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Validation of the actuator disc approach in PHOENICS using small scale model wind turbines

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Abstract. In this study two wind turbine setups are investigated numerically: (a) the flow around a single model wind turbine and (b) the wake interaction between two in-line model wind turbines. This is done by using Reynolds averaged Navier–Stokes (RANS) and an actuator disc (ACD) technique in the computational fluid dynamics code PHOENICS. The computations are conducted for the design condition of the rotors using four different turbulence closure models. The computed axial velocity field as well as the turbulent kinetic energy are compared with PIV measurements. For the two model wind turbine setup, the thrust and power coefficient are also computed and compared with measurements. The results show that this RANS ACD method is able to predict the overall behaviour of the flow with low computational effort and that the turbulence closure model has a direct effect on the predicted wake development.

1. Introduction
The study of wake properties is important for assessing the optimal layout of modern wind farms. Wind turbine wake development may be studied by field experiments, small scale wind tunnel measurements or numerical simulations with the use of computational fluid dynamics (CFD). There are several advantages of CFD over field experiments and small scale wind tunnel measurements e.g. no violation of similarity requirements, control over inflow conditions and whole flow field data of relevant parameters. However as CFD results are sensitive to the experience and knowledge of the user of the CFD code and of the numerous computational parameters involved in the computation, it is imperative to perform validation studies. Previous work on validating CFD wake models against large wind turbine wind tunnel measurements have been presented by Simms et al. [1] for the NREL experimental rotor and by Schepers et al. [2] for the MEXICO project. These studies have demonstrated that there was a significant deviation between the various prediction tools and the wind tunnel measurements. Similar results for a small scale model wind turbine are reported by Krogstad and Eriksen [3] for the “Blind test 1” workshop and Pierella et al. [4] for the “Blind test 2” workshop indicating the importance of validating existing wind turbine modelling tools and methodologies. The aim of the present study is the validation of the actuator disc model in the CFD code PHOENICS. This model is intended to be used for industrial purposes and therefore needs to provide accurate and reliable results with low computational effort. Simulations are performed according to the “Blind test 1” and “Blind test 2” invitation workshops organised by NOWITECH and NORCOWE [5; 6]. The goal of both workshops is to serve as an ideal test case for CFD tools by providing detailed measurements of the thrust coefficient, the power coefficient and the wake properties behind...
the rotor both in terms of mean flow and turbulence kinetic energy within a controlled wind tunnel environment. This paper presents computational results compared with experimental results for the normalised axial velocity and turbulent kinetic energy along the horizontal line in the crosswise direction through the wake center at three downstream positions. The results are obtained for two different configurations, the first case consists of a single wind turbine (setup A) and the second case consists of a configuration with two wind turbines positioned in-line (setup B). For setup B, the experimental thrust and power coefficients results of the model wind turbines are also compared with the computations.

2. Experimental Setup

The wind tunnel test section has width and length dimensions of $W \times L = 2.710 \text{ m} \times 11.150 \text{ m}$, Figure 1. To maintain a zero pressure gradient along the streamwise direction the height, $H$ of the wind tunnel increases from 1.801 m to 1.851 m. Regarding setup A, the three bladed wind turbine is positioned at a distance of 3.660 m from the inlet. The model wind turbine has a tower that consists of four cylinders of different radii, the nacelle is circular with a radius of $R_{Nac} = 4.5 \text{ cm}$ and the front portion of the nacelle is covered by a circular hub. The hub height is $H_{hub} = 0.817 \text{ m}$. The rotor radius is $R = 0.447 \text{ m}$ and the NREL S826 airfoil is used for the blades. To increase the Reynolds number of the blades, a chord length of approximately three times longer than normal was used. The blades have a circular shape close to the nacelle primarily to allow them to be attached to the hub. The transition from the airfoil section of the blade to the circular section is abrupt. The total blockage effect is defined as the fraction of the total tower and rotor swept area to the wind tunnel cross section and is approximately 12%. As a result the flow will be impacted by the walls and this interference will lead to artificial speed up effects. Further information on the details of the experimental investigations are reported by Krogstad and Adaramola [7] and Krogstad and Lund [8].

