

Wake Modeling of an Offshore Wind Farm Using OpenFOAM



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ENGLISH

Summary

The aim of this study is to test the availability of the Computational Fluid Dynamics (CFD) tool OpenFOAM to estimate offshore wind turbine wakes. For this purpose, required libraries of the tool are investigated and developed. In this simplified CFD wake model, wind turbines are modeled by an actuator disk which applies an axial momentum source on the wind flow. The uniform and radial load distributions on the actuator disk are assessed and the radial actuator disk library is modified. In addition, two various groups of coefficients of the standard $k-\epsilon$ turbulence model and afterwards an additional turbulence model are checked. In each part of these test cases, the results are evaluated using measurement data of the Sexbierum wind turbine experiment. Finally, Alpha Ventus wind farm is simulated for certain wind directions and the results are validated using measurement data from the offshore mast FINO1 in terms of wind speed deficit and turbulence intensity and compared with a reference simulation obtained by the commercial CFD package PHOENICS.

Introduction

Undoubtedly development of the wind energy as one of the primary clean sources is an inevitable way to achieve sustainable and green energy supply. In this respect, offshore wind farms are rapidly getting bigger. Wind turbines operating in a wind farm will be exposed to the wake influence of neighboring turbines. Wake behind a wind turbine leads to a reduction of the mean wind speed and an increase of turbulence level. Therefore in order to design an optimum layout for a wind farm, the evaluation of the wind turbine wake effect is essential because it leads to high fatigue, which reduces significantly the turbine lifetime, and decreases the energy extraction for the downstream wind turbines. There are different approaches to model the wind turbine wakes, from analytical models to three-dimensional CFD rotor modeling. Today, most of the site assessment CFD simulations are performed using commercial packages like PHOENICS [2]. As an alternative to those commercial packages, the open source CFD toolbox OpenFOAM [1] is getting more important. Due to the open source concept, the toolbox license is free of charge and the free access to its source codes which gives the ability for self-enhancing and extending the program, makes OpenFOAM very interesting for wind farm developers. For

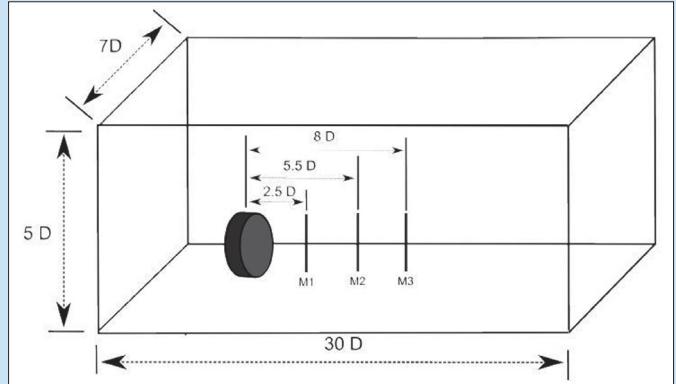


Fig. 1: Outline of the Domain and location of met masts

Tab. 1: Optimum grid resolution at the rotor after the mesh independence analysis (Nz number of the nodes below hub height) [6]

Axial direction (Δx)	Crosswise direction (Δy)	Vertical direction (Nz)
0.06D	0.16D	15

Tab. 2: The standard k- ϵ model coefficients for an industrial-type flow

C_μ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	σ_k	σ_ϵ
0.09	1.44	1.92	1	1.3

Tab. 3: The standard k- ϵ model coefficients for the flows in atmospheric boundary layers

C_μ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	σ_k	σ_ϵ
0.033	1.176	1.92	1	1.3

Tab. 4: k- ϵ RNG model coefficients

C_μ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	σ_k	σ_ϵ	η_0	β
0.0845	1.42	1.68	0.71942	0.71942	4.38	0.012

this work, OpenFOAM 2.1.1 has been used and all the simulations were run in a workstation of 16 GB RAM quad core Intel 3.4 GHz processor [4] and conducted through the solver simpleFoam. Thrust is the only force applied on the wind flow by the actuator disks and the atmospheric stratification is assumed to be neutral throughout the project.

