State of the Art in Application of Flow Models for Micrositing

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1. Abstract

The limits of the European Wind Atlas methods for calculation of the wind conditions in complex terrain are well known. So in general a growing interest for application and validation of flow models can be observed. Different meso-scale models are applied to describe the state of the atmosphere, but also micro-scale flow models are considered to resolve the small scale variations of wind speed and turbulence within a wind farm in complex terrain.

In the presented paper an overview of the state of the art in application of flow models for Micrositing purposes is given. The state of the art does not relate to the newest development in computational fluid dynamics (CFD), but covers several aspects important for the application of CFD models for Micrositing purposes.

A short overview and classification of the applied flow models and their properties with regard to the application is given. The relevant flow phenomena, as determined by comprehensive measurement campaigns in flat or complex terrain, are shown as typical problems to show the complexity of the task. Exemplary verifications of flow model results against measurement data show, that complicated flow patterns can be simulated quite well by an appropriate flow simulation. However, it becomes clear that this requires not only appropriate models, but also that the application scheme and resolution must be chosen appropriate, otherwise no realistic results can be expected. An appropriate flow simulation can provide a complete description of the flow field and hence can allow a new standard for description of site conditions, especially concerning parameters which are relevant for the loads on the wind turbine in complex terrain, like turbulence, wind speed gradients and flow inclination. The potential of this and the big advantages are shown on base of exemplary investigation of a large wind farm site in complex terrain. Last but not least, the requirements and obstacles for flow model application in wind energy are described. In this context, a Round Robin Test of Flow Models in Wind Energy is announced, which is expected to become an important guideline for assessment of the uncertainty of flow model results.

2. Flow Models Applied in Wind Energy

Numerous flow models of different type and complexity have been applied for wind energy purposes. In Figure 1 a brief and certainly incomplete overview is given, showing the names of some models and doing a classification of the models regarding their main properties. The typical magnitude of the spatial resolution is given as additional information.

The European Wind Atlas methods [1] can be seen as standard for wind energy purposes. The limits of the European Wind Atlas methods for calculation of the wind conditions especially in complex terrain are well known, but still the methods are predominantly applied as they have the advantage of being easy and practical to apply, being assessable for many situations and comparable. Besides the WASP program and some products, which directly make use of the WASP results, like WindPro or Wind-Farmer, the main principles are also implemented on a rectangular grid basis in the model LINCOM, which is included in the product WASP-Engineering. The flow model capabilities are very limited and consist of a set of simplified descriptions of wind flow in the atmospheric boundary layer, derived among others from potential flow theory, and further semi-empirical correction models. The model resolution usually is very high, and the computational requirements very low. Some result properties like the symmetric behaviour of orographic effects are clearly unrealistic, and only due to the strong simplification and low complexity of the model.

Another class of models are the so called mass-consistent models. The basis of probably all of these models is the NOABL model [2], and several modifications or commercial variants like MCF, AIOLOS or WindMap exist. This class of models apply only a very small subset of the physical flow equations, which are solved numerically. The usual resolution of these models is medium to high and the computational requirement is quite low.

The mass consistent models do have similar limits than the European Wind Atlas results, an their results often show quite similar behaviour to the European Wind Atlas results [6]. A significant enhancement compared to the European Wind Atlas model is mostly not visible.

Both model classes described so far are diagnostic models, which means that the results strongly depend on the input data (initialisation). A more realistic flow simulation bases on the numerical solution of the main physical flow equations, what is done with a so called prognostic model. Often “real” flow simulation is associated with the application of a prognostic model, which allow to gather new knowledge about the flow from the results of the simulation. Models of this category are very complex and do have high computational demands.

The prognostic models applied for wind energy can be divided into meso-scale atmospheric models and micro-scale Reynolds-equation solver.

The meso-scale atmospheric models, like KAMM, MM5, Fitnah or GESIMA, usually base on research work in the frame of weather prediction or atmospheric dispersion simulation, and provide a quite complete set of atmospheric phenomenon like radiation or clouds. Furthermore, these models are usually prepared to make use of comprehensive data sources coming from numerical weather prediction. The limit of the meso-scale atmospheric models is mostly the typical finest resolution in the magnitude of 1×1 km², which is too coarse to resolve relevant small-
scale variations within complex terrain. Furthermore, the usual meso-scale models are not capable of simulating turbulence generation by the topography and its transport, as the turbulence in atmospheric models usually is formulated dependent from the mean flow properties.

