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Heat and Flux

Increase of Wind Farm Production by Reduction of the Axial Induction

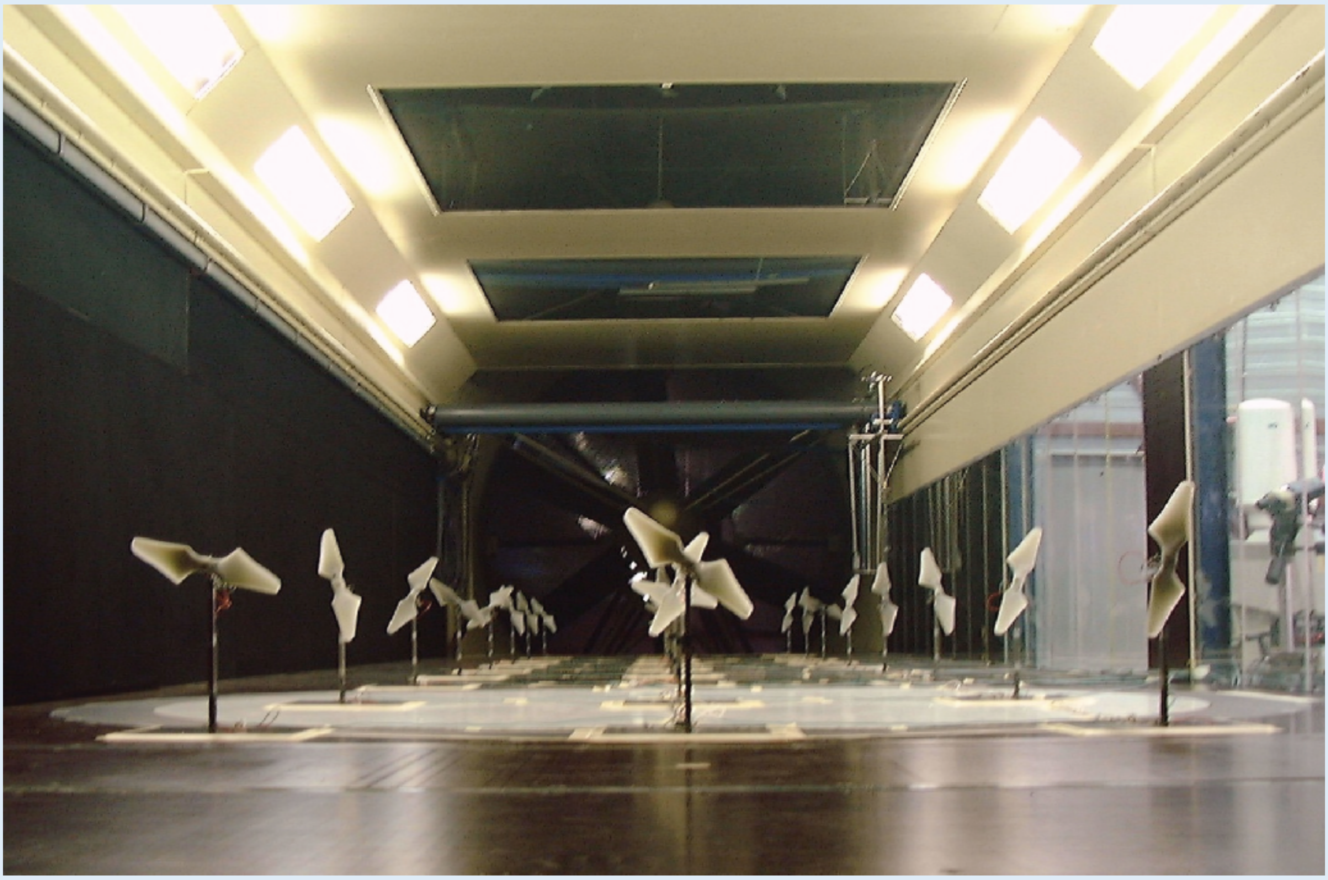

Photo: ECN wind farm existing of 24 turbines of 25 cm diameter in the wind tunnel of TNO Apeldoorn. The farm represents a 100 MW offshore farm scaled by a factor of 400.

