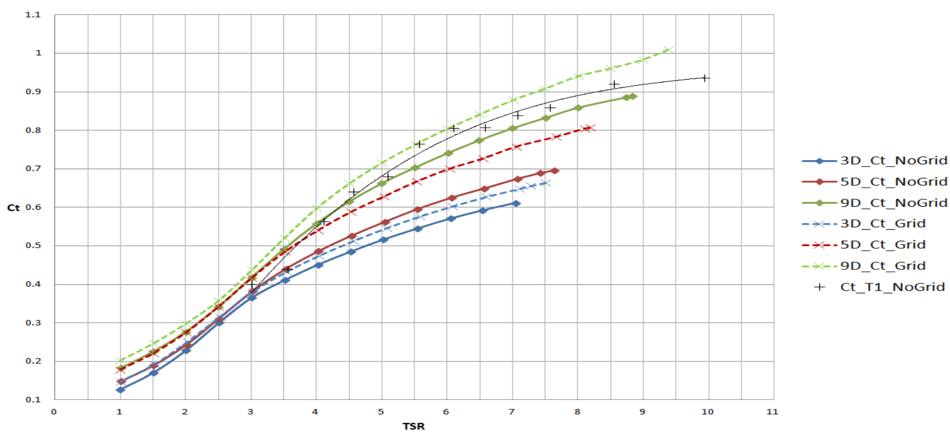


Fig. 13. Thrust (C_t T_2) curves for T_1 TSR=6 for different separation distances and different inlet turbulence.

Table 4 contains spatial graphs of C_t T_2 in all combinations of TSR.

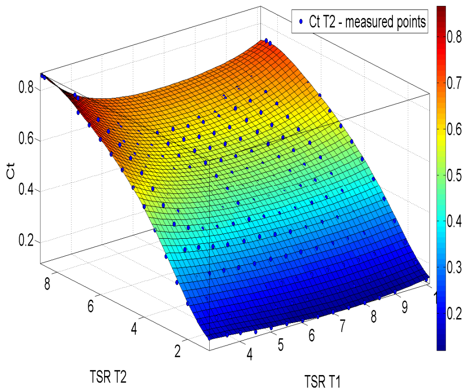
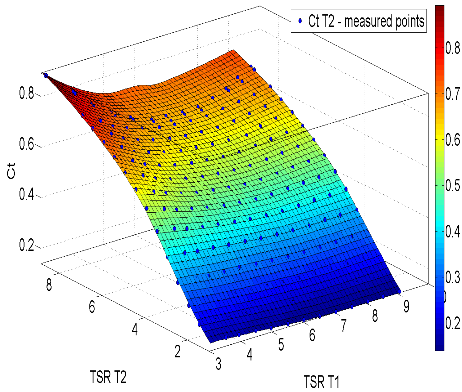
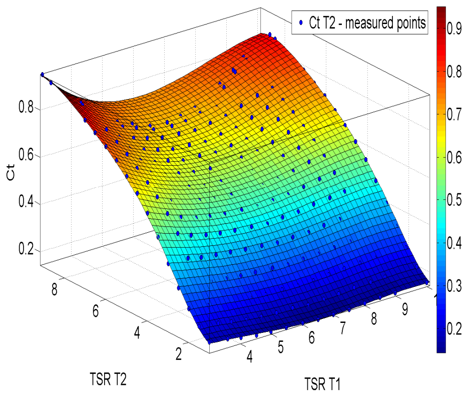
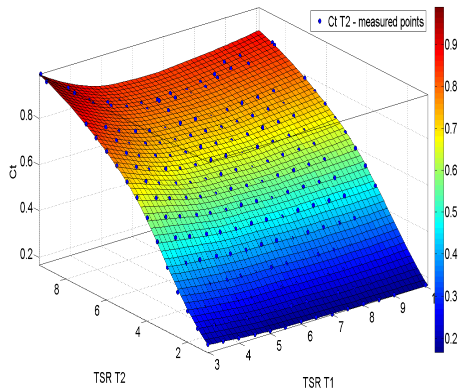
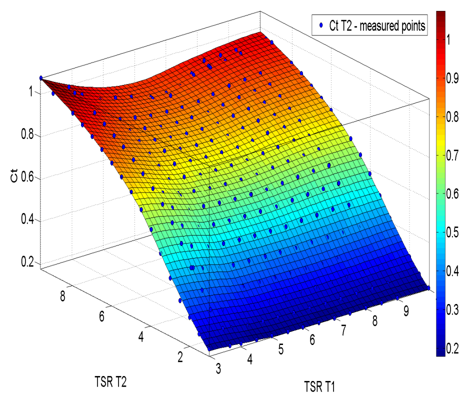
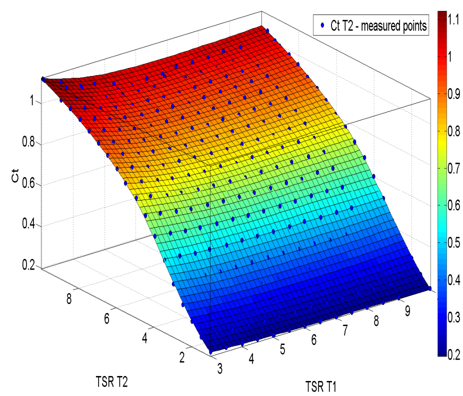
	Inlet TI = 0.23 %	Inlet TI ≈ 10 %
S/D= 3		
S/D= 5		
S/D= 9		

