Renewable Energy 50 (2013) 325–333

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

“Blind test” calculations of the performance and wake development for a model wind turbine

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ARTICLE INFO

Article history:
Received 14 November 2011
Accepted 25 June 2012
Available online 31 July 2012

Keywords:
Wind turbine
Prediction method comparisons
Experiment blind test

ABSTRACT

This is a summary of the results from the “Blind test” Workshop on wind turbine wake modeling organized jointly by Nowitech and Norcowe in Bergen, October, 2011. A number of researchers were invited to predict the performance and the wake development for a model wind turbine that has been developed by and extensively tested at the Department of Energy and Process Engineering, NTNU. In the end, contributions were received from eight different groups using a wide range of methods, from standard Blade Element Momentum (BEM) methods to advanced fully resolved Computational Fluid Dynamics (CFD) and Large Eddy Simulation (LES) models. The range of results submitted was large, but the overall trend is that the current methods predict the power generation as well as the thrust force reasonably well, at least near the design operating conditions. But there is considerable uncertainty in the prediction of the wake velocity defect and turbulent kinetic energy distribution in the wake.

1. Background

The NREL full scale wind tunnel tests, completed in 2000, and the following blind comparison predictions by a large number of calculation methods (Simms et al. [1]) demonstrated how important it is to have detailed data to validate predictions against. The comparison showed that there was large uncertainty in the prediction methods, which called for more refined computer codes. Discussions of some of the issues that surfaced after the tests were presented in the special issue of *Wind Energy*, which was published in 2002 (Schreck [2]).

Since the NREL tests, significant improvements in turbine performance and wake development prediction methods have emerged. The progress in wake predictions over a decade of research may e.g. be found by comparing the review papers by Crespo et al. [3] and Sanderse et al. [4]. From simple analytical wake models based on classical theories, the standard is now to solve transport equations for turbulence properties or solving the turbulent field in time and space using large eddy simulation. But even at these levels of sophistication the results obtained rely heavily on assumptions incorporated by the modeler. This was clearly demonstrated in the comparisons of wake predictions performed by Cabezón et al. [5] using various turbulence transport equation models.

Many wake model studies have used full scale turbine wake data for validation. The disadvantages with this procedure is that the amount of data is sparse and initial and boundary conditions are not known in sufficient detail to allow one-on-one simulations to be made. In this respect wind tunnel studies are preferable, even though the models operate at much lower Reynolds numbers than found at full scale, since the flow conditions may be specified at all levels required to set up a proper simulation. As part of the joint norwegian research programs denoted Nowitech and Norcowe it was decided to set up a model experiment to be used as a data source when testing out turbulence models or developing new tools. Together Nowitech and Norcowe are involved in research on most aspects of offshore wind turbine technology and have about 35 PhD or PostDoc members, many involved with wind turbine aerodynamics. Before the data was released it was deemed a good idea to arrange an open blind comparison test to find how the current models used would perform if only the turbine geometry was known.

The wind turbine model used for these tests was designed in 2008 with the specific aim to form a test case for prediction methods. Therefore this is not a typical wind turbine layout, since measurement and wind tunnel restrictions, combined with test case challenges, had to be considered. For a test case it was important to use a simple geometry while also introducing effects that might be difficult to handle by a prediction method. This led to the design shown in Fig. 1. As may be seen from the photo, the turbine has 3 blades and the rotor sits on top of a stepped tower consisting of 4 cylinders of different diameters. The nacelle is also

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http://dx.doi.org/10.1016/j.renene.2012.06.044

Fig. 1. Model in the wind tunnel.

circular with a diameter of $d = 90$ mm. It has an almost semi spherical hub cover at the front and back.

The model was tested in a wind tunnel that has a test section which is almost 12 m long. The height is about 2 m and the width almost 3 m. For details, see one of the references, Adaramola & Krogstad [6], Krogstad & Adaramola [7] or Krogstad et al. [8]. The rotor diameter is $D = 0.894$ m and the centre of the rotor is located $z = 0.817$ m above the floor level.

The main considerations when operating a model of a large scale structure like a wind turbine in a wind tunnel are wall interference and Reynolds number effects. A rule of thumb is that rotor swept area should not exceed 10% of the tunnel cross section for the measured drag forces not to be seriously affected by wall interference. This requirement was slightly violated for the test model, as the tower and swept rotor area is about 12% of the test section cross section. However, as a test case this was not considered very important since a full simulation would normally take the walls into account. Just as important as the area is the distance from the model to the walls. Therefore, the tower height to rotor diameter was chosen to be about correct for a full scale turbine. Hence interference effects from the ground would be about as expected at full scale.

With a nacelle centered roughly 80 cm above the floor, this leaves of the order of 1 m above the nacelle and about 1.4 m to either side to the nearest walls. This corresponds to distances from about 1D–1.5D. As the flow develops downstream the wake could therefore be somewhat affected by the walls, which may have to be accounted for in the predictions by imposing rigid side walls in the calculations.

The next concern is the large difference in Re that will affect the shear flows. To make the difference as small as possible, the model should be tested at as high velocity as possible and the relevant length scales should be as large as the tunnel size allows. To reduce the gap in Re the blades were therefore laid out with a chord length which was about 3 times what would normally be used. This implied that the required lift coefficient when the model operates at design conditions is quite low. Although the wind tunnel used is capable of operating at speeds up to about 30 m/s, the experience is that when operating at high speeds for extensive periods of time, the temperature rise in the flow will be so high that the air density and viscosity is affected. Therefore the model was designed to operate at 10 m/s with a tip speed ratio of TSR = 6, which is typical for a full scale turbine. In order to test the Reynolds number dependence of the flow, the performance of the turbine was measured over a wide tip speed range for reference velocities ranging from about $U_{ref} = 7$–15 m/s. The power and thrust coefficients were found to be independent of Reynolds numbers for $U_{ref} > 9$ m/s (see e.g. Krogstad & Adaramola [7]).

1.1. The blade geometry

To make the blade specification simple, the same airfoil was used all along the span. The airfoil selected is the 14% thick NREL S826 airfoil. It is originally intended to be used near the tip of a full scale turbine. The blades were made of aluminum and the maximum load on each blade was estimated to be about 15 N. It was assumed that the blades had sufficient stiffness so that geometrical changes due to the loads could be neglected. Therefore this slender airfoil could be used also for the root sections. The airfoil is shown in Fig. 2.

At the nacelle the blade has the usual circular cylinder used to fix the blade to the hub. We expect that many prediction methods may have problems with reliable estimates of the flow where the geometry changes rapidly. Therefore no attempts were made in making a smooth transition from the circular section to the airfoil sections. Between the last circular section and the first NREL profile a simple linear transition region was added, producing a sharp corner at the base of the blade (see Fig. 1). It is expected that if this part is not properly resolved, the spanwise flow due to rotational effects will not be correctly captured, which might lead to severe problems when the blade operation approaches stall. Similarly, the tip of the blade was cut off sharply which will cause a challenge if the tip effects are not well handled.