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This report has been presented as an oral presentation in the session BT4.2 "Development of Measurement Methods" at the European Wind Energy Conference, EWEC 2003, June 16-19, 2003, Madrid, Spain.

The poster on the next page was presented at HUSUM*wind* , September 13-17, 2003, Husum, Germany

Heat and Flux

more power - less loads

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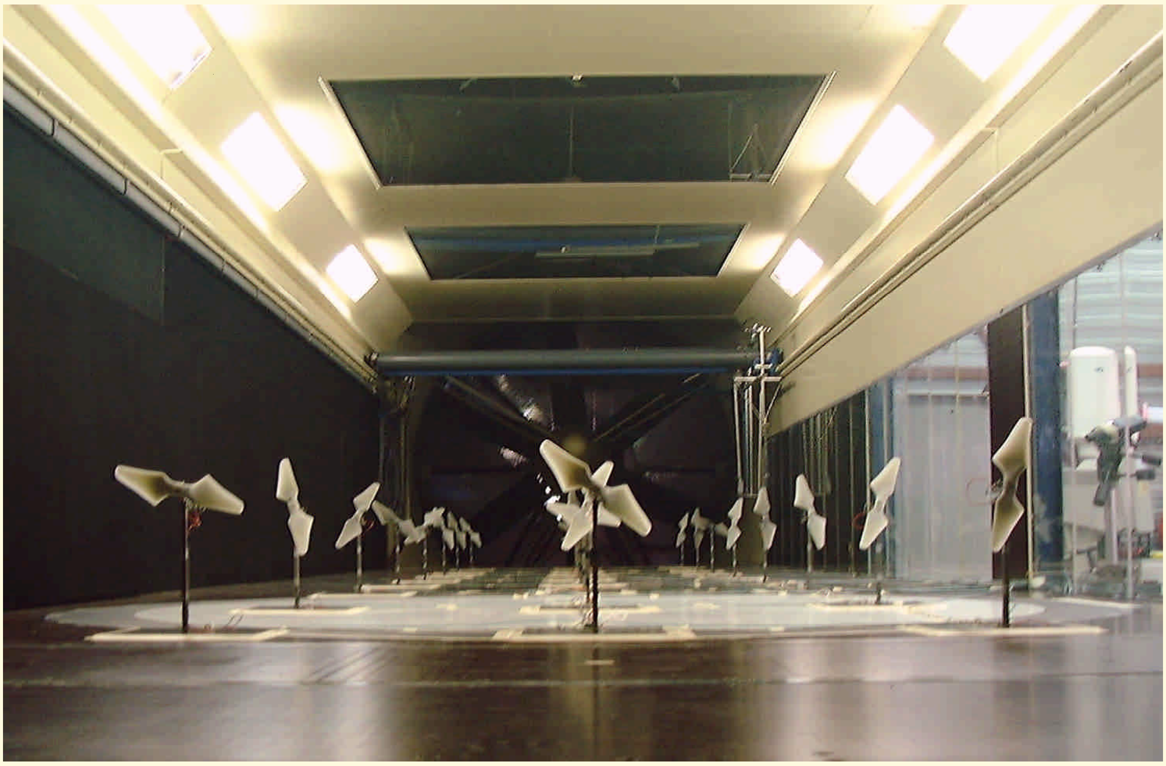
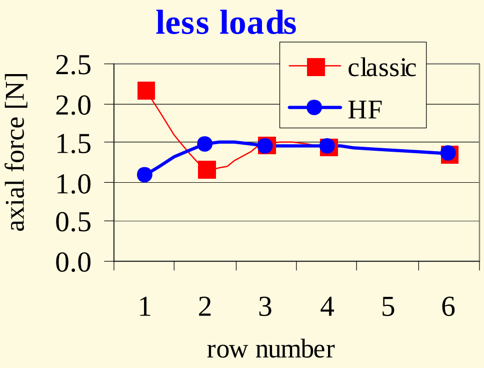
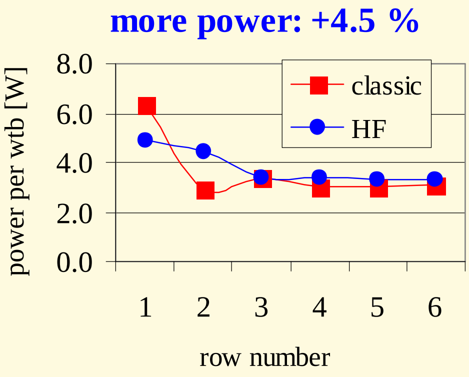