Sexbierum experiment

Sexbierum wind farm is located in Netherlands. The main goal of the Sexbierum measurement campaign was to measure and analyze the wake flow behind a conventional horizontal wind turbine. For this purpose, a meteorological mast was placed at 2.8D upstream of the wind turbine and three met masts downstream, at distances of 2.5D, 5.5D and 8D. The wind turbine produced a rated power of 310 kW and had a rotor diameter and hub height of 30m and 35m respectively [5]. The terrain around the wind farm is considered flat with the closest town 3 km away. The local roughness length was $z_0 = 0.0018$ and the thrust coefficient at inflow velocity of 10 m/s and under neutral conditions was $C_t = 0.75$. The results of the simulations in each section of this chapter are validated using the measurement data extracted from [5, 6].

Model Set-up Strategy

The inlet boundary is defined by the vertical logarithmic profile. For the back and front sides, slip condition is considered and the top boundary is defined by setting the inlet conditions of the wind. The ground is assumed to be a wall, for which the equilibrium condition between the turbu-

lence production and dissipation rate is approximately true [7]. The outlet boundary is defined by the zero gradient condition for all variables except the pressure which is set to 0. The simulation is resolved in a computational domain representing the surface boundary layer (SBL) with the length of 30D in the axial direction, 25D downstream and 5D upstream of the wind turbine. The width of the domain is 7D and the height is 5D. The outline of the domain and location of the met masts are illustrated in Fig. 1. The domain size is taken from [6] where a similar work was done using the commercial software package Fluent. In [6] a grid independence study has been carried out in which different resolutions at each direction were tested and the resolution shown in Tab. 1 gave grid independent results. The same resolution is used in this part. In order to limit the number of the grid points, a stretching factor of $r = 1.12$ is applied in the vertical direction from the ground with the cell height of 1m till the domain top where the resolution reaches to 8m. In addition, a stretching factor of 1.04 is used in the axial direction downstream of the wind turbine.

The standard k- ϵ coefficients sensitivity test

Among the standard k- ϵ model coefficients, $C_{\epsilon 1}$ can be calculated after setting C_μ and using Eq. (1) which is valid for local equilibrium condition in the ABL according to the Richard and Hoxey proposal [7].

$$\sigma_\epsilon = \frac{\kappa^2}{(C_{\epsilon 2} - C_{\epsilon 1})\sqrt{C_\mu}} \quad (1)$$

For C_μ , two values are mostly suggested [8, 9] upon which the other coefficients are calculated. Tab. 2 represents the

coefficients recommended for an industrial-type flow [8] and Tab. 3 corresponds to those suggested for a wind flow in the ABL [9].

Fig. 3 compares the simulation results with measurement data at 2.5D and 8D downstream of the wind turbine. In this figure the results of a similar simulation, which was carried out by Cabezon [10] using Fluent 6.3 (solver) in combination with ANSYS ICEM 11 (grid generator), are also shown to compare OpenFOAM with those softwares (the simulations setup from domain size and grid resolution terms are the same). The main point that can be taken from the plots is the underestimation of the wind velocity by the standard k- ϵ model. It is noticeable that none of the simulations can resolve the problem with an acceptable amount of accuracy. At the distance of 2.5D and wind direction of 0°, the error of $C_\mu = 0.09$ reaches 47% while it is 38% for $C_\mu = 0.033$. The error of the Fluent simulation is even more and equals 61%. At 8D behind the wind turbine, the results are closer to the measurement data. The maximum errors of OpenFOAM for $C_\mu = 0.09$ and $C_\mu = 0.033$ are 11.25% and 8.7% respectively while for Fluent it is 16.25% (around double). The results above show that OpenFOAM simulation could give better prediction compared to Fluent. Respective the turbulence model coefficients, $C_\mu = 0.033$ is a more suitable choice and will be applied in later simulations.

Comparison of the turbulence models

The standard k- ϵ model is the simplest and simultaneously most common two-equation model and other k- ϵ models have been proposed after some modifications of this model. The k- ϵ RNG (Renormalization Group) [19] is one of the developed models for which the equation of energy dissipation was corrected. This section tests this turbulence model and draws a comparison of that with the standard k- ϵ model. In the k- ϵ RNG the coefficients given in Tab. 4 are used and the other setups remain constant.