The model performance and wake data have been previously reported in references [6,7,9,10].

1.2. Test case description

The test case was described in detail in the report by Krogstad et al. [8]. This contains tables describing the geometry and a CAD file for the blades and nacelle was provided. Except for the geometry specifications and wind tunnel inlet conditions, no further information was given by the organizers. Thus, if the participants needed e.g. lookup tables to determine the load distributions on the blades, they would have to generate this information themselves. The way this was obtained would have impact on the results. Hence, the first compulsory output was predictions of the power and thrust coefficients for tip speed ratios from TSR = 1–12. (The runaway TSR had been measured to be about TSR ≈ 11.5.) To get further information about how well the airfoil characteristics were modeled, the spanwise blade loads were required for TSR = 3, 6 and 10.

The main focus of the blind test was on the wake development behind the turbine. The participants were therefore asked to

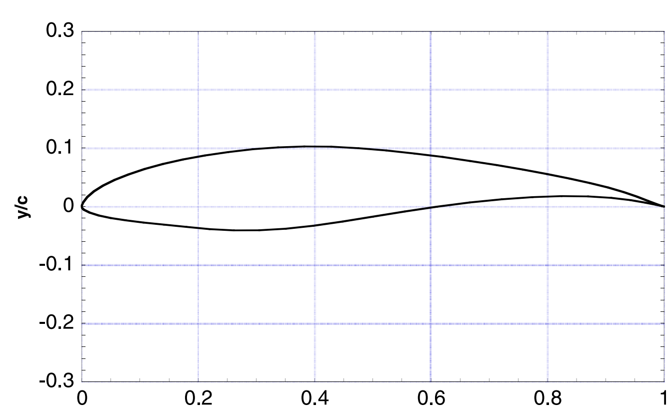

Fig. 2. Shape of the NREL S826 airfoil.

provide profiles of the velocity defect, $(U_{\mathrm{ref}} - U)/U_{\mathrm{ref}}$, and turbulent kinetic energy, $X/D = 5$ at three downstream positions, $x/D = 1$, 3 and 5, measured from the plane of the rotor. The data should be provided along a vertical and a horizontal line through the centre of the wake for three operating conditions, TSR = 3, 6 and 10, so that asymmetries due to the tower wake could be detected.

The predictions were compared with thrust forces measured by a 6 component balance on which the model was mounted. The power coefficient was measured using a torque transducer mounted on the shaft driving the rotor which also provided the speed of rotation. Velocities were measured using x-wire anemometry after the signals had been suitably amplified and filtered. The data was sampled for 60 s at 14 kHz, giving a total of 840,000 samples per measurement point. For verification, some of the measurements were repeated using pitot-static tubes and laser Doppler anemometry. The uncertainty in the measurements of the mean velocity were estimated to be less than $\pm$ 2% of U_{ref} and $\pm$6% of U_{ref}^2 for k^2.

The incoming freestream was measured to be uniform to within $\pm$1% measured over the area swept by the rotor and the turbulence intensity was $\sqrt{u_x^2}/U_{\mathrm{ref}} = 0.3\%$.

2. Participants and methods

Calculations were submitted by eight groups, some of whom supplied multiple predictions, giving a total of eleven submissions. In order to start the wake calculations, the power and the thrust coefficients of the turbine must first be estimated. This was therefore compulsory output. Except for two groups, this data was obtained using a Blade Element Momentum method. Three simulations resolved the flow down to the level of the boundary layer on the blade and thereby avoiding the assumptions implied in the BEM methods. One group had managed to find the C_P and C_T data from a previous report on the measurements (reference [9]) and therefore totally avoided any computational errors in the initial conditions for the wake calculations.

Below is a list of participants and the essence of their methods. More details about their methods may be found in the description they provided, which is included in the workshop report by Krogstad & Eriksen [11].

2.1. Agder Energy Production

J. A. Lund of Agder Energy Production used the software *openFoam* in combination with the k–ω SST turbulence model to calculate the wake flow. The rotor was modeled by means of an actuator disk where C_P and C_T were taken from a BEM model. It was documented that the numerical setup was grid-independent. The results will be labelled **Lund** k–ω **SST** in the plots.

2.2. Alcona Flow Technology

E. Manger of Alcona Flow Technology was the only participant who modeled the wind tunnel test case as it was performed. The entire model, including the rotor, tower and nacelle, located in the test section was meshed using 5.3×10^6 cells. A sliding mesh was used to allow the blades to rotate. The flow was solved using the *Ansys Fluent v.13-0* software and the k–ω SST turbulence model was incorporated in the solution. The results will be referred to as **Manger** k–ω **SST**.

J. Kvalvik of the same company performed a simulation using *openFoam*. Kvalvik used a cylidrical rotating grid containing the three rotor blades which was freely suspended in a short square box (about 2.3 m long) without the inclusion of the nacelle nor the tower. The turbulence model used was the one-equation model of Spalart and Allmaras and grid independence was demonstrated using up to 1.8×10^6 cells. Because the computational domain was relatively short, no wake data were submitted. The label used for these data is **Kvalvik**.

2.3. CMR Prototech

CMR Prototech submitted data, performed by T. Hansen, for a simulation that resolved the full flow details down to $y^+ \approx 1$ on the actual blade geometry. The software package used was *STAR CCM+* and the turbulence was modeled using the k–ω SST turbulence model. Hansen assumed axisymetry and therefore did not include the tower. Only one blade sitting on the hub was modeled and periodic boundaries were applied to include the effects of the other blades. A grid refinement test with up to 23×10^6 cells was performed to demonstrate grid independence. His predictions will be denoted as **Hansen** k–ω **SST**.

2.4. DTU Mechanical Engineering

J. N. Sørensen and R.F. Mikkelsen at DTU, Denmark, did in principle provide 3 sets of simulation data, although two of these are closely related. The simplest was a BEM method for a turbine in an unbounded flow field (labelled **Sørensen & Mikkelsen BEM-nocorr**).

As mentioned previously, the model size is in the upper range of what may be considered a free field operation. Sørensen & Mikkelsen had therefore also estimated appropriate corrections for C_P and C_T due to the blockage caused by introducing a drag force in the tunnel. Thus the correction depends on the estimated C_T and at high thrust values corrections up to about 10% were made to the estimated free field C_T. The label used for these data is **Sørensen & Mikkelsen BEM-wtcorr**.