The benefits of ‘Heat and Flux’ operation, increased production and decreased loading, were confirmed by wind tunnel experiments . Scale effects could have amplified the production rise in ‘Heat and Flux’ operation. June 14, 2003 ECN applied for a patent (no. NL 10 23666) on the technology.


less loads


more power: +4.5 %

Heat and Flux

Increase of Wind Farm Production by Reduction of the Axial Induction

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ABSTRACT: At the windward side of a wind farm, we propose to operate the wind turbines at an axial induction factor below the Lanchester-Betz optimum of 1/3. Our analysis shows that the power of the turbines under the lee will increase more than the decrease of the power of the turbines at the windward side, so that the power of the farm as a whole increases. Measurements with a 1:400 scaled model of a wind farm confirmed the hypothesis.

Keywords: wind turbine farm, axial induction, production, wake, interference

1. INTRODUCTION

The implementation of wind energy increases by about 30% per year. A decade ago, most turbines appeared as solitary turbines or in small clusters. Presently new turbines are often part of large wind turbine farms. Large wind farms are therefore a new development in wind energy. By the introduction of many large farms, it has become relevant to deal in a proper way with interference or wake effects between the wind turbines.

In this paper we will show that wind turbines in a farm should not be operated in a way that their individual output is at a maximum. Instead, the entire farm, as an energy extracting body should be optimised. It will be shown that the output of a farm as a whole can increase by decreasing the power of individual turbines at the windward side. This will be explained by two different physical mechanisms: Heat and Flux. In literature [4] it can be found that the output of a wind farm can be enhanced by reducing the tip speed ratios at the upwind side of a farm. Simulation results have been the argument for this conclusion from 1988. In this actual paper we come up with the first physical explanations.

2. HEAT

By the end of the year 2000, at ECN, it was concluded that actuator discs (the basic model for a wind turbine) extract 50% more kinetic energy from the wind than what they generate electrically [1]. The classic thought is that those amounts are about equal (despite of losses due to 'technical imperfections' like aerodynamic drag of the airfoils and losses in the bearings, the generator and the gearbox). The new insight is that an actuator disc extracts about 50% more kinetic energy from the wind for fundamental reasons.

The additional 50% are dissipated as heat in the very far wake behind the disc.

The 50% heat loss mentioned above is only valid at the Lanchester-Betz limit. For the more general situation it has been derived that the efficiency of an actuator disc η = (useful power)/(used power) depends on the axial induction factor a by $\eta = 1 - a$ [1]. In this context it is relevant to mention that most literature introduces $c_p = 4a(1-a)^2$ as the efficiency. This is physically not correct, c_p is the fraction of useful power extracted compared to the kinetic power that would flow through a disc without induction. So, it is not the efficiency, but more a kind of conversion factor.

Figure 1 shows three curves as a function of a. The curve in the middle shows the useful power $4a(1-a)^2$ according to the classical Lanchester-Betz relation, which reaches its maximum of 16/27

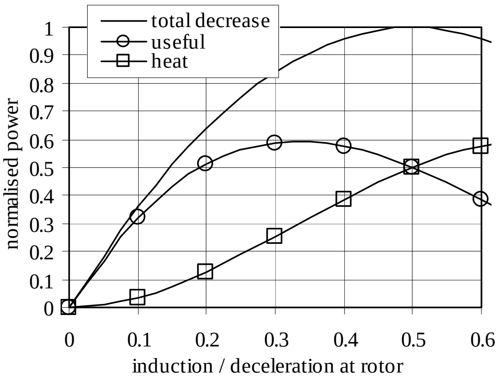

Figure 1: the classical Lanchester-Betz curve, our relation for the heat loss and the total decrease of kinetic energy in the wind.