For setup B the dimensions of the wind tunnel are similar to setup A. Here two in-line wind turbines horizontally centered in the wind tunnel are investigated. Both wind turbines are three bladed with the same blade geometry and airfoil i.e. NREL S826 airfoil. As the nacelle diameter of the upstream wind turbine is somewhat larger, the turbines have slightly different rotor diameters. The rotor radius of the upstream wind turbine $T_1$, is $R_{T_1} = 0.472 \text{ m}$ and the radius of the downstream wind turbine $T_2$, is $R_{T_2} = 0.447 \text{ m}$. The tower of $T_1$ is a constant cylinder of $R_{Tow_1} = 5.5 \text{ cm}$, while the tower of $T_2$ consists of four cylinders of different radii. The hub height for both wind turbines is $H_{hub} = 0.817 \text{ m}$ and the separation distance between them is $6R_{T_2}$. The distance of $T_1$ from the inlet is $2R_{T_2}$. Further information on the details of the experimental investigations are reported by Krogstad and Adaramola [7] and Krogstad and Lund [8].

3. Numerical Method

The simulations are performed with the commercial CFD code PHOENICS [9] in which the Reynolds Averaged Navier-Stokes equations (RANS) are solved using four different turbulence models. The turbulence models are the standard $k-\varepsilon$ [10], the RNG $k-\varepsilon$ [11], the KL $k-\varepsilon$ [12] and Wilcox’s $k-\omega$ turbulence model [13]. The flow variables are stored in a uniform fully structured staggered grid and the Cartesian coordinate system is used. The SIMPLEST [14] algorithm is used to solve the RANS equations and Spalding’s hybrid differencing scheme [15] is used to discretise the convective terms. In the computations, the wind tunnel conditions are replicated, that is the incoming reference velocity is considered to be uniform with $U_{ref} = 10 \text{ m/s}$ and the streamwise turbulence intensity is $I_u = 0.3\%$. A zero static pressure is applied at the outlet plane. The lateral, top and bottom faces of the domain are set to be impermeable and frictionless.
Figure 1. Illustration of wind tunnel layout (a) one model wind turbine setup and (b) two in-line model wind turbine setup. The three downstream positions \( x = 2R, 6R, 10R \) and \( x = 2R, 5R, 8R \) are where the measurements are extracted, radius \( R = 0.447 \text{ m} \).

The presence of the rotor is modelled using an actuator disc method based on the 1D momentum theory. The thrust force \( F_i \) of each individual cell of the disc is calculated according to

\[
F_i = C_T(U_{1,i}) \frac{1}{2} \rho \left( \frac{U_{1,i}}{1 - \alpha_i} \right)^2 A_i.
\]

Where \( U_{1,i} \) is the velocity of the flow at the individual cell numbered \( i \) of the disc, \( \alpha_i \) is the axial induction factor calculated for each individual cell of the disc, \( \rho = 1.2 \text{ kg/m}^3 \) is the air density, \( A_i \) the surface area of the cell facing the undisturbed wind flow direction and \( C_T(U_{1,i}) \) is a modified thrust coefficient curve dependent on the velocity at the disc \( U_{1,i} \). Details on how each parameter is calculated may be found in Simisiroglou et al. [16]. The total thrust force applied to the flow is calculated by summing the individual thrust forces according to \( F_{tot} = \sum F_i \) over the disc area. This total thrust force may then be distributed in different ways over the disc. In this work, three different thrust distributions are tested; a polynomial, a triangular and a trapeze distribution. Their equations are presented in Table 1. The different thrust distributions possibly will produce different wake properties e.g. with respect to the velocity deficit and turbulent kinetic energy of the wake. Two questions thus arise, which thrust distribution better captures the wake produced by a wind turbine and up to which distance does the thrust distribution have an effect on the wake?