Finally the group delivered data for a combined actuator line/Large Eddy Simulation (LES) using a program called *EllipSys3D*. The forces on the flow as generated by the rotor were represented by rotating actuator lines and the rest of the flow was resolved using the Navier–Stokes equations on a very fine mesh. Only the sub-grid turbulence is modeled while the large scale turbulence is predicted directly from the Navier–Stokes equations. Hence, this solution would normally be considered very accurate, but the accuracy in the wake also depends on the modeling of the rotor loads from the BEM methods. Their predictions are labelled **Sørensen & Mikkelsen LES**.

2.5. GexCon

The GexCon group, consisting of J.A. Melheim, L. Sælen and M. Khalil, performed calculations using the software package *FLACS–Wind* which is developed by GexCon. This is a transient CFD solver which in this case used the standard k–ε turbulence model. The computational domain was similar to the wind tunnel dimensions, but the increase in tunnel height to compensate for the growth of side wall boundary layers was not included. The rotor was represented as an actuator disk and the disk data was obtained using a BEM method. The effects of the tower were not included in the simulations. These predictions have been denoted **Melheim et al.** k–ε.

2.6. National Institute of Advanced Industrial Science and Technology, Japan, and NTNU

T. Kono was on leave from National Institute of Advanced Industrial Science and Technology, Japan, staying at Dept. Energy and Process Engineering, NTNU, at the time of the workshop.

He supplied the second set of data generated using LES with a software package called *Front Flow/red*. The rotor was simulated as an actuator disk where the data was taken from a conventional BEM simulation. The simulations were performed in a domain representing the wind tunnel test section and the effects of the tower and the nacelle were included by adding body forces. 2.4×10^6 cells were used. His data is labelled **Kono LES**.

2.7. NTNU

Data was submitted from the Department of Civil and Transport Engineering, NTNU, by L. Suja and P. Thomassen. The performance of the wind turbine was predicted using the aero-elastic code called *ASHES*, which makes use of the BEM theory. The method predicts C_P and C_T, as well as the radial distribution of the blade loadings, but is not able to provide information about the wake development. The results from this group will be labelled **Suja & Thomassen BEM**.

2.8. StormGeo/Univ. Stavanger

These simulations were submitted by S. Kalvig. She has used the software *openFoam* and represented the rotor as an actuator disk. C_P and C_T data for the disk was obtained from the measurements reported in Krogstad et al. [9]. The calculations were performed in a domain corresponding to the test section of the wind tunnel using a standard $k-\varepsilon$ method, but the effects of the tower were not included. The predictions have been denoted **Kalvig** $k-\varepsilon$.

3. Results

3.1. Predicted performance

We start by presenting the compulsory outputs of the turbine performance. The power coefficient is shown in Fig. 3(a) and the thrust coefficient in Fig. 3(b). The symbols used will be the same in all figures with measurements presented as the large black dots to distinguish them from the predictions. The predictions by the Hansen $k-\omega$ SST, Kvalvik Spalart-Allmaras and Manger $k-\omega$ SST methods are also represented by filled symbols to highlight the methods that solve the flow over the blades in detail, instead of relying in the BEM methods.

The spread in the power predictions (Fig. 3(a)) is surprisingly large, considering that most of the predictions use the same Blade Element Momentum theory as the basis. The turbine peak performance is generally predicted within ±10% and most methods predict the peak performance where it should be, around the design tip speed ratio of TSR = 6.

For the very low TSRs, where the blades are deeply stalled, the deviation from the measured power coefficient, C_P, is mostly small, while at very high TSRs there is significant spread in the predictions. Previous studies (Krogstad & Lund [10]) have shown that the first signs of stall occur around TSR = 4 and it was therefore expected that the principal signs of departure from the measurements would be found here. But except for the predictions by Kvalvik, none of the methods appear to have special problems here. As the stall deepens, however, (at TSR = 3 the blades are fully stalled) the spread becomes larger. But for the deep stall region for TSR < 3, all methods behave well. This suggests that the predictions of the airfoil data, that has to be performed before a BEM calculation can be made, have been successful for most participants, possibly with some inaccuracies in the transition region from the first signs of stall until the profile is completely stalled.

The fully resolved predictions of Hansen $k-\omega$ SST and Manger $k-\omega$ SST do in general perform well. At design TSR they predict virtually identical C_P which are only marginally higher than the

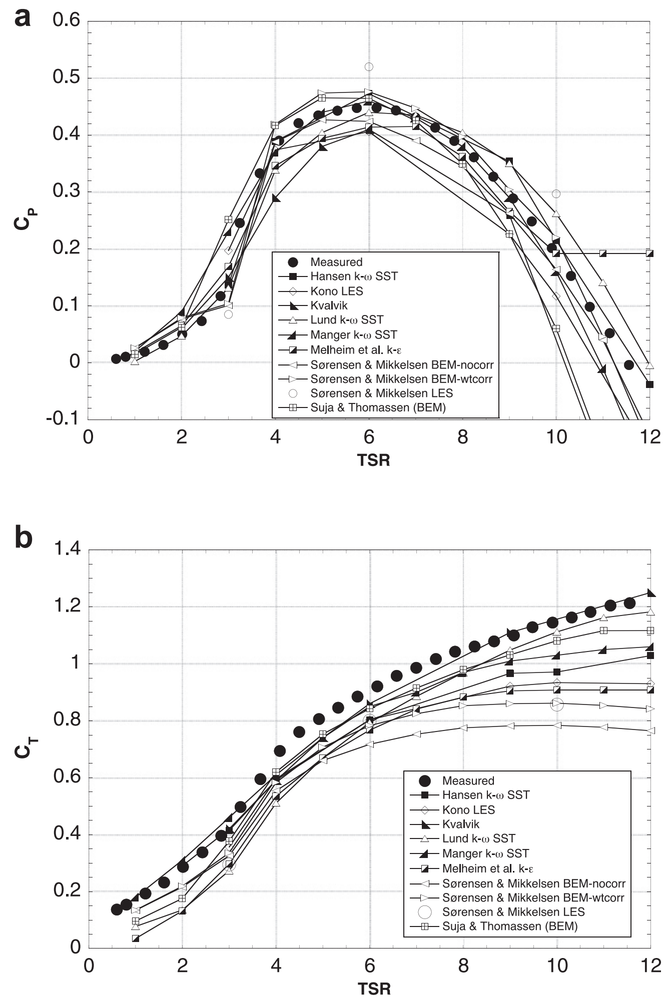

Fig. 3. Turbine performance. (a) Power coefficient, (b) Thrust coefficient.

measurements. The Hansen $k-\omega$ SST method does not appear to have any problems in the fully stalled region either (TSR < 4), but the computations of Manger $k-\omega$ SST tend to over-predict C_P here. At high TSR the two methods predict the correct trend, but while one is consistently producing slightly high data, the other set is correspondingly low.