The family of the Reynolds-equation solver base on computational fluid dynamics (CFD) methods or services provided for industrial applications like the optimisation of vehicles or the design of turbine blades. The use of CFD methods is fully established for such purposes and several highly developed, flexible CFD packages are available. These can be adjusted to the specific application requirements, like the wind modelling in the boundary layer, which means that specialised know-how is required to apply these models. Usually these CFD models comprise a higher order turbulence model, are flexible regarding the calculation grid used, work very efficient and are validated for many application cases. The resolution for wind energy purposes is, due to the size of the required model area, limited to a finest resolution in the order of 20 m, and hence is capable of resolving small scale height structures. Due to the mostly used $k-\varepsilon$ turbulence model, the generation of turbulence by the topography and its transport can be simulated in principal.

Most of the described models were already tested by the authors. The WASP model within the scope of some research investigations [5][6] and as part of the daily project work, within this scope also WindMap. The meso-scale model GESIMA was tested during extensive research work [3][4][6]. A comprehensive model comparison, including the above mentioned and several other models of different complexity, including LINCOM, AIOLOS and others, was performed during a European research project [6]. The MMS model application is described in another paper [7], whereas in the following the investigations are conducted on base of the micro-scale model PHOENICS, which is provided by Cham LTD, UK.

As base for the calculations, the PHOENICS model was adjusted by DEWI to the atmospheric boundary layer environment. This encloses the development of an appropriate application scheme, the selection of the correct submodels and parameterisations and as important aspect the adjustment and verification of the turbulence parameterisation for boundary layer conditions [8].

As these issues have a considerable influence, it is important to emphasise that the model results as presented in the following have to be considered as exemplary results, which can potentially be obtained, if a principally validated micro-scale flow model is adjusted and applied carefully and correct within the developed application scheme. The aim is not, to derive a general statement regarding the capabilities of the applied model, and this would not be possible, as such a property would be connected more to the way of application of the model, than to the specific model itself.

3. Wind Profile Verifications

As part of the systematic verification of the flow model capabilities a verification campaign with the measurement data of the 130 m-mast near to the test site of DEWI, north of Wilhelmshaven, near to the coast of the North Sea, was performed. The high quality, long term data allow a reliable wind profile measurement on base of the wind speed measurement heights 11 m, 32 m, 62 m, 92 m and 126 m and additional meteorological measurements to determine e.g. the temperature stratification.

The wind profile measurement was compared to the calculation on base of the logarithmic wind profile and the CFD simulation results for different situations. The most clear situation is shown in Figure 2, where this comparison is shown for a situation of a wind direction sector with low and uniform roughness length, neutral temperature stratification and wind direction coming from inland.

The wind profile as calculated by the logarithmic wind profile, which is identical to the WASP principle for this (idealised) conditions, shows a quite good agreement with the measurement data up to heights of about 60 m. For larger heights the actual wind speed is underpredicted by the logarithmic wind profile by several percent. The wind profile as calculated by the CFD method fits very well to the measured profile for all measurement heights. It turns out that for this situation the extrapolation of the wind speed measured at 11 m to the highest anemometer at 126 m can be done by the CFD calculation with an error far below 1%.

This is a noticeable small error, which however should not be assumed to be valid in general and transferable to any other situation, as especially the homogenous roughness conditions for this situation are quite ideal. However, the close match of the CFD results to the measurements is clear, and also true for other situations and directions.

![Figure 2: Wind profile as calculated with the logarithmic wind profile and the CFD methods, relative to the 32 m measurement value.](image)

It turns out that for this situation the logarithmic wind profile, where the WASP principle bases on, for the shown roughness conditions and the inland wind direction systematically underpredicts the wind speed in large heights. This fits to experience, which are gained with other large measurement mast data, however, which are known to be dependent from site properties, usually smaller than for the shown idealised situation and not generally to be transferred to other sites.

Noticeable is the fact, that this effect is observed for neutral stratification cases, because such an effect often was associated with stratification influence. So this effect seems to be a pure turbulence effect, which obviously can be described very well by a good turbulence model.