For the first part of the simulations (setup A) the numerical domain was defined according to the wind tunnel geometry as reported in Krogstad et al. [5]. However a constant height along the domain of \( H = 1.801 \text{ m} \) was assigned. Numerical simulations, in contrast to wind tunnel experiments, have no need of height variations in order to keep a zero pressure gradient along the domain. For the simulations no tower or hub effects are considered. The measurements used for the comparison are performed for a single model wind turbine operating at its optimum condition with a tip speed ratio (TSR) of \( \lambda = 6 \). Initially, empty domain simulations were conducted to assess the extent of unintended streamwise gradients for the mean velocity and turbulence parameters. For this purpose horizontal profiles of the \( U_0, k \) and \( \varepsilon \) are extracted at the
Table 1. Thrust distributions over the disc, where \( r \) is the distance from the center of the disc and \( R \) is the radius of the disc.

| Distribution | Equation | \( b \) | Range of application |
|--------------|----------|--------|----------------------|
| Polynomial   | \( F_{pol,i} = b F_{tot} \left( \frac{r}{R} \right)^2 \left( 1 - \left( \frac{r}{R} \right)^2 \right) \) | 6 | \( 0 \leq r \leq R \) |
| Trapeze      | \( F_{tra,i} = b F_{tot} \left( 4 \frac{r}{R} + 1 \right) \) | \( \frac{3}{2} \) | \( 0.2R \leq r \leq R \) |
| Triangular   | \( F_{tri,i} = b F_{tot} \left( \frac{r}{R} \right)^3 \) | \( \frac{3}{2} \) | \( 0 \leq r \leq R \) |

inlet, turbine location and \( x/R = 10 \) downstream of the turbine position. A grid independence study is also carried out according to the recommended procedure of Celic et al. [17]. A uniform grid is used based on the cells per rotor diameter and Table 2 presents information regarding the grid levels. The computed results are compared against PIV measurements for the normalised axial velocity \( \frac{U}{U_{ref}} \) and normalised turbulent kinetic energy \( \frac{k}{U_0^2} \), at the three downstream positions \( x/R_{T1} = 2, 6 \) and 10 along the horizontal line through the center of the wake in the crosswise direction.

Table 2. Grid levels and size.

| Grid level | Cells per rotor diameter | Cells in the domain |
|------------|--------------------------|---------------------|
| 1          | 40                       | \( 48 \times 10^6 \) |
| 2          | 30                       | \( 20 \times 10^6 \) |
| 3          | 20                       | \( 6 \times 10^6 \)  |

As in setup A, setup B will only consider results where the two wind turbine rotors are operating at their design conditions. The domain geometry and the positioning of the wind turbines are in accordance with the invitation sent out by Pierella et al. [6]. The height of the domain was set to \( H = 1.801 \) m. The computed results are compared against PIV measurements for the normalised axial velocity \( \frac{U}{U_{ref}} \) and normalised variance of the axial velocity component \( \frac{\overline{u'^2}}{U_0^2} \), at the three downstream positions \( x/R_{T1} = 2, 5 \) and 8 along the horizontal line through the center of the wake in the crosswise direction. Further the power coefficient, \( C_P = \frac{2P}{\rho U_0^3 A} \) and thrust coefficient \( C_T = \frac{2T}{\rho U_0^3 A} \) of the two wind turbines are compared with the experimental results, where \( A \) is the rotor cross section of each individual wind turbine. Here it should be noted that even though the thrust coefficient curve is an input to the simulation, the thrust coefficient value applied against the flow depends upon the velocity at the disc, that in turn changes as the simulation progresses.