It is also obvious that the wind tunnel corrections by the Sørensen & Mikkelsen BEM-wtcorr method have performed well for the high and low parts of the TSR range. It appears, however, to have over-compensated the C_P predictions for TSR = 4 and 5, where the uncorrected data agrees well with the measurements.

Looking at the thrust coefficient (Fig. 3(b)), it is seen that the general trend is that C_T is under-predicted by all models. There is considerable disagreement about its value for high TSR. The spread in the predictions at high TSR does not appear to have a systematic trend with respect to prediction methods in the sense that the BEM and CFD methods both appear to be distributed over the entire range of predicted values. It should also be noted that while the Sørensen & Mikkelsen BEM-nocorr method predicts the lowest C_T values for TSR > 5, this can not be because it does not include the restrictions caused by the wind tunnel walls. The Suja & Thomassen BEM method, which also assumes infinite flow domain, is one of the best performers for TSR higher than the design condition.

The fully resolved simulations of the Kvalvik Spalart–Allmaras method perform excellent over the entire range of operations, which is remarkable since the computational domain is terminated only 2D downstream of the rotor and the predicted C_P was not particularly good. The predictions of Hansen k–ω SST, Kvalvik Spalart–Allmaras and Manger k–ω SST are in close agreement over the full range of TSR, with Kvalvik performing slightly better. At high TSR the Manger k–ω SST method performs slightly better than the one by Hansen k–ω SST in predicting C_T, suggesting that the latter method slightly under-predicts the airfoil performance at low angles of attack. Since the Hansen k–ω SST simulations use about five times as many grid points as Manger k–ω SST, and the turbulence model used is the same, this may suggest that Manger k–ω has been more successful in distributing the points wisely.

4. Wake data

The participants were asked to provide predictions of the spatial distribution across the wake at zero angle of yaw for three positions downstream of the rotor plane, at $X/D = 1$, 3 and 5 for three operating conditions, TSR = 3, 6 and 10. Space does not allow the results for all stations and all parameters to be shown here, so we restrict the presentation to the mean velocity and turbulent kinetic energy distributed along a horizontal line across the wake for some of these conditions. Most methods relied on the assumption of axisymetry. Virtually symmetric distributions are also expected from the measurements and the fully 3D calculations along the horizontal plane, except for the few cases where the wake rotation was sufficiently strong to bring the wake behind the tower up to the horizontal plane. (It should be mentioned that the two prediction methods that included the tower geometry also produced the expected asymmetry in the vertical plane, but since most methods produced the same profiles in the two planes, only the data along the horizontal line are presented.)

4.1. *Design conditions, TSR = 6*

The simplest case should be the wake behind the turbine when it operates at its design condition, because the geometry was laid out to produce an almost constant pressure drop across the rotor. Hence one might expect the initial wake profile to be more or less top hat shaped and the turbulent stresses to be small except for a thin region near the tip and root.

4.1.1. *Mean velocity defect profiles at TSR = 6*

The first station for which data was requested was at $X/D = 1$ when the turbine is operating at TSR = 6. Here X is the distance measured from the plane of the rotor. The profiles from the participants at this station are compared with the measurements in Fig. 4(a).

The measurements along the horizontal line shows an asymmetry in the form of a peak around $y/R \approx 0.2$, the reason for which is being investigated, but is unknown at the present. They are, however, also present in the predictions of the two methods that include the full tower and nacelle geometry (Kono LES and Manger k–ω SST), although to a much smaller extent. All predictions show the same shape with a dip in the centre. This is partly due to the flow acceleration caused by the displacement effect of the nacelle and partly because the blades do not extend all the way in to the nacelle, so there is no energy extraction here.

The predictions by Sørensen & Mikkelsen LES perform well over most of the rotor plane, but predicts virtually no velocity reduction behind the nacelle. The same is the case for the predictions of Melheim et al.k–ε, but their wake strength is less than that measured, in agreement with low estimates for C_P and C_T. It is interesting to observe that the *STAR CCM+* predictions by Hansen, using the k–ω SST turbulence model, produce almost identical results to the LES predictions at this station. And so does the predictions by Lund k–ω SST, who uses a different solver but the same turbulence model. In fact these methods give a better collapse with the LES of Sørensen & Mikkelsen than the LES of Kono does. Kono reports that his data is based on 60 s averaging, but it is not known how long the averaging time used by Sørensen & Mikkelsen is, so it is difficult to determine if this is the main cause for difference. Both Lund k–ω SST and Kono LES use actuator disks to set their initial condition so the difference between the LES methods is not likely to be due to Sørensen & Mikkelsen LES using actuator line theory while Kono LES uses actuator disk.