Table. 4. Matrix of thrust coefficient for T_2 in function of TSR combination.

Comparing thrust coefficients of T_1 and T_2, in almost all cases (beside 9D with the grid) all T_2 C_t curves are under T_1, and according to previous dependencies also C_t values are increasing with increasing separation distance and for cases with higher turbulence intensity. In table 4 can be observe deflection on C_t T_2 curve, this is rising together with shrinking of distance between turbine and almost disappear for biggest distance.

4.4 Wake effect between two turbines

The measurement of velocity field between the two turbines was performed along the tunnel symmetry axis. Figure 14 presents the normalized vertical velocity u/U_{ref}, where u is local velocity. The main differences between velocity in case with and without the grid are maximal level of velocity deficit and the size of their changes. Almost all the time in every separation distance deficit of velocity is higher for case without the grid.

Charts for higher inlet turbulence seems to be more symmetric and smooth. The best example are the two last (8D and 9D) charts. In every chart on bottom it can be observed higher deficit then on the top. This is due to the influence of the turbine tower. Plots for cases without the grid are more distorted with well-delineated downwash effect of upstream turbine tower (displacement of wake centreline) on 8D and 9D positions. In this case, flow also need more space to align.

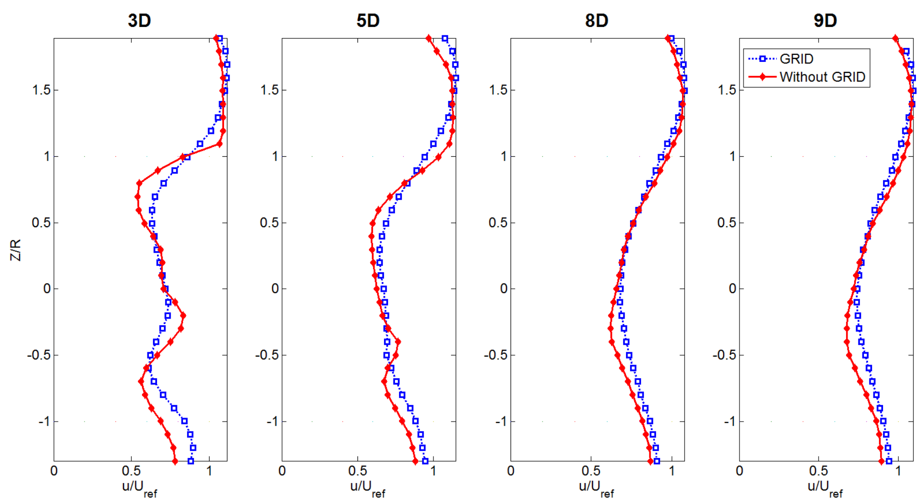


Fig. 14. Vertical axis normalized mean velocity u/Uref [-] between two model wind turbines at 3D, 5D, 8D and (9D behind T_1) operating in low (red) and high (blue) turbulent inlet flow. Parameters of the turbines: T_1 TSR=6.0; T_2 TSR=5.0.