(≈0.59) for $a = 1/3$. The lower curve shows the newly discovered effect of heat dissipation. It can be seen that the dissipated heat increases rapidly with increasing a around the Lanchester-Betz optimum. The upper curve shows the total amount of extracted kinetic energy from the wind by the disc. It can be seen that the useful power hardly decreases, when a becomes (not to much) less than 1/3. However at the same time, the wasted heat reduces much, so that the disc would also extract less kinetic energy from the wind.

For solitary turbines the effect is of no practical relevance, for wind farms however, the situation is different. The waste of kinetic energy by converting it partly into heat is, of course, disadvantageous for the turbines under the lee.

In a farm it is therefore important that turbines at the windward side do not only extract much energy, but also perform at high efficiency. By simply reducing a at the upwind side this can be realised. As a result the turbines under the lee will produce more and the output of the farm as a whole increases.

3. FLUX

In 2002, further analysis of the Heat-theory confirmed the heat loss, but also showed that there were two other relevant effects, which are in short denoted by the term flux. Simulation runs with the heat loss switched off, still showed that more power (less than with heat switched on) was generated by reducing the axial induction at the windward side. The simulation results can be clarified by three different effects [2]:

1. The above explained 'heat',
2. When the induction factor of upwind turbines is reduced slightly (by $-\delta a$) from its optimum, the power will hardly decrease since $-dP/da \cdot \delta a = 0$. The wind speed in the wake of those wind turbines will rise by $d[V(1-2a)]/da \cdot -\delta a = 2V \cdot \delta a$, and turbines under lee will take advantage of this.
3. With larger values of a, the expansion of the stream tube enclosing the rotor increases and therefore the cross section of the wake is enlarged. The larger the wakes of the upwind turbines, the larger the probability that wind turbines under the lee are located in those wakes (which causes production losses).

Effects 2 and 3 are illustrated by figures 2a and 2b for the situation of two turbines on a line parallel to the wind. The upper situation corresponds to the classical operation of both turbines at the Lanchester-Betz limit. The lower picture is the situation at 'Heat and Flux'-operation, where the axial induction of the upwind turbine is reduced. It can be seen that the resources of the second turbines are better in figure 2b and that the wake of upwind turbine is smaller in this figure. Figure 3 shows the outputs of the actuator discs as a function of the axial induction factor of the first turbine. The

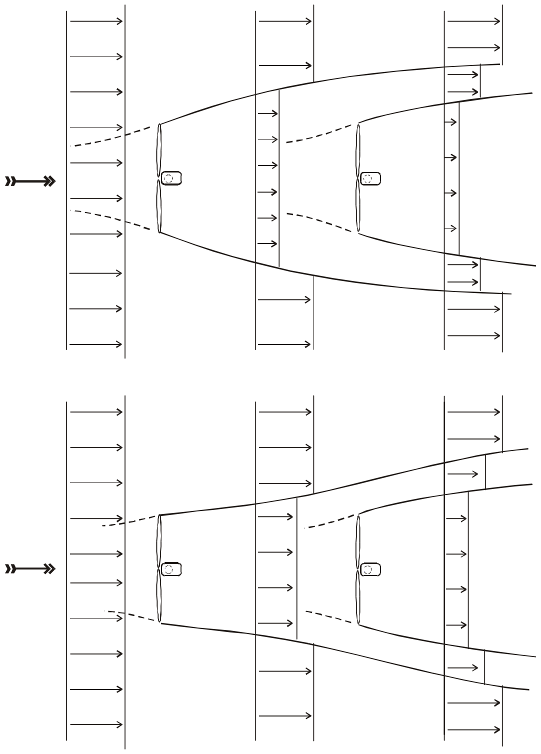

Figure 2: two turbines on a line parallel with the wind. The upper figure shows the classical situation and the lower curve the situation in 'heat and flux'-operation, wherein the induction of the upwind turbine is lower than the individual optimum.