From Fig. 3, which validates the simulation results, it can be seen that the velocity field produced using k- ϵ RNG is considerably more in agreement with the measurement data. At near wake (2.5D behind the turbine), the error improves from 38% to less than only 5% and at far wake (8D downstream), it reduces from 9.2% by around half. This significant improvement in results implies that the k- ϵ RNG turbulence model modification can successfully resolve the wind velocity overestimation problem encountered for the standard k- ϵ model. The difference between these two models is considering the effects of smaller scales of motion (smaller eddies) by the k- ϵ RNG model, in contrast to the standard k- ϵ model, where the eddy viscosity is regarded only from one turbulence length scale. It can be concluded that ignoring other eddies by the standard k- ϵ model causes a large inaccuracy for evaluating the wake of a wind turbine.

Non-uniformly Loaded Actuator Disk

OpenFOAM non-uniformly loaded actuator disk library

OpenFOAM 2.1.1 provides a new actuator disk library in which a radial distribution for thrust is applied (radialActuationDiskSource). According to the equation inside its codes, thrust obeys the following equation:



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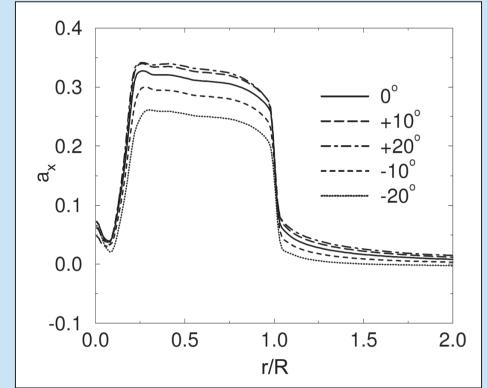


Fig. 2: Axial induction factors for various rotor cone angles. Tjaereborg wind turbine at $U_0 = 10 \text{ m/s}$ [12].

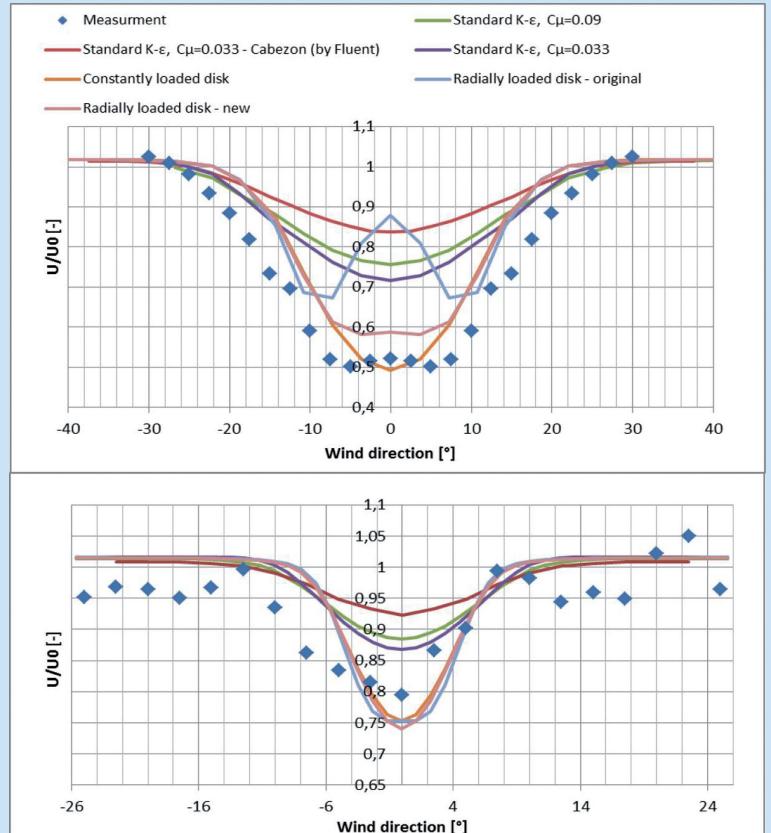


Fig. 3: Cross-sectional dimensionless wake velocity deficit at 2.5D (top) and 8D (bottom) downstream of the wind turbine.

