Heat and Flux Configurations on Offshore Wind Farms

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Abstract. This study aims to determine the best configurations of the Heat and Flux concept for more profitable and utilizable settings in a wind farm in terms of increase in the energy yield and reduction in loadings. The computations are performed with alteration of a single parameter at a time.

The reference farm for this study is EWTW, the ECN test farm in Wieringermeer, as this farm was also the reference for the validation of both the Heat and Flux concept and the software tool FarmFlow. All the studies are performed with FarmFlow developed by ECN, which computes wake deficits and turbulence intensities, resulting in the energy yield of all turbines in the farm.

1. Introduction

Creating a better and a sustainable world started being one of the crucial issues of the mankind. Relatively the evitable global problems need especially determined governments with decisive solutions. It is believed that global problems, such as insufficient supply of energy, energy security, wars, nuclear weapons, global warming, economy and water sustainability; each have more than one reason lying behind, but the main ones indicate the direct relation with energy. As a solution to the energy problem, sustainable energy tends to be very prominent, consisting of renewable energy and energy efficiency. Eventually, combination of these energy issues reveals that energy generation methods from renewable sources should have maximized efficiencies.

Nowadays it is more explicit that wind energy is becoming a flagship among the other renewable energy sources as the learning curve of the wind industry indicate a reduction in the costs and thus an increase in the progression rates. On the other hand, subsidies especially in European countries are started being cut down which create indefiniteness for the future investments in the sector.

Due to the utilizable high quality wind sites and the economic reasons, wind turbines are generally considered in clusters, called wind farms or wind parks. Especially for offshore investments, the costs of individual installations would reach to peak as the grid integrations have to be built separately. On the other side, most of the wind turbines in a wind farm are exposed to the wake of upwind turbines. With regard to this problem, the patented Heat and Flux concept of ECN provides an increase in the energy yield of the whole wind farm; meanwhile the loading reductions on the turbines become significantly important. The main focus of this study is to find out the best configurations of the Heat and Flux concept [1].
2. FarmFlow and Heat and Flux concept
FarmFlow tool has been developed by ECN for precise calculations of the wake effects in offshore wind farms [2,3]. The fundamental wake model used in FarmFlow is the UPMWAKE code [4]. This is a model with a 3D parabolized Navier-Stokes code and a $k-\varepsilon$ turbulence model for turbulent process in the wake. The method of Panofsky and Dutton is used to model ambient flow [5]. The free stream wind speed is specified with a wind profile for prescribed ambient turbulence intensities and the Monin-Obukhov length, which takes into account the atmospheric stability. In FarmFlow, stream wise pressure gradients are calculated by an axisymmetric vortex wake model to realize the expansion and deceleration of wind turbine wakes. In the near wake region, with including an adapted near wake turbulence model, this hybrid method of wake modelling provides adequately accurate results in reasonable computational time periods.

A wind farm shall be considered as a single body for energy extraction instead of a combination of individual wind turbines. The Heat and Flux concept-very recently started being called Active Flow Control-put forward the arguments that the classical operation (at the Lanchester-Betz optimum) of wind turbines in a wind farm may not result in the maximum power output. However, when the most upwind turbines in a wind farm operate below the optimum, the downward turbines start producing more power and the net production of the wind farm slightly increases. Besides, average loadings on the most upwind turbines are reduced as well. This concept is validated with both tunnel and on-site testing [6].

3. Power optimization with Heat and Flux for ECN test farm
The ECN Wind Turbine Test Station Wieringermeer, EWTW, is located in the Netherlands near Wieringermeer. The test farm used in this study consists of 5 units of variable speed, pitch controlled research turbines with a rotor diameter and hub height of 80 meters and 2.5MW of rated power.

The research turbines are aligned in an array with a distance of 3.8 rotor diameters between each other. The most eastern turbine is located approximately 0.9km away from the lake IJsselmeer. The row is positioned at a 95° angle with respect to north.

The wind regime has an approximate Weibull distribution with a shape parameter of 2 and a scale parameter of 7. The wind data is received from a meteorological mast at 71.6 meters height [7].

3.1. Optimal Heat and Flux configuration
In this section, pitch angle settings and turbulence intensity effects on the power production of the ECN test farm will be evaluated.

3.1.1. Heat and Flux configuration effect. The goal of the Heat and Flux configuration study is to determine the optimal pitch angle settings for each turbine in order to optimize the power production. The second turbine in a row experiences a single wake effect, while the third turbine in a row experiences a double wake effect. From this, one may expect that the second turbine produces more power than the third turbine. The graph below proofs that this is not necessarily true. The added turbulence in the wake of the first turbine accelerates the recovery of the wake of the second turbine. As a result, the effect of a single wake can be stronger than the total effect of multiple wakes.
A beneficial effect of turbulence is that it accelerates the recovery towards an equilibrium state. A mixing process requires sufficient input of energy which is readily available in a turbulent flow [8]. Therefore the graph shows no further decrease of power production after the second upwind turbine.