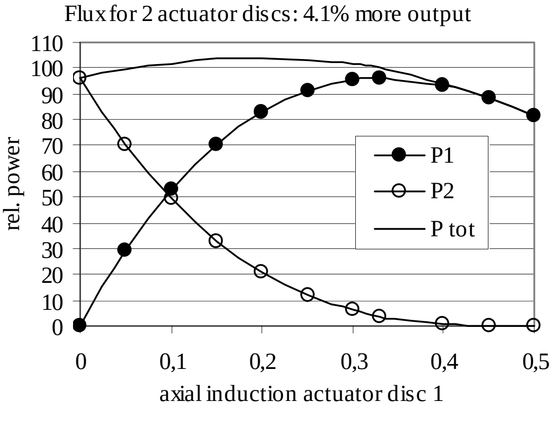

Figure 3: Two actuator discs are positioned on a line parallel to the wind. The downwind disc is fully in the wake of the upwind disc. The combination reaches maximum output when the axial induction factor of the upwind disc is 1/5 and that of the downwind one is 1/3. Then the output is 4% higher compared to the situation that both discs are operated at the Lanchester-Betz optimum (a=1/3).

curve of the first turbine (P1) follows the classical Lanchester Betz relation, that of the second turbine (P2) is also a function of the axial induction of the first disc. The second disc always operates at its optimum at $a = 1/3$. The production of the combination (curve P-tot) reaches its optimum for $a=1/5$ for the first turbine. Then it exceeds the classical situation by 4.1%. The numerical result is valid for the situation that momentum inflow from outside is neglected and that the wake of the first turbine is fully developed before it enters the pressure field of the second turbine.

4. HEAT and FLUX

The new insights are denoted shortly by 'Heat and Flux'. Preliminary models indicate that the application of 'Heat and Flux' has the potential to increase production by 1% and to reduce the average axial force in a wind farm by 7%. Those numbers are valid below nominal wind speed only. The three effects summarised in the chapter 2 all demand the same measure: reduction of the axial induction at the windward side of wind farms. This measure can be implemented easily by minor changes in the control algorithms. A more significant change will be the adaptation of SCADA systems to control the induction parameters of the individual wind turbines in wind farms. Nevertheless the implementation of Heat and Flux is simple since it does not require new hardware. Another benefit is that the turbulence generated by the windward turbines decreases in 'Heat and Flux'-operation. Since turbulence is a major factor in the loading of the first turbines behind the windward turbines this is a valuable property.

Figure 4 Wind turbine model, 25 cm diameter, NACA 0009 airfoils, 4 pitch settings.

The potential of Heat and Flux was such that ECN initiated several projects to further develop the physical understanding, to implement the effects in wind farm design codes and to test the hypotheses experimentally. Also a patent was applied on the technology. The next chapter presents the first experimental proof of principle.

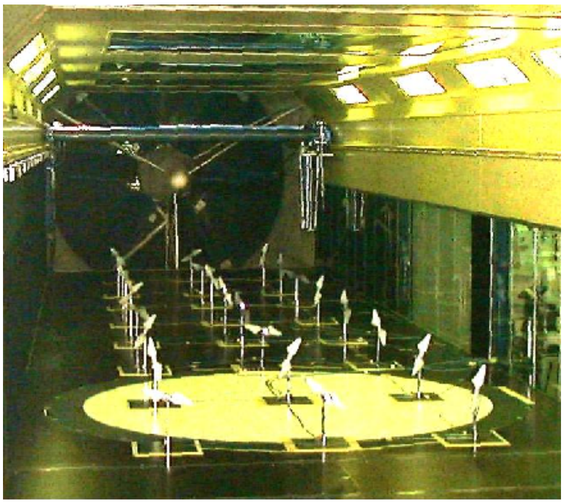

Figure 5: model wind farm of 8 by 3 turbines in the boundary layer tunnel.

5. WIND TUNNEL EXPERIMENT

5.1 Set-up

To check our physical insight an experiment with a model of a wind farm in a wind tunnel was set up. We designed wind turbines with a behaviour which was as much as possible comparable to that of large commercial wind turbines. Since the lift and drag characteristics of airfoils become very Reynolds dependent for Reynolds numbers below 40.000, we had to use large chords and a minimum rotor diameter of 25 cm (see figure 4). Furthermore we choose the NACA 0009 airfoil over most of the span (Naca 0012 near the root), since this profile has low Reynolds dependency at low speed. Due to the relatively high aerodynamic drag of small airfoils, the design tip speed ratio was low: about 4.5. This and our aim to obtain high Reynolds numbers explains that the relative length of the chord of the model rotors exceeds that of large commercial wind turbines by a factor of 3. The rotors were made of glass fibre reinforced plastic and were made in one piece. We produced rotors with 5 pitch angles varying from -2.5° to +7.5°, step +2.5°. Adjusting the pitch angle was performed by changing the rotor. Rotors with angle 0° were designed to have an axial induction factor of 1/3 at a tip speed ratio of 4.5. The rotors with larger angles were meant to reduce the axial induction factor in order to conduct 'Heat and Flux'-experiments. The measurements took place in the boundary layer tunnel of TNO at Apeldoorn, the