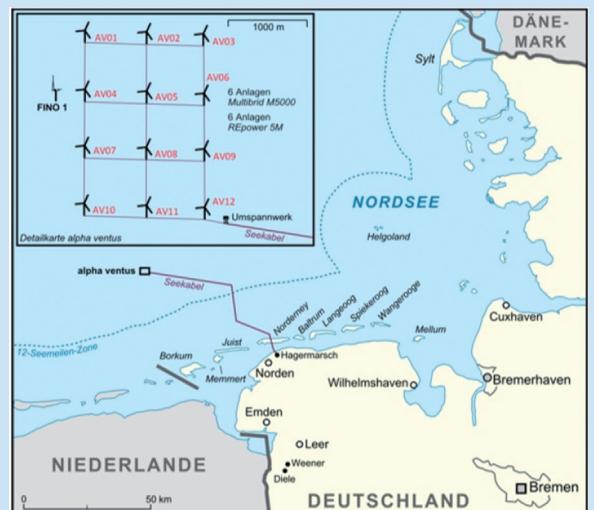


Fig. 4: Location of the offshore platform FINO1 and the wind park alpha ventus in the North Sea [17].

Axial direction (ΔX)	Crosswise direction (Δy)	Vertical direction (Nz)
10m	18m	37

Tab. 5: Grid resolution (Nz number of the nodes below hub height)

$$T(r) = \frac{T}{C_0 + \frac{C_1 R^2}{2} + \frac{C_2 R^4}{3}} \times (C_0 + C_1 r^2 + C_2 r^4) \quad (2)$$

where T is the total thrust force and C_0 , C_1 and C_2 are the function coefficients which are given by user.

Modification of the radial actuator disk library

An investigation on a 2MW Tjaereborg wind turbine [11] has been performed by Mikkelsen [12]. As shown in Fig. 2, Mikkelsen calculated the distribution of the axial induction factor on the wind turbine rotor for different cone angles by means of the BEM theory [13]. Considering the plot in Fig. 2 the thrust profile can be approximated:

$$T(r) = \begin{cases} 0 & r_{cell} < r_{hub} \\ T_{max} & r_{cell} > r_{hub} \end{cases} \quad (3)$$

From Fig. 3, which compares the simulation results with measurement data, the main difference between the plots is found in the center region (near to 0°) where the plot of the original radial disk increases rapidly and reaches 88% of the inflow wind speed and gives an error of 76%. The plot of the new radial disk remains nearly constant in this region and leads to 18% error (it clearly depends on the r_{cell} length used). The closest results to the measurement data still belong to the uniform disk with 4% difference from the measured data. However, only the curve of the new radial disk is able to capture the most similar shape to the measurement data in contrast to the original disk that gives very unrealistic results. At 8D behind the disks, no considerable difference between the results can be seen. It implies that along this distance, the wind recovery is too much to reveal any difference between the disks.

Alpha Ventus Wind Farm Simulation

Alpha ventus [18] is the first offshore wind farm installed in Germany. The wind park is located in the North Sea, to the east of the meteorological mast FINO1 [1] (Fig. 4). It consists of six REpower 5M (AV1-AV6) and six AREVA M5000 (AV7-AV12) wind turbines, each with a rated power output of 5 MW. The hub height and rotor diameter of the REpower wind turbines are 92m and 126m and those of AREVA are 91.5m and 116m respectively. The height level of FINO1 is 91.5m and it is located at a distance of 3D to 23D downstream of the wind turbines [17].

Model Set-up Strategy

In this simulation the wind speed reduction at FINO1 for different wind directions will be determined. To achieve this, the following parts of the simulation will rotate with changing the wind direction: domain vertices, grid, the axis of the actuator disks and their orientation vectors. The distance between the inlet boundary and the first actuator disk is chosen as 5D, whereas the distance between the outlet and the last disk is selected as 25D. The lateral distance amounts to 5D, while the top side of



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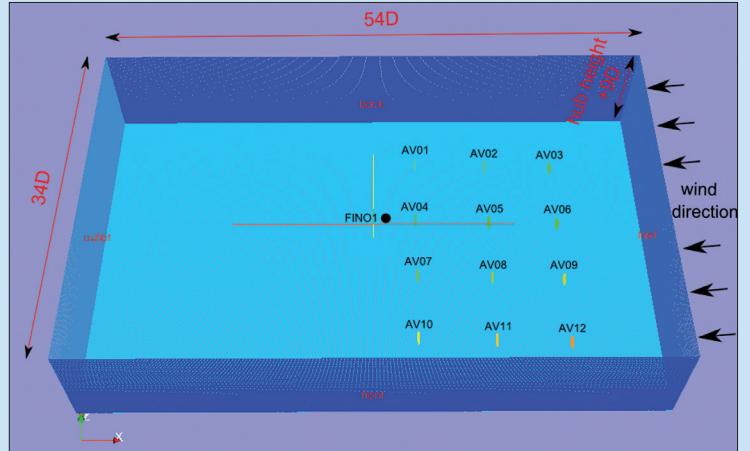


Fig. 5: The minimum domain size for all wind directions.