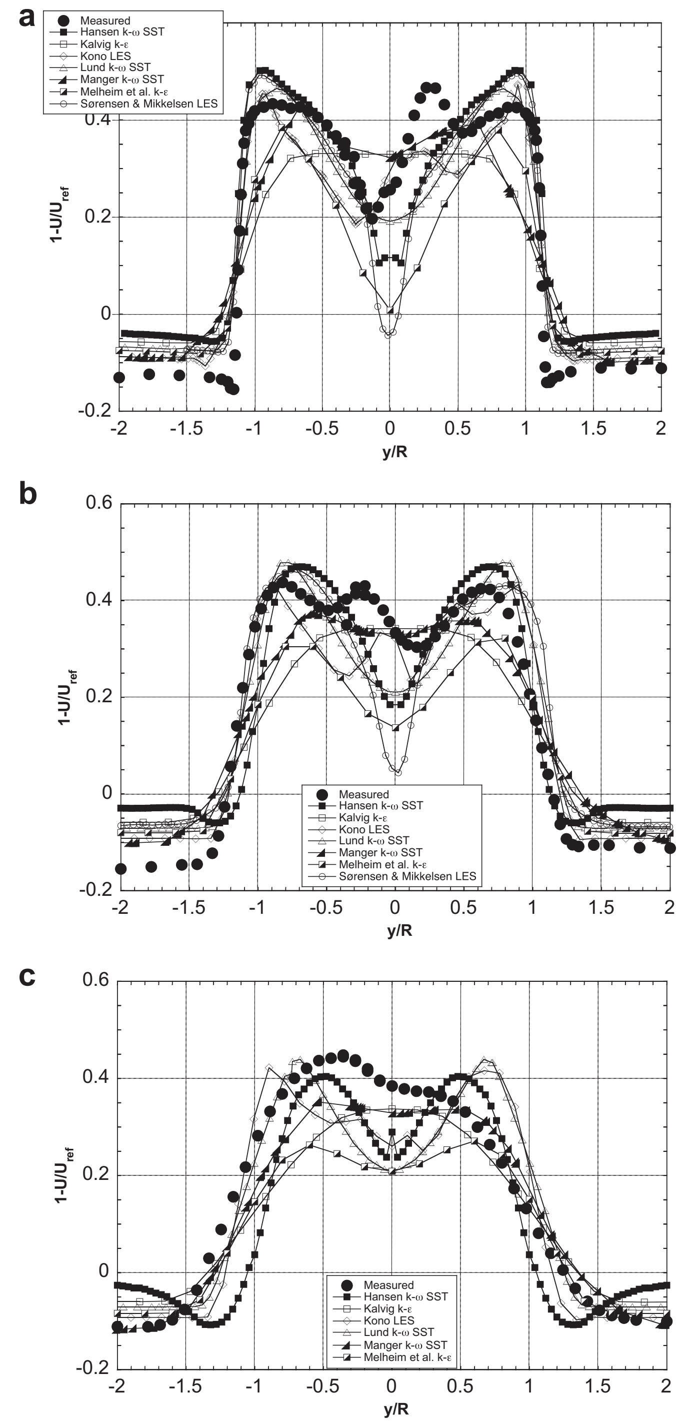

Fig. 4. Mean velocity profiles along a horizontal line for TSR = 6. (a) $X/D = 1$, (b) $X/D = 3$, (c) $X/D = 5$.

The method of Kalvig $k-\varepsilon$, which starts from a disk of uniform conditions can of course not capture the details of the wake and therefore predicts a rounded top hat profile.

The wake profiles obtained at $X/D = 3$ are shown in Fig. 4(b). The same comments that were made for $X/D = 1$ apply here. There is no disagreement about the growth rate for the wake, as all methods appear to give about the same wake width. Again the predictions of Lund $k-\omega$ SST and of Hansen $k-\omega$ SST are in very good agreement with the LES result of Sørensen & Mikkelsen, except that the wake width predicted by Hansen $k-\omega$ SST is somewhat smaller. The asymmetry in the predictions of Kono LES at $x/D = 1$ are still present at $x/D = 3$. Using the width where the velocity defect has been reduced to half the peak value, the measurements and all prediction methods (with the exception of those of Hansen $k-\omega$ SST), indicate that the wake has only expanded by about 10% of the diameter of the rotor.

Finally we show the wake profiles at the last measurement station, $X/D = 5$ (Fig. 4(c)). (This is outside the calculation domain for the LES of Sørensen & Mikkelsen, so no results are available here.) The measurements have started to develop an asymmetry here in the form of a stronger velocity defect on the left hand side than on the right side. It is believed that this is a footprint of the tower wake which slowly rotates in the opposite direction to the rotor motion. This asymmetry is possibly also captured to some extent by the predictions made by Manger $k-\omega$ SST and by Kono LES that incorporated the tower in the computational domain. The other methods, which all assume axisymetry, do of course produce symmetric profiles. The methods of Hansen $k-\omega$ SST, Melheim et al. $k-\varepsilon$, and the one by Lund $k-\omega$ SST continue to produce a strong dip near the centre, i.e. a much higher velocity here than found in the measurements.

The method of Hansen $k-\omega$ SST still does not indicate any growth in the wake width.

4.1.2. *Turbulent kinetic energy profiles at TSR = 6*

The normalized turbulent kinetic energy along the horizontal line at $X/D = 1$ is shown in Fig. 5(a). (Note that the ordinate axes are logarithmic for these quantities since the range of the energy across the span is large and because the various prediction methods estimate quite different turbulence levels.) The turbulent kinetic energy distribution is characterized by strong peaks generated by the tip vortices from the blades. These peaks are captured by the predictions of Melheim et al. $k-\varepsilon$, Kalvig $k-\varepsilon$, Lund $k-\omega$ SST, and by Sørensen & Mikkelsen LES, although the levels are one order of magnitude lower than in the measurements. It is surprising that the LES of Kono did not pick up these peaks very well and gave so different turbulent energy from the LES predictions of Sørensen & Mikkelsen along the outer half of the wake. The profiles of Hansen $k-\omega$ SST have the correct shape, but the peak near the tip is more than two orders of magnitude too low.

The measurements also indicate a high turbulence level behind the hub which could only be captured by the predictions where the hub of the model was included, i.e. by the predictions of Kono LES, by Manger $k-\omega$ SST and those of Hansen $k-\omega$ SST. It was probably also included in the predictions of Sørensen & Mikkelsen LES (but this is not clear from their method description). The calculations by Manger $k-\omega$ SST and Kono LES were able to predict the asymmetry along the vertical line (not shown) produced by the wake behind the tower.

Moving downstream to $X/D = 3$ (Fig. 5 (b)) it may be seen that the turbulent energy distribution across the wake has been smoothed considerably by the spanwise turbulent diffusion and the peaks generated by the tip vortices are now less distinct. The decay of turbulent energy from $X/D = 1$ to $X/D = 3$ obviously happened considerably faster in the wind tunnel experiment than in most of