Netherlands. The boundary layer was adjusted to offshore roughness and the entire farm was sclaed by a factor of 400. The tunnel has a test section of over 10 metres length and a cross section of 3 metres width by 2 metres height. The wind speed can be adjusted between 1 and 13 m/s. To test the correctness of our new models, we installed a model wind farm of 8 rows of 3 turbines in the tunnel (see figure 5).

5.2 Results

We took measurements from the farm in the classical situation. This meant that rotors of pitch 0° were installed on all turbines. All turbines were operated at their individual maximum output like in actual commercial wind farms. Those measurements were compared to measurements with a 'Heat and Flux'-wind farm. This means that we installed rotors of +7.5° pitch angle (positive is towards vane) on the turbines in the first two rows at the windward side. The remainder of the farm is equal to the classic farm.

The average power per row for the two operational modes is shown in figure 6. It can be seen that the experiment confirmed our models: the output of the first upwind turbine in the 'Heat and Flux'-farm decreased since the induction factor was decreased much. Therefore this turbine had become more transparent for the wind so that the wind speed for the second rotor increased considerably. Therefore the second rotor produced more and also the remainder of the farm at the lee side did produce slightly more. 'Heat and Flux'-operation increased the output of the farm as a whole by 4.6%, even more than we expected. It should be noted that part of this increase is due to the small size of the turbines and the low Reynolds numbers. In figure 7 the average axial loading per row is shown. Those results are consistent with our models too. The axial force on the first tow decreased by almost 50%!, the loading on the second row increased by about 10 percent and the loading on the downwind rows remained the same. It can be seen that the axial loading is more uniform in the 'Heat and Flux'-farm than in the classic farm, of course a significant advantage.

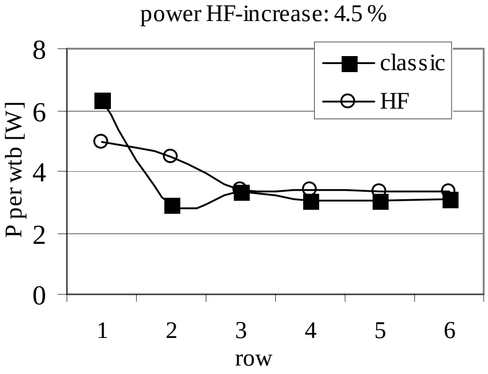

Figure 6: The power per wind turbine averaged over the three turbine per row. The curve 'HF' represents 'heat and flux' operation and shows that the first row generates less power, the second row more and the remaining rows slightly more.

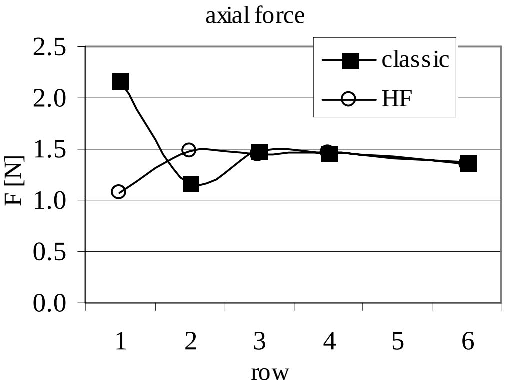

Figure 7: The axial force per wind turbine averaged over the three turbines per row. The curve 'HF' represents 'heat and flux' operation and shows that the loading of the first row has reduced by about 50%, and that the loading has become more or less uniform over the entire farm.

6. CONCLUSION

We conclude that the maximum extractable useful energy shall not occur when all turbines operate individually at maximum output. By decreasing the axial induction factor below the Lanchester-Betz limit at the windward side of a wind farm, the overall output of the farm increases and simultaneously the maximum axial loading decreases.

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