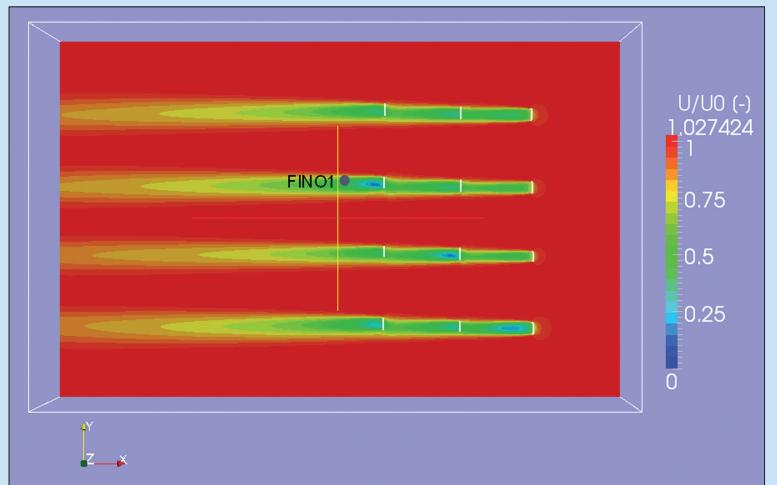


Fig. 6: The normalized wind speed contour at Alpha Ventus at hub height in relation to the free wind velocity of 10 m/s and wind direction of 90°

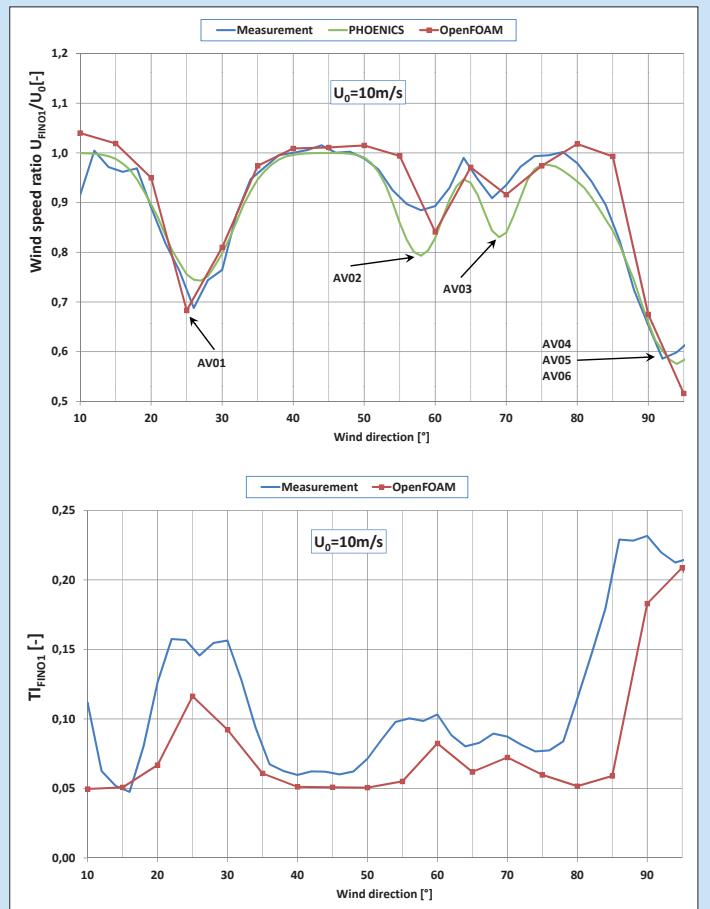


Fig. 7: CFD simulations results and the measured data for different wind directions, $U_0=10\text{m/s}$. Top: wind speed. Bottom: Turbulence intensity.