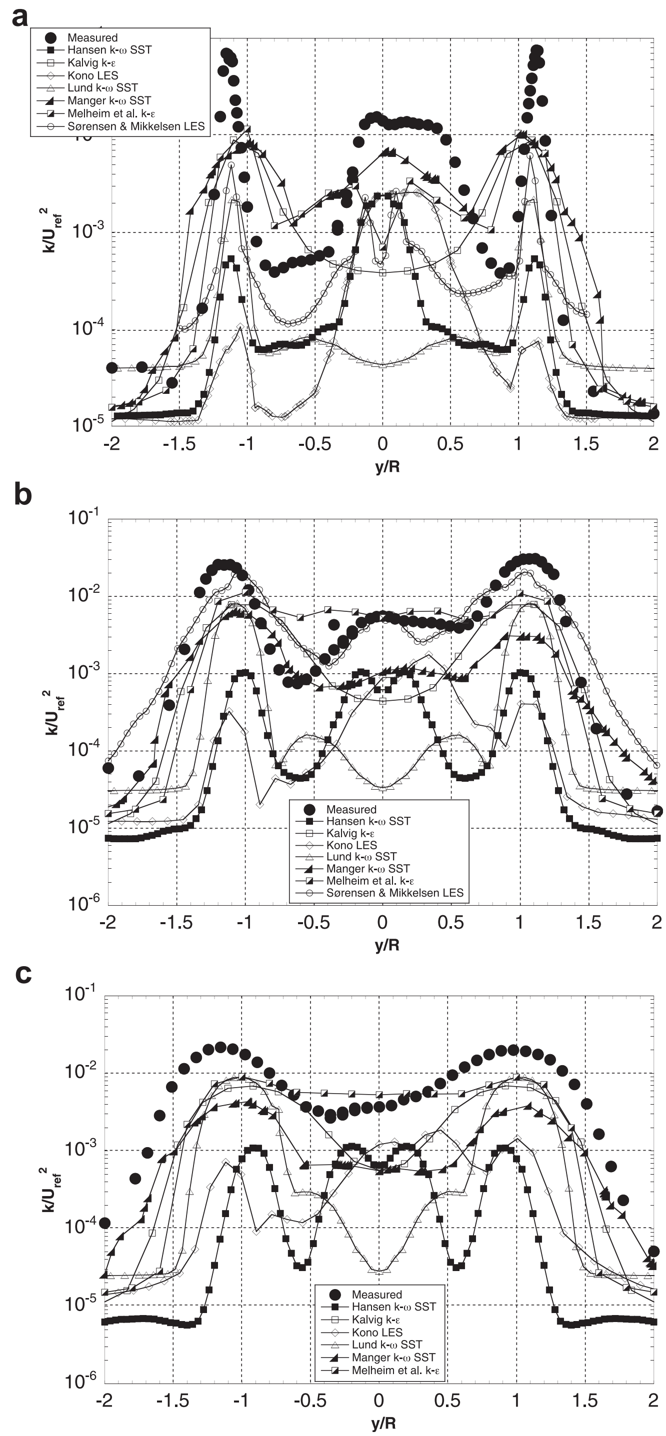

Fig. 5. Turbulent kinetic energy profiles for TSR = 6. (a) $X/D = 1$, (b) $X/D = 3$, (c) $X/D = 5$.

the predictions, which are now much closer to the experimental data. Especially the methods of Sørensen & Mikkelsen LES and by Melheim et al. $k-\varepsilon$ are performing very well here. Considering that the ordinate axis is logarithmic, the general impression is still that most methods predict too low turbulence level, and sometimes rather odd distributions. It appears that this is not a question of one turbulence model performing better or worse than the others, since the variation between the three methods that incorporate the $k-\omega$ SST turbulence model is about the same as the spread in the predictions from the other models.

Finally, Fig. 5(c) shows the distributions at $X/D = 5$. Surprisingly, the simple actuator disk/$k-\varepsilon$ model of Kalvig is now performing very well as it gives the right shape as well as roughly the correct level. The predictions by Manger $k-\omega$ SST also show the correct shape, although the turbulent kinetic energy level is low. But the method of Melheim et al. $k-\varepsilon$ is the one that appears to represent the measurements the best. The other methods, which all predict roughly the same k levels, show very ragged distributions, indicating that the spanwise turbulent diffusion is underestimated.

It is hard to select a best method or turbulence model from the presented wake and turbulence distributions due to the large variations in the results. But most predictions are at least able to predict the general shape of the velocity defect profiles as well as the location of the tip vortices and how they grow downstream. Overall it appears that the LES method of Sørensen & Mikkelsen is producing the most consistent results, but this comes at considerable computational costs.

4.2. Off-design operation

The participants were also requested to predict the wake development at two off-design operating conditions, i.e. at tip speed ratios TSR = 3 and 10.

TSR = 3 was chosen for two reasons. The turbine is here operating in an almost fully stalled mode. Hence its predictions should be very sensitive to the airfoil data used if the performance is predicted using a BEM method. It should also provide a challenge for those who want to do a full CFD calculation which includes the flow over the blades in their method. Departures from the measurements should show up in their predictions, if they are not able to resolve the boundary layers properly.

We have also chosen TSR = 10 for one of the output conditions. At this TSR the power produced is roughly the same as for TSR = 3, but the thrust coefficients are significantly different. This ought to bring out effects associated with swirl, combined with large differences in turbulent diffusion, as the wake profiles obviously must be quite different. Finally the pitch of the vortex spiral will be very small and this is expected to lead to vortex pairing and vortex interactions in the near field which will affect the wake growth rate and the turbulence production.

From the studies by Krogstad & Lund [10], which included estimates of the blade load distributions, it was observed that the inner part of the blade starts to get negative axial loading near the root at a tip speed ratio of about 10. This will lead to power input to the flow near the root while the blade continues to extract energy from the flow by the outer part of the blade. Therefore large spanwise gradients are expected, which could affect the predicted streamwise development of the wake.

4.2.1. Mean velocity profiles at $X/D = 3$

We present here the results at $X/D = 3$ for TSR = 3 (Fig. 6(a)) and 10 (Fig. 6(b)) as examples on how the prediction methods perform at off-design conditions. The information about the accuracy of the methods that may be extracted at this station is also typical for the results that were obtained at $X/D = 1$ and 5.

When comparing these results with those at $X/D = 3$ for TSR = 6 (Fig. 4(b)) it is apparent that the methods have considerable problems predicting the wake distribution correctly in this case. There is very little consensus among the methods about what the wake should look like.

For TSR = 3 (Fig. 6(a)), the LES method of Sørensen & Mikkelsen, and the $k-\omega$ method of Lund predict a wake that loses its strength as r increases, in the same way as observed in the measurements, while Melheim et al. $k-\varepsilon$ suggests that the wake strength is highest near the rotor tip. Only the two methods that have included the tower, i.e. Manger's $k-\omega$ SST method and the LES of Kono, have been able pick up the strong defect near the centre. Both these predictions are in good agreement with the measurements. The Sørensen & Mikkelsen LES method and the Melheim et al. $k-\varepsilon$ model predict a velocity increase near the centre which can not be found in the measurements. The method of Kalvig $k-\varepsilon$, is unable to account for the radial load variation of the rotor, and therefore produces a top-hat type of wake distribution. In this method the measured thrust coefficient was used as input. Yet the wake strength predicted, is considerably stronger than that of the measurements. This is somewhat puzzling because e.g. Manger $k-\omega$ SST predicted a C_T that was virtually the same as the experimental value for this operating condition. Yet his wake is both much more narrow and less deep than that of Kalvig $k-\varepsilon$. One would therefore expect the profiles generated by Kalvig's method and those by Manger $k-\omega$ SST to produce very different C_T's. The prediction by the Hansen $k-\omega$ SST method is quite close to the one produced by Kalvig $k-\varepsilon$.