4. Flow Simulations at Oberzeiring Site

For the verification of complex terrain flow modelling capabilities, but also to show the complexity of the flow phenomenon itself, the evaluation of mast measurement data, SODAR data and wind farm energy yield data from the
wind farm Oberzeiring was evaluated. The wind farm Oberzeiring (Figure 3) is located in Austria, Niedere Tauern, on a height of approximately 1900 m above sea level, and hence is the highest wind farm in Europe. It operates since end of 2002. The site is very complex and shows steep, long slopes with large height differences and important orographic structures, which have a considerable effect on the wind flow. In Figure 4 a small section from the digital terrain data is shown, to get an overview of the terrain structure.

A comprehensive measurement campaign has been performed at the site to measure the wind conditions and to provide the basis for a good modelling of the wind conditions. Besides wind measurements at one 50 m mast, a measurement at hub height (65 m) to measure the wind turbine power curve and several SODAR measurements at 4 different locations within the wind farm were performed. In Figure 4 also the positions of most of the measurements are shown.

As subject of the first investigations the wind variation within the wind farm was evaluated. The mean wind conditions in the wind farm area were calculated by means of the CFD model and evaluated as value relative to the wind speed measured at the 65 m mast. In Figure 5 this variation is shown as colour map, in the upper map for a wind direction situation of 327°, for the lower map for a wind direction of 331°. It turns out, that the comparatively tiny wind direction change of 4 degrees leads to a change of the relative wind speed of 3% at some locations of the wind farm. This sensitivity on the wind direction is extreme and was not expected. This effect can be observed also in evaluating the energy yield data from the wind farm.

With systematic evaluation of the flow fields for different slightly changing wind direction it becomes clear, that the strong sensitivity is not only caused by the orographic speed-up effects in the wind farm area, but that also some kind of a flow separation happens at the northern slope of the wind farm, where the flow behaves totally different passing a certain height structure westwards than passing eastwards.

The described effect has the important impact, that the simulation of the wind conditions for the wind farm Oberzeiring has to be performed with extreme resolution of the wind direction, if the result should be realistic. A simulation with fixed wind direction sectors would not make sense at the Oberzeiring site.

Taking into account these findings, it is possible to consider the complicated but relevant flow effects correctly. In Figure 6 the variation of the energy yield at the wind farm Oberzeiring, as actually observed, as calculated by WASP
and as calculated by CFD are shown. It becomes clear, that the variation is very large, but can be reproduced quite well by the CFD results, much better than the WASP model. The average deviation of the CFD results are 2.3%, whereas the WASP average deviates by 9.1%. A part of both of this deviation may be caused by slightly different performance of the wind turbines, which could not be evaluated in detail.

The CFD result fits quite well, whereas the WASP model is not capable even to extrapolate the wind conditions measured at hub height to the different wind turbines.

In addition to the measurement mast data, the data from the SODAR measurement were evaluated. In Figure 7 and Figure 8 the measured SODAR profile and in comparison the calculation results for the respective wind direction sector are shown for an exemplary selection of situations. It can be observed, that the variation of the calculated wind profile is large, sometimes a clear negative profile is calculated, sometimes the result gives a positive gradient. Actually the SODAR measurement denotes a very similar behaviour, except for usually the lowest wind speed measurement, which can assumed to be disturbed. As a result, also this issue leads to a good correspondence of the CFD simulation and the measurement.

5. Site Assessment in Complex Terrain

Megawatt-wind turbines are being installed increasingly also in very complex terrain. This development does not only increase the requirements for energy yield assessment, but the aspect of the site assessment regarding the suitability of the wind turbine for the site becomes more important.

This assessment is done with respect to the safety requirements as defined in the IEC standard 61400-1 [9] or [10] and includes the parameters relevant for the wind turbine loading, which are especially the mean wind speed, extreme wind speed, ambient turbulence, wake turbulence, wind shear and flow inclination. Most of these parameters are part of the flow field as obtained from the flow simulation. Many of these parameters are not possible to estimate realistically without performing a flow simulation.

As visible in Figure 9, the wind gradients and the flow inclination, respective their maximum values or the values within the rotor area, can be derived from the flow model result, as it provides the complete flow field. In Figure 10 another effect, the generation and transport of turbulence is shown (the colour value represents the value of the turbulent kinetic energy). Especially in the region with large wind gradients, as on the top of the shown hill, the production of turbulence is increased, which affects by transport by the mean flow also the next wind turbines.