4. Results

Results for the axial velocity and turbulence parameters extracted at cross-sectional horizontal profiles at the inlet, turbine location and at a position \( x/R = 10 \) downstream of the turbine location for the empty domain, show approximately a 0.005% difference for the axial velocity. The turbulence parameters \( k \) and \( \varepsilon \) decrease steadily from the inlet to \( x/R = 10 \), this is due to the lack of a turbulence generating mechanism such as wind shear. The difference however is five orders of magnitude lower than when an ACD model is present in the computations. Figure
2 illustrates the axial velocity contours for setup A and B. The polynomial thrust distribution is used along with the $k-\varepsilon$ turbulence closure model. It is clearly seen that by positioning a second turbine in the wake of the first the axial velocity of the flow is further reduced. This is due to further energy extraction of the second wind turbine from the mean flow. The dashed lines in Figure 2 indicate the positions at which flow values are extracted and compared with the PIV measurements. The three sets of grids used for the grid independency study have $6 \times 10^6$, $20 \times 10^6$ and $48 \times 10^6$ cells, respectively. The normalised axial velocity profile extracted at a position of $x/R = 2$ has oscillatory convergence occurring for 10% of the 40 points. The local order of accuracy $p$, varies from 0.08 to 18.61, with an average value of 3.04. The grid convergence index (GCI) or numerical uncertainty due to discretisation error varies from 0.02% to 6.1%, with an average value of 1.9%. Table 3 illustrates discretisation error results obtained for the profiles at $x/R = 2, 6$ and 10.

The computed results are validated against PIV measurements for the normalised axial velocity, $U/U_{ref}$, and normalised turbulent kinetic energy, $k/U_{ref}^2$, at the three downstream positions $x/R = 2, 6$ and 10 along the horizontal line through the center of the wake in the crosswise direction, see Figure 4. To investigate the influence of the thrust distribution on the wake development, simulations using the same turbulence model with different thrust distributions were conducted and the results can be seen in Figure 5. Here the normalised axial velocity and turbulent kinetic energy for different thrust distributions and the $KL k-\varepsilon$ turbulence model are shown.

| Downstream distance | $p_{global}$ | GCI$_{global}$ | Oscillatory convergence |
|---------------------|--------------|----------------|------------------------|
| 2R                  | 3.04         | 1.9%           | 10%                    |
| 6R                  | 2.08         | 2.3%           | 0%                     |
| 10R                 | 2.39         | 1.3%           | 15%                    |

Results for the simulations performed with the two in-line wind turbine case are shown in Figure 6 and Figure 7. The normalised axial velocity and streamwise variance of the velocity at three positions downstream of the second turbine are shown in Figure 6 for different turbulence models when using the polynomial thrust distribution. A similar trend of results is found when using the triangular or trapeze distribution instead of the polynomial and changing the turbulence model. The effect of the thrust distribution on the wake is investigated by varying the thrust distribution while keeping the same turbulence model $KL k-\varepsilon$, see Figure 7. Results of the power and thrust coefficient values for the upstream and downstream wind turbine are summarised in Table 4, here the $k-\varepsilon$ turbulence model is used.

5. Discussion and Conclusions
For each grid, the axial velocity profiles are clearly converging with grid refinement as shown in Figure 3 and the error of the finest grid is 2.3%. Hence, for the purpose of this investigation a uniform grid resolution of 40 cells per rotor diameter is found suitable for the simulations. From Figure 4(a) it is observed that the $k-\varepsilon$ and the $KL k-\varepsilon$ turbulence model produce fairly similar results to the PIV measurements with the $KL k-\varepsilon$ model being less diffusive in the crosswise direction than the $k-\varepsilon$ model. Because all thrust distributions used in this study assume axisymmetry, the simulated profiles are therefore symmetrical to the rotor center. This is not the case however with the measurements, where they exhibit asymmetric profiles as
Figure 2. Axial velocity contours for the $k - \varepsilon$ turbulence model using the polynomial thrust distribution. (a) One model wind turbine setup and (b) two in-line model wind turbine setup.

Figure 3. Normalised axial velocity computed behind a single model wind turbine (setup A) at (a) $x/R=2$, (b) $x/R= 6$ and (c) $x/R=10$ for the k-epsilon turbulence model and the polynomial distribution.