Maybe observed differences in mean velocity profiles are not very big , but because energy flux contained in the flow depends on velocity to the power of 3 it can completely explain higher power coefficients received on the downstream turbine T_2 especially when the grid was installed.

Similarly to the velocity, the turbulence intensity plots are more smooth for the case when the grid was installed as presented in Fig. 15. Even if difference in turbulence intensity at inlet, between the cases was almost 10%. Behind T_1 turbulence levels are not anymore so different, Case with grid have higher turbulence intensity, but also more uniform.

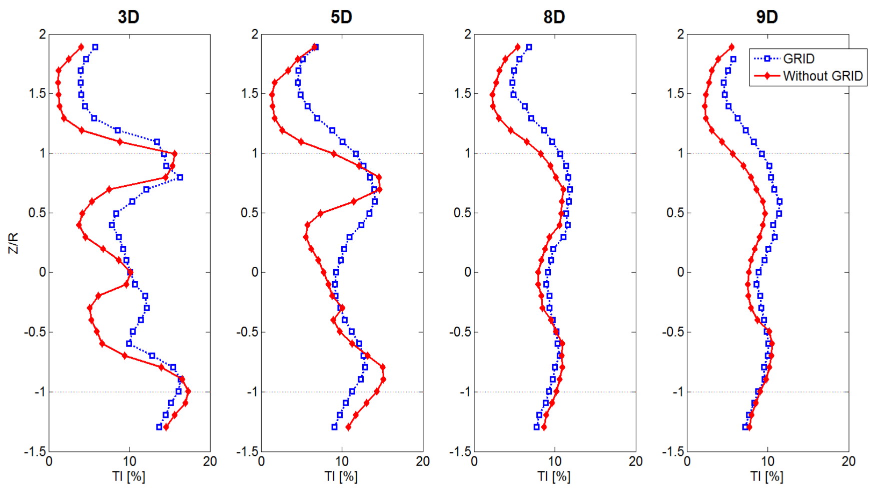


Fig. 15. Vertical axis turbulence intensity T_I [%] between two model wind turbines at 3D, 5D, 8D and (9D behind T_1) operating in low (red) and high (blue) turbulent inlet flow. Parameters of the turbines: T_1 TSR=6.0; T_2 TSR=5.0.

In two last positions at 8D and 9D, bottom of the charts are almost equal, along with the height, can be observe increasing of differences in turbulence intensity between cases. At 3D separation distance the highest turbulence position is covering with edge of the rotor. Further into the tunnel the highest turbulence intensity regions tend to develop near the turbine centreline.

5 Conclusions

After analysis of the experimental results, several main conclusions have been found:

- Total power production of two turbines have been increased along with the increase of the separating distance between them thereby increasing of maximal wind farm efficiency from 64% (3D) to 81% (9D). This observation is consistent with conclusions obtained by other cited researchers.
- Applying the uniform higher inlet turbulence (grid cases) caused in grow of T_1 and T_2 power coefficients, what also had influence on maximization of total power production. The use of a higher turbulence caused an increase in productivity for individual cases: 3D - 3%, 5D - 7%, 9D - 8% as compared to cases with low turbulence intensity.
- In total power productions lower level of turbulence means flattered curves, which gives more TSR combinations with maximal C_p points.
- The performance of a downstream turbine is closely related to the performance of upstream turbine. Best operating point for T_1 was always around TSR=6, for T_2 it depends on separation distance: 3D - TSR=4, 5D - TSR=4-4.5, 9D - TSR=5.
- Higher turbulence intensity is characterized with the faster flow recovery behind upstream turbine.

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