As the second turbine has a vital importance for the yield of the wind farm, different pitch angle settings of the 1st and the 2nd upwind turbines in the row have been calculated. All results are averaged with the Weibull probability function.

To determine the most effective scenario for maximizing the yield of EWTW wind farm, turbulence intensity (TI) of 9% was chosen, which is a normal value at EWTW wind farm. The Weibull probability function is used to average the results of all wind speeds.

Configuration numbers consist of 5 digits where each digit represents the turbine pitch angle for the turbine in that row. Configurations 30000 and 40000 produce the highest yields.

![Figure 1: Influence of wake effects on power performance](image1)

![Figure 2: Power comparison of different pitch angle settings](image2)
3.1.2. *Influence of turbulence intensity*. The turbulence intensity is one of the crucial parameters that affect the power production, especially when many turbines in several rows are to be installed.

The presence of a wind turbine will influence the wind flow locally. It decreases the wind speed behind the wind turbine and turbulence is produced due to the large velocity gradients. This phenomenon of wind turbine influenced turbulence is known as wake effect. Wake effects need to be considered for wind turbines installed behind other turbines. This is particular interest wherever wind farms with many turbines in several rows are to be installed [9].

To investigate the influence of turbulence intensity on Heat and Flux results, a basic comparison is done between the best values obtained from the simulations (30000) and the results for normal operation (00000).

| TI  | 5%  | 7%  | 9%  | 11% | 13% | 15% | 17% |
|-----|-----|-----|-----|-----|-----|-----|-----|
| P(30000) - P(00000) | 1.04% | 3.34% | 3.46% | 2.50% | 1.40% | 0.49% | -0.07% |

**Table 1**: Influence of turbulence intensity on Heat and Flux results (power comparison of the Heat and Flux configurations)

The influence of the turbulence intensity is obvious, as the benefit of Heat and Flux rises up to 3.46% at a turbulence intensity of 9% and turns into negative at very high turbulence intensities of more than 17%. It is concluded that Heat and Flux has a positive contribution to the yield at normal turbulence intensity levels.

3.2. *Influence on loading*

Although the power production is the major concern in this study, loading is also considered, as it determines the lifetime costs of a wind turbine design. In particular, scenario and second turbine effects are analyzed in this section. Figure 3 shows the effect of Heat and Flux configurations on the average wake turbulence intensity.

![Figure 3](image_url)

**Figure 3**: Effect of Heat and Flux configurations on the average turbulence intensity

The trend of the graph shows a general decrease in the average turbulence intensity of in-wake turbines when the pitch angle of the most upwind turbine increases. In combination with the power productions of these configurations, 30000 is still the most advantageous case with maximum power production and significant reductions of the average turbulence. Additionally, the reason of the low turbulence intensities for 4 m/s free stream wind speed is that some turbines are not operating due to the lower wind speeds in the wake compared to the cut-in wind speeds of the turbines.
3.3. **Distance effect of Heat and Flux results**

The in-row distance of an array has a large effect on the benefit of the Heat and Flux concept. To investigate this effect, the results of configurations 30000 and 00000 are compared for different spacing between the turbines. The Weibull probability function is used to average the results for all wind speeds.

![Figure 4: Heat and Flux effect on different row lengths and turbulence intensities](image)

The profitable range of the Heat and Flux concept is limited to a maximum turbine spacing of 7D and a maximum ambient turbulence intensity of 13%.

3.4. **Array length effect**

The array length (the number of turbines in a row) has an influence on the effect of the Heat and Flux concept, as confirmed in the work of C. van Gestel (2010). The reason is obviously due to the change in the wind profile that passes the most upwind turbine in the row because of the pitched blades. Hence all the successive downwind turbines are exposed to higher wind speeds and thus produce more power. Beneath, the results of the computations ran in FarmFlow are presented to visualize this influence. The free stream turbulence intensity is 9%, as in the previous simulations for the EWTW test farm.

![Figure 5: Average power productions of the turbines in a row of ten units with NO and Heat and Flux settings](image)
As expected, the first wind turbine in the row has a power drop while the rest of the turbines enhance their power productions. This graph helps us to interpret that, as the number of turbines in a row increases, the Heat and Flux effect increases as well.

4. Conclusion
Heat and Flux is a concept, patented by ECN. It provides power increase in a wind farm while reducing the loadings on the wind turbines. The main goal of this study was to find an approach to the implementations of the Heat and Flux concept for the optimum case. This case stands for maximizing the total energy yield of a wind farm by reducing the axial loads.

The ECN test farm, EWTW, is used as reference farm. Optimal Heat and Flux configurations are determined for this test farm. The influence that ambient turbulence intensity, array length and spacing between the turbines have on the effect of Heat and Flux is also investigated.

The results show that the Heat and Flux concept can be commercialized according to the specific site conditions. With the application of the Heat and Flux concept, the power production of a wind farm can be increased on the order of 1%, while at the same time the loading of the turbines is decreased.

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