In Figure 11 an overview of the investigated complex terrain site is given, shown are 7 km × 7 km in which the height varies from 20 m to 640 m above sea level. The planned wind farm consists of approximately 50 wind turbines. A very good coverage of the wind farm area with 10 measurement masts of high quality and the height 20 m - 55 m is given. This is a valuable base for investigation and verification purposes.

For the assessment of the site conditions, and as possible input for a site specific certification of the wind turbines, a set of parameter is defined, which covers the most important requirements of the IEC 61400-1:
The wind farm turbulence is calculated by means of two different models, the Frandsen model [11], which represents the standard to perform wind farm wake assessment for fatigue load relevant issues, and an Eddy-Viscosity model, which should provide a realistic, not necessarily conservative result for the wake turbulence.

For the most important parameters the spatial resolution is shown by calculation of a colour map. Figure 12 shows a colour map of the characteristic turbulence intensity as defined in the IEC 61400-1. As the IEC proposes the values 18% and 16% for the class A and B, it is obvious, that from the map clear hints for optimisation of the wind farm configuration can be derived.

Regarding the verification of the calculated parameters, it has to be considered that not all parameters can be verified by measurements, because some of the parameters are even impossible or difficult to measure. However, it is quite obvious that for these kind of parameters the performance of a flow simulation according to the state of the art is the best possible way to estimate these.

So for each of the wind turbine positions a site assessment document is provided, which contains all the required information.

Figure 9: Vertical slice through a CFD flow field.

Figure 10: Section of CFD turbulence field. The colour value shows the turbulent kinetic energy.

Figure 11: Overview of the wind farm site. Legend: ● wind turbine positions, + measurement mast positions

Figure 12: Calculated spatial variation of characteristic turbulence intensity. Calculated by CFD on base of the turbulence measurement data.
As the mean wind speed and turbulence values were measured at 10 masts at the site, the measurement values were used as the base for verification calculations. In the following the verification is performed in the way, that for each measurement mast the values at all other masts are calculated (only on base of one mast data) and compared to the measured values. As the wind farm clearly consists of two part, separated by a quite deep valley, each of the two parts is considered separately.

For the wind speed the following values for the deviations are derived: The mean absolute deviation within the eastern respectively western part of the wind farm amount to 2.3% - 2.5% in wind speed.

For the turbulence intensity the following values for the deviations are derived: The mean absolute deviation within the eastern respectively western part of the wind farm amount to 1.8% - 2.2% absolute percent.

Considering the complexity of the site, these are low uncertainty values. For both values it has to be emphasised, that this is the uncertainty of the verification on base of one mast, and that the uncertainty of the application is noticeable lower, as for this the measurement data from all the masts are applied.

6. Conclusion and Outlook

The capabilities of appropriate flow models to calculate the wind flow conditions have been shown. It has to be emphasised that these results are considered as exemplary and not intended to have general meaning. However these results give an outlook on the potential of flow modelling, but also emphasise that the modelling of complex flow pattern require a sufficient effort.

On the other hand, the uncertainties of energy yield prognosis based on the European Wind Atlas Method are obvious and become an increasing problem, as the complexity of the sites increase, the hub height exceeds the scope of validity of the underlying theory, and at the same time the accuracy demands increase. Furthermore, the interest in getting a more complete view of the flow, including turbulence and further load relevant properties, is rising.

So the requirement for a progress in the Micrositing methods is quite obvious. However, as flow models and their results are difficult to assess, and transferable experience is not available, from the financing point of view there are some reservations to abandon the standard, which still is the European Wind Atlas Method.

In this situation DEWI has announced a Round Robin Numerical Flow Simulation in Wind Energy. Within this blind test of flow models it is planned to provide an environment to perform comparable flow simulations to CFD service providers, and to perform an independent evaluation and assessment of the results by DEWI. The aim is to come to transferable findings regarding the uncertainty assessment of the flow models, which are in the market.

There is a great interest among CFD service providers all over the world to participate. Moreover a group of sponsors including some of the most relevant companies in wind farm financing and developing in Germany and one wind turbine manufacturer support the Round Robin test and ensure, that the project will be performed effective and will result in applicable findings.

The project will be supported also by the German Ministry of Environment. The start of the project is scheduled to start in 2004 respectively beginning of 2005 and will come up with results still in 2005.

So, as supplement to the ongoing technical development, the Round Robin Numerical Flow Simulation in Wind Energy is expected to provide important progress in practise and acceptance of flow simulation in Micrositing.

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8. References

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