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the domain is 9D above hub height (Fig. 5). The domain size is considered to be fixed for different wind directions and the limits mentioned above for the cross- and stream wise margins for all the wind directions are always satisfied. The simulation grid contains approximately 12.6 million hexahedral cells. In both directions, stream- and crosswise, the cell sizes are uniform and as shown in Tab. 5, amount to 10m and 18m respectively. An uniform grading was applied for the vertical direction, the cell closest to the ground has a height of 1m and the cell at the top of the domain is of 50m height. It leads to an amount of 37 nodes below hub height. The convergence criteria (residuals) for the velocity, TKE and ϵ were set to $1e^{-3}$ and for p was $1e^{-2}$. The computational time depends on the wind direction. On average, a simulation takes around 10 hours, while 600 iterations were made. The k- ϵ RNG model is implemented since previously it showed a relatively accurate velocity deficit and is a suitable choice for this kind of simulation.

Actuator disk model

Before using the uniformly loaded actuator disk library available in the OpenFOAM package, its codes need to be checked and verified for the case of simulating a wind farm. Eq. (4) and (5) are used within the library to calculate the thrust generated by the actuator disk:

$$T = 2\rho A U_{up}^2 a(1-a) \quad (4)$$

$$a = 1 - \frac{C_p}{C_T} \quad (5)$$

where U_{up} represents the upstream velocity. User has to give the upstream point coordinates for which the program calculates the velocity and substitutes it in Eq. (4). Results of this approach are significantly sensitive to the upstream point. For a case where only one wind turbine is situated in the domain or several turbines which are not in the wake of the others, the upstream point can be somewhere in front and far enough from the disk, so that its flow velocity is not disturbed by the disk. The problem arises for the wind directions at which some wind turbines are found in a line parallel to the wind flow. At this condition, the upstream points of the wind turbine are in the downstream region of another one. For such a case, which happens frequently in a wind farm, this approach is not reasonable anymore. A possibility to avoid this problem is to transform Eq. (4). From actuator disk theory:

$$U_{up} = \frac{U_{disk}}{1-a} \quad (6)$$

where U_{disk} is the wind velocity at the disk. Replacing U_{up} by U_{disk} in Eq. (4) results in:

$$T = 2\rho A U_{disk}^2 \frac{a}{1-a} \quad (7)$$

Besides, Eq. (5) is not a proper way to calculate the axial induction factor a , because the thrust coefficient C_T is a function of the velocity, but the velocity is not already known and is to be calculated by the simulation itself. Alternatively, by referring to a C_T curve for REpower 5M and AREVA M5000, value of the axial induction factor, as a func-

tion of U_{disk} , is calculated and entered into the codes. This enables the modified library to calculate the thrust for different wind speeds.

Results

The results of the conducted simulations are shown in Fig. 6. It illustrates the plot of normalized wind velocity contour on a horizontal plane at hub height for wind direction of 90°. It can be observed, that the mast FINO1 is directly exposed to the wake of three wind turbines. The wake effect on the power production of the wind turbine is clearly visible. As the second and third turbine rows only face wind velocities which are between 50% and 75% of the inflow velocity, the power production at those turbines can be expected to be severely lower compared to the wind turbines in the first row of the farm.

The speed reduction and turbulence intensity at FINO1 is calculated by the developed simulation tool for different wind directions. It is compared with measurement data and the results from a similar simulation conducted by PHOENICS [17] (Fig. 7). At three wind directions of 25°, 60° and 70°, FINO1 experiences wake of wind turbines AV01, AV02 and AV03 respectively. For all these wind directions, the OpenFOAM results stay close to the measurement data and the maximum error, which occurs at the wind direction of 60°, is about 5.8% while the corresponding error from PHOENICS is around two times larger. Although FINO1 is not located in the wake of any wind turbine at wind direction of 10°, the measured wind speed data decreases. This could be related to measurement post-processing.

Conclusion

The k- ϵ turbulence model proved to be significantly sensitive to its coefficients. After comparing the two most common groups of coefficients, $C_\mu = 0.33$ showed a better agreement with the measured data. The results were also compared with another simulation [6], which had been performed within ANSYS Fluent. Although both simulations had similar setup in terms of domain size, grid resolution and turbulence model parameters, the OpenFOAM simulation led to better results in both near and far wake regions. Changing the turbulence model from the standard k- ϵ to the RNG k- ϵ , using the same simulation setup, leads to considerably more realistic results. One of the main problems of the standard k- ϵ turbulence model is the overestimated wind velocity, as reported in other works [9, 14, 15]. In contrast, the RNG k- ϵ , which takes more eddies into account, could successfully resolve this problem.