Table 4. Power and thrust coefficients using the $k - \varepsilon$ turbulence model for the first and second wind turbine.

|               | Thrust Coefficient $(C_T)$ | Power Coefficient $(C_P)$ |
|---------------|-----------------------------|----------------------------|
| $T_1$         | $T_2$                       | $T_1$                      | $T_2$                      |
| Experimental  | 0.883 0.363                 | 0.469 0.121                |
| Polynomial   | 0.777 0.350                 | 0.462 0.125                |
| Trapeze       | 0.805 0.345                 | 0.476 0.117                |
| Triangular    | 0.802 0.365                 | 0.484 0.126                |

seen in Figure 4(a). According to Krogstad and Eriksen [3] this asymmetry may be produced by the slowly rotating tower wake e.g. at the downstream position of $x = 10R$. The $k - \omega$ turbulence model seems to give results that are too diffusive, hence the wake recovery is too high in comparison to the velocity measurements. On the other hand the $RNG k - \varepsilon$ turbulence
Figure 4. (a) Normalised axial velocity and (b) normalised turbulent kinetic energy computed behind a single model wind turbine (setup A) at x/R=2, x/R= 6 and x/R=10 for different turbulence models using the polynomial distribution.

Figure 5. (a) Normalised axial velocity and (b) normalised turbulent kinetic energy computed behind a single model wind turbine (setup A) at x/R=2, x/R= 6 and x/R=10 for different thrust distributions and the $KL k−\varepsilon$ turbulence model.

model is not diffusive enough therefore the velocity profile preserves the initial shape due to the thrust distribution over the disc, even at a downstream position of $x = 10R$.

The blockage effect is more pronounced for the experimental results than for the simulated results as seen in Figure 4(a). This effect is apparent outside the wake region ($|y/R| > 1.5$) where the simulated normalised axial velocity values are lower than the experimental. Considering the normalised turbulent kinetic profiles in Figure 4(b), the shape of the profiles is not successfully predicted by any of the turbulence models. While the turbulent kinetic energy level is almost captured by the $k−\varepsilon$ and the $KL k−\varepsilon$ turbulence model. The $k−\omega$ turbulence model tends to over-predict the wake recovery and turbulent kinetic energy production, in contrast the $RNG k−\varepsilon$ tends to under-predict the wake recovery and turbulent kinetic energy production. The irregular shape of the turbulent kinetic energy profile when using the $RNG k−\varepsilon$ model further indicates that the crosswise turbulent diffusion is underestimated. When keeping the turbulence model constant and changing the thrust distribution it is observed in Figure 5 that the effect of the thrust distribution is pronounced in the near wake region and diminishes further downstream.
Figure 6. (a) Normalised axial velocity and (b) normalised turbulent kinetic energy computed for the two in-line model wind turbines (setup B) at x/R=2, x/R=5 and x/R=8 downstream of the second wind turbine different turbulence models using the polynomial distribution.

Figure 7. (a) Normalised axial velocity and (b) normalised turbulent kinetic energy computed for the two in-line model wind turbines (setup B) at x/R=2, x/R=5 and x/R=8 downstream of the second wind turbine for different thrust distributions and the KL $k-\epsilon$ turbulence model.

There is no substantial difference in the velocity profile at $x = 10R$. Regarding the turbulence kinetic energy, both the Trapeze and Triangular distribution seem to capture the position of the tip vortices. The increased turbulence production due to the breakdown of the tip vortices at the $x = 2R$ position is not captured by any combination of thrust distribution and turbulence model. Further as for the case with the normalised velocity profiles at $x = 10R$, the results of the normalised turbulence kinetic profiles do not seem to vary significantly at $x = 10R$ when using different thrust distributions.