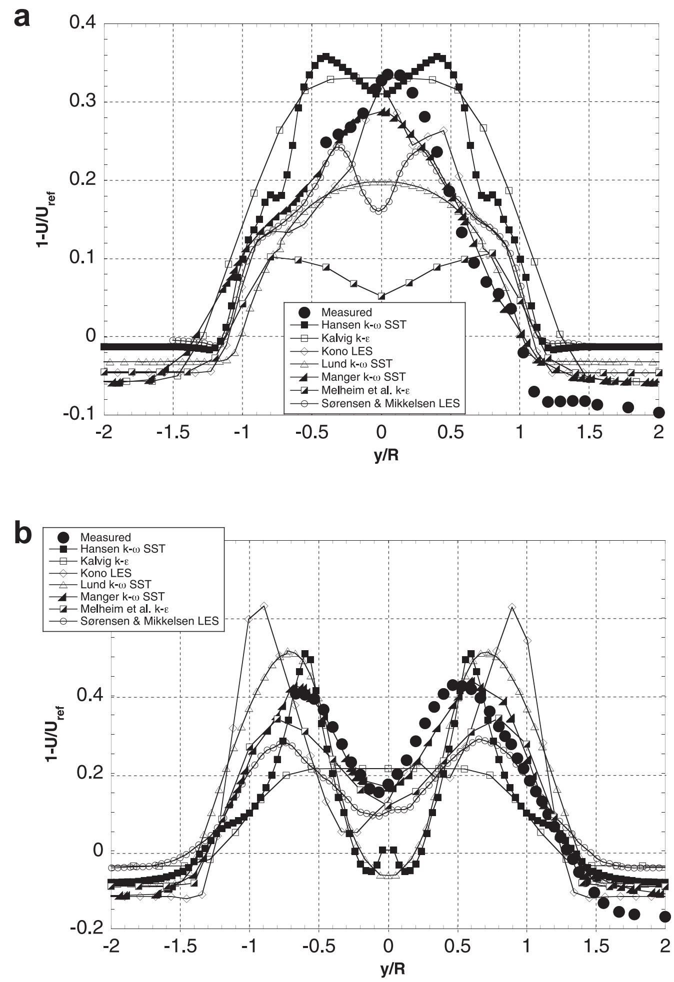

Fig. 6. Mean velocity profiles at $X/D = 3$. (a) TSR = 3, (b) for TSR = 10.

The figure also shows why the Melheim et al. $k-\varepsilon$ method underestimated the thrust coefficient almost by a factor two.

The velocity defect for TSR = 10 at $X/D = 3$ is shown in Fig. 6(b). The wake is characterized by a strong defect near the tip of the rotor. At the first measurement station ($x/D = 1$; plots not shown here) the flow was almost completely blocked near the tip of the blade and the velocity near the centre was virtually the same as the reference velocity. Hence the measured $1 - U/U_{ref}$ ranged from about 0.8 at the tip to -0.05 near the centre.

As the flow is convected downstream, the wake is widened and the gradients reduced by diffusion, so that by $X/D = 3$ the strength of the wake is reduced roughly by a factor two (Fig. 6(b)). The characteristic dual peak profile is predicted by all methods (except the one by Kalvig $k-\varepsilon$). Interestingly, the two LES methods represent the extremes as to the amplitude of the wavynes. They also disagree strongly as to how fast the wake decays. The Sørensen & Mikkelsen LES method predicts a peak to valley ratio of about two in the wake, while Kono's method has a ratio of almost five. The predictions by Hansen $k-\omega$ SST and by Lund $k-\omega$ SST are very similar in the sense that both produce a very high velocity near the centre, while the maximum velocity deficits are the same. The Hansen $k-\omega$ SST peak is very thin, but is predicted at the right radial position, compared to the measurements. All the other methods predict a broader peak, more in line with the experiment.

The prediction by Manger $k-\omega$ SST agrees very well with the measurements. The profiles generated by the Melheim et al. $k-\varepsilon$ method and those generated by the LES of Sørensen & Mikkelsen are also in close agreement, but indicate that the spanwise diffusion in the calculations may have been too active in making the flow more homogeneous. The wake strength predicted by Kalvig $k-\varepsilon$ agrees roughly with the bulk value from the Sørensen & Mikkelsen LES method, but cannot reproduce their radial dependence.

4.2.2. Turbulent kinetic energy profiles at $X/D = 3$

Fig. 7(a) shows that data for $x/D = 3$ and TSR = 3, while Fig. 7(b) gives the same information for TSR = 10. The predictions for the turbulent kinetic energy for these cases vary by almost two orders of magnitude. Considering that the vertical axis is logarithmic, the spread in the data is substantial.

For TSR = 3 (Fig. 7(a)) the profile, as evidenced by the measurements, is characterized by an almost uniform turbulent kinetic energy distribution. This is because the boundary layer is separated over most of the radius, which throws large amounts of turbulent energy into the flow. The turbulence from the tip vortices actually shows up as a reduction in kinetic energy, rather than as the high peak seen at design condition (see Fig. 5(b)).

These features are captured by the prediction of Hansen $k-\omega$ SST, although the reduction in tip vortex energy is overestimated. His method also produces a dip at the centre which is not present in the measurements. Since his calculation domain includes the nacelle, this suggests that spanwise diffusion is underestimated. The predictions by Manger $k-\omega$ SST and by Sørensen & Mikkelsen LES reproduce the shape of the experimental distribution reasonably well, although the turbulence level across the rotor is low by a factor 4 or 5. The simple model of Kalvig $k-\varepsilon$ produces the correct turbulence level near the rotor edge, but must underpredict the kinetic energy near the centre because the initial distribution is assumed to be independent of r.

Just like the predictions by Manger $k-\omega$ SST, the Melheim et al. $k-\varepsilon$ method produces a virtually constant kinetic energy level across the wake, but generates some low turbulence level pockets over the centre part of the blades. These pockets were even more evident at the initial station, $x/D = 1$ (not included here.) Kono's LES also generates a high energy level near the centre, but the energy near the tip of the blade is much too low. The turbulent kinetic energy predicted by Lund $k-\omega$ SST is extremely low all the way across the wake, being almost two orders of magnitude lower than the results from the LES of Sørensen & Mikkelsen, and close to three orders below the measurements in the central region.

Comparing the turbulent kinetic energy for TSR = 10 at $X/D = 3$ (Fig. 7(b)) with the distributions for TSR = 3 (Fig. 7(a)) or TSR = 6 (Fig. 5(b)), it is clear that the turbulent field across the wake is very different. The strong energy peaks found near the blade tips at TSR = 6 and which were significantly reduced for TSR = 3, are