As the wind turbines in the present work are modeled by actuator disks, it is crucial to apply a load distribution on the disk which can represent a realistic momentum extraction. For this purpose, the radial actuator disk available in OpenFOAM 2.1.1 was investigated. It was observed that its load distribution curve was very far from theory [12], and the results showed a large deviation from measurement data of Sexbierum experiment [5] in the region behind the disk center. Considering this fact, a new radial actuator disk model was implemented and tested. It was able to capture the real shape of the wind speed deficit plot.

In the last section, the wind farm alpha ventus was simu-

lated. Using a thrust curve for the wind turbines installed at the wind farm, CFD simulation for two wind speeds and a wide range of wind directions were performed. Finally, the results were evaluated and compared with a similar simulation [17] carried out within PHOENICS and validated using measurement data. From the results obtained in this work, and their validation with the measurement data, it can be concluded that CFD simulation using CFD toolbox OpenFOAM, seem to be a promising tool for wind turbine wake assessment purposes and due to the open source concept of the program, more modifications have to be applied to further improve the results.

References

- [1] FINO1, 2013. URL <http://www.fino1.de/>.
- [2] PHOENICS; Concentration, Heat and Momentum Limited (CHAM) Engineering-Software Company, 2013. URL <http://www.cham.co.uk/>.
- [3] OpenFOAM, 2012. URL <http://www.openfoam.com>.
- [4] Intel Corporation, 2013. URL <http://www.intel.com>.
- [5] J.W. Cleijne. Results of Sexbierum wind farm. Technical report, Report MT-TNO Apeldoorn. 92-388, 1992.
- [6] D. Cabezon, E. Migoya, and A. Crespo. Comparison of turbulence models for the computational uid dynamics simulation of wind turbine wakes in the atmospheric boundary layer. Wiley Online Library, 14:909{921, 2011.
- [7] N.N. Soerensen and J.Johansen. UPWIND, aerodynamics and aero-elasticity rotor aerodynamics in atmospheric shear ow. PhD thesis, EWEC Milano, 2007.
- [8] N.N. Sorensen. General Purpose Flow Solver Applied to Flow over Hills. PhD thesis, Riso-DTU, 1995.
- [9] H.A. Panofsky and J.A. Dutton. Atmospheric Turbulence Models and Methods for Engineering Applications. John Wiley & Sons, 1984.
- [10] ANSYS Fluent package, 2013. URL <http://www.ansys.com>.
- [11] S. Oye. Tjaereborg Wind Turbine: Dynamic ow measurement. PhD thesis, AFM Notat VK-233, Dept. of Fluid Mechanics, Technical University of Denmark, DTU, 1992.
- [12] R. Mikkelsen. Actuator Disc Methods Applied to Wind Turbines. PhD thesis, Technical University of Denmark, 2003.
- [13] J.F. Manwell, J.G. McGowan, and A.L. Rogers. WIND ENERGY EXPLAINED THEORY, DESIGN AND APPLICATION. John Wiley and Sons, Ltd, 2009.
- [14] D. Cabezon, J. Sanz, I. Martí, and A. Crespo. CFD model of the interaction between the surface boundary layer and rotor wake comparison of results obtained with di_erent turbulence model and mesh strate-gies.
- [15] E. Furbo, J. Harju, and H. Nilsson. Evaluation of Turbulence Model for Prediction of Flow Separation at a Smooth Surface. Technical report, Uppsala Universitet, 2009.
- [16] P.J. Richards and R.P. Hoxey. Appropriate boundary conditions for computaional wind engineering models using the k-epsilon turbulence model. Wind Engineering and Industrial Aerodynamics, 46-47:145{153, 1993.
- [17] A. Westerhellweg and T. Neumann. CFD SIMULATIONS AND MEASUREMENTS OF WAKE EFFECTS AT THE ALPHA VENTUS OFFSHORE WIND FARM. In EWEA OFFSHORE Amsterdam, 2011.
- [18] Alpha Ventus., 2013. URL <http://www.alpha-ventus.de>.
- [19] V. Yakhot, S. Thangam, T.B. Gatski, S.S. Orszag and C.G. Speziale. Development of turbulence models for shear flows by a double expansion technique. Technical report, Institute for Computer Applications in Science and Engineering NASA Langley Research Center, 1991.