The power and thrust coefficient values summarised in Table 4 for the $k-\epsilon$ turbulence model agree quite well with the measured data and have approximately less than 4% and 10% difference respectively. These differences increase when considering different turbulence models, this is due to the different wake development corresponding to the different turbulence models. When considering the $k-\omega$ turbulence model the computations greatly overestimate the values of the power and thrust coefficient for the second wind turbine and vice versa for the RNG $k-\epsilon$. Similar to the results with one wind turbine, in the two in-line case the $k-\epsilon$ and
the KL $k-\varepsilon$ turbulence models produce results in agreement with the measurements. The $k-\omega$ turbulence model again over-predicts the wake recovery and over estimates the normalised streamwise variance of the velocity. On the contrary the RNG $k-\varepsilon$ under-predicts the wake recovery and under estimates the normalised streamwise variance of the velocity. The blockage effect is under-estimated as well for all turbulence models and thrust distributions. The wake expansion is accurately predicted when using the $k-\varepsilon$ and the KL $k-\varepsilon$ turbulence models. When keeping the turbulence model constant and changing the thrust distribution (Figure 7) it is observed that the effect of the thrust distribution is less pronounced than for the single wind turbine case due to the higher turbulent diffusion. There is no substantial difference in the velocity profile at $x = 10R$ produced from the use of the different thrust distributions. Regarding the turbulence kinetic energy both the Trapeze and Triangular distribution capture the position of the tip vortices.

The main conclusions of this study are summarised as follows: (i) the present results, considering the simplicity and low computational needs of the method show, in general, satisfactory agreement between the computations and the measurements used for both the one wind turbine setup and the two in-line wind turbine setup. (ii) The effect of using different thrust distributions on the profiles is generally present in the near wake and almost completely absent in the far wake. Moreover, the impact on the near wake is more pronounced for the single wind turbine setup than in the two wind turbine setup. (iii) Changing the turbulence model has a noticeable impact on the wake development. When using the $k-\varepsilon$ and the KL $k-\varepsilon$ turbulence models the results are in agreement with the measurements, but this is not the case with the $k-\omega$ and RNG $k-\varepsilon$ turbulence closure models. (iv) The Trapeze method when using the $k-\varepsilon$ turbulence model has the closest agreement with the thrust coefficient, however the Polynomial method when using the $k-\varepsilon$ has the closest agreement with the power coefficient.

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References
[1] Simms D A, Schreck S, Hand M and Fingersh L 2001 NREL unsteady aerodynamics experiment in the NASA-Ames wind tunnel: a comparison of predictions to measurements (National Renewable Energy Laboratory Golden, CO, USA)
[2] Schepers J, Boorsma K, Cho T, Gomez-Iradi S, Schaffarczyk P, Jeromin A, Shen W Z, Lutz T, Meister K, Stoovesandt B et al. 2012
[3] Krogstad P Å and Eriksen P E 2013 Renewable energy 50 325–333
[4] Pierella F, Krogstad P Å and Sætran L 2014 Renewable Energy 70 62–77
[5] Krogstad P Å, Eriksen P and Melheim J 2011 Summary report 10
[6] Pierella F, Eriksen P E, Sætran L and Krogstad P Å 2012 Dept. Energy and Process Eng., NTNU, Trondheim, Norway
[7] Krogstad P Å and Adaramola M S 2012 Wind Energy 15 743–756
[8] Krogstad P Å and Lund J 2012 Wind Energy 15 443–457
[9] Spalding D B 1981 Mathematics and computers in simulation 23 267–276
[10] Launder B E and Spalding D 1974 Computer methods in applied mechanics and engineering 3 269–289
[11] Yakhot V and Smith L M 1992 Journal of Scientific Computing 7 35–61
[12] Kato M 1993 Ninth Symposium on Turbulent Shear Flows, 1993
[13] Wilcox D C 1988 *AIAA journal* **26** 1299–1310
[14] Spalding D B 1980 *NASA STI/Recon Technical Report N* **81**
[15] Spalding D 1972 *International Journal for Numerical Methods in Engineering* **4** 551–559
[16] Simisiroglou N, Karatsioris M, Nilsson K, Breton S P and Ivanell S 2016 *Energy Procedia* **92**
[17] Celik I B, Ghia U, Roache P J *et al.* 2008 *Journal of fluids Engineering-Transactions of the ASME* **130**