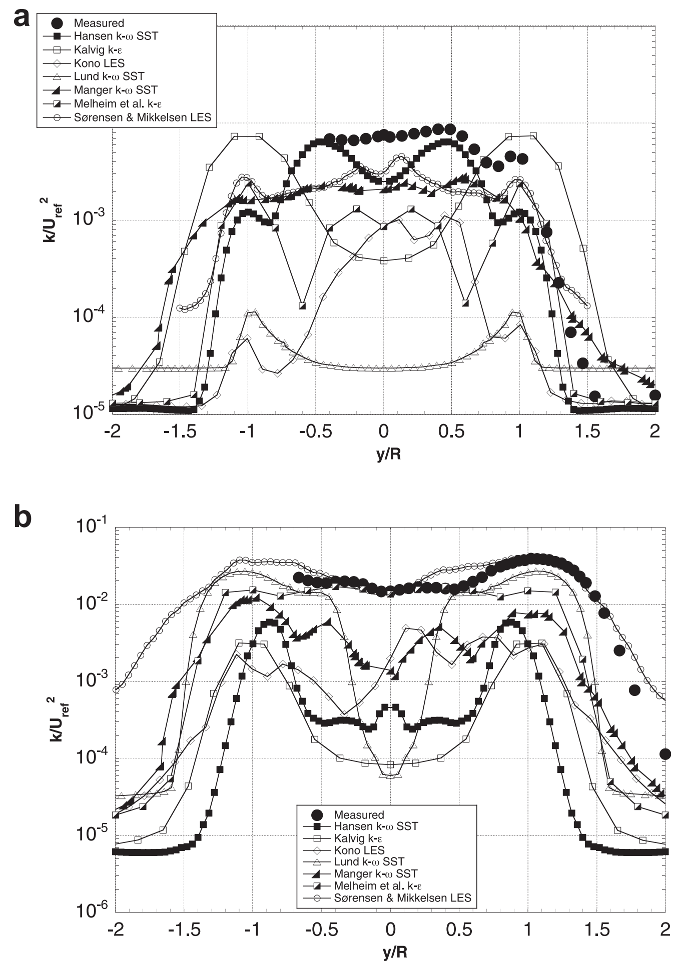

Fig. 7. Turbulent kinetic energy profiles for $X/D = 3$. (a) TSR = 3 and (b) TSR = 10.

now the dominant feature of the flow. Not only as local peaks as in the TSR = 6 case, but expanding over a wide r range. The velocity vector seen by the blade is now almost entirely in the plane of rotation, implying that the airfoils operate at very low angles of attack. Hence the lift coefficient is generally low and the pressure difference across the blade is correspondingly small. Therefore the tip vortices will be weak and the turbulence seen behind the rotor is primarily the vorticity in the boundary layers on the blade which has been shed from the trailing edge and convected downstream.

It is remarkable that the way the various methods generate wake turbulence depends so strongly on the TSR. While the Lund $k-\omega$ SST method was producing many orders of magnitude too low turbulent kinetic energy for TSR = 3, the predictions are now almost spot on in the range $0.5 < y/R < 1.5$ compared to the measurements, which are now higher by a factor 2 at $y/R = 1$. The LES of Sørensen & Mikkelsen is reproducing the data perfectly except at the outer extremities. However, since the ordinate is logarithmic, the differences here are insignificant and could be due to differences in the free stream turbulence used in the LES and those actually found in the wind tunnel.

The Melheim et al. $k-\varepsilon$ method, which provided good results for TSR = 6, but under-predicted the turbulent energy for TSR = 3, performs much better at TSR = 10. In contrast to the improvements achieved in the predictions of Lund $k-\omega$ SST and those of Melheim et al. $k-\varepsilon$, both the distribution predicted by Manger $k-\omega$ SST and the one obtained by the Hansen $k-\omega$ SST method are less accurate.

This applies especially to the data provided by Hansen $k-\omega$ SST. While the measurements indicate that the kinetic energy level in the centre is roughly the same in the centre part of the wake at TSR $= 3$ and TSR $= 10$, the Hansen $k-\omega$ SST method produced a reduction in k for $y/R < 0.5$ by a factor of about 100.

Kono's LES method produces an almost constant turbulence level across the wake, as in the measurements, but the turbulence level is still too low, and the LES almost ignores the broad peak in the outer region, reproduced by the Sørensen & Mikkelsen LES method. The Hansen $k-\omega$ SST predictions of the turbulent kinetic energy resembles those of Kono LES in shape if not in level. The profile predicted by Kalvig $k-\varepsilon$ is only marginally different from the one produced for TSR $= 3$.

5. Concluding remarks

The performance of a model turbine and the wake formed by the rotor has been predicted by eight individual groups, delivering a total of eleven different simulations. The methods comprised all levels of sophistication that are being used today, ranging in complexity from simple standard Blade Element Momentum methods to Large Eddy Simulations.

In most studies reported in the literature, where the aim is to sort out the best turbulence model to be used, the same operator uses the same program and grid distribution while incorporating different models in an attempt to best reproduce a reference distribution. This could be experimental results or other reliable references. A blind test like the one reported here takes away the target and therefore opens up for the uncertainty connected with the operator. This is more like the environment a design engineer works in. Using the code available he/she tries to set up the calculation to the best of his/her skills. This, of course, makes it difficult to objectively sort out a best prediction method but gives valuable information about the state of the art of the computations that are routinely made for wind turbines.

The spread in the results was probably larger than was initially expected. The uncertainty in the predicted turbine performance is of the order of $\pm 10\%$ near the design conditions, but increases considerably as the tip speed ratio increases. Three predictions were submitted that includes fully resolved simulations of the flow over the turbine blades. Unfortunately it is not possible to say that these predictions are superior to the BEM methods. Two performed quite well, while the other produced the lowest estimate of C_P in the normal operating range ($4 <$ TSR < 8). Curiously, the same method was by far the best in predicting the thrust coefficient. In general C_T was underestimated by all methods and at TSR $= 10$ the span in predicted values was $0.80 < C_T < 1.15$, which is quite wide.

To compute the wake flow, two methods used a standard $k-\varepsilon$ model, three used the $k-\omega$ SST model and two produced large eddy simulations, which only models the small scale turbulence. There is no obvious winner when it comes to the turbulence model used. There is as much variation within the group using the $k-\omega$ SST model as there is between these and the other models. Unfortunately the picture was not much clearer with the LES simulations either, but the differences here are probably due to different initial conditions. One method used actuator disk theory to model the rotor forces, while the other used actuator line theory, performing calculations for a rotating turbine. In general this gave results that were more in line with the experimental data.

It is a pity that the measurements could not have been carried further downstream. It would have been interesting to see how the methods would perform down to, say $X/D = 10$, since it appears that some of the methods have problems accounting for the spanwise turbulent diffusion and therefore retain spanwise inhomogeneity over much longer distances than are indicated in the measurements and the LES calculations. However, the limited streamwise range was determined by the model size and was a compromise between size, spatial resolution and measurement accuracy.

It is apparent from this exercise that when it comes to wind farm planning, the estimates of wake development has not reached the reliability that is necessary for accurate estimates of turbine interactions. Both the predictions of power reduction caused by placing a turbine in the wake of an upstream turbine and the estimates of extra dynamic loads appear to be rather uncertain. At the present stage, the blind test reported here demonstrates that the most reliable predictions are obtained using large eddy simulations. However, this must be combined with detailed blade loading estimates of initial conditions, such as actuator line or some other time resolved method. If steady state area averaged initial conditions are used, such as actuator disks, the present blind test exercise has demonstrated that the large eddy simulations perform no better than the methods that solve the Reynolds averaged Navier–Stokes equations.

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