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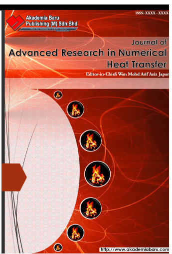

A study of inflow parameters on the performance of a wind turbine in an atmospheric boundary layer

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ABSTRACT

In this research a CFD simulation of an isolated wind turbine using the actuator disk model is presented. Actuator disk models (AD) are among the most convenient methods of modelling a wind turbine. Using the principles of momentum theory, this approach replaces the rotor with an actuator disk that uniformly exerts force in the axial direction. This study employs an SST k-ω RANS-AD model to investigate the aerodynamics of a wind turbine located in a rough atmospheric boundary layer. This model is validated Using a set of wind tunnel data and is then used to investigate the effects of CFD inflow conditions, Power law and logarithmic profiles. The results show that despite the popularity of the logarithmic formulation, the power law profiles yield better results. Additionally, a study of the actuator disk thickness depicted that the thickness ratio is a relatively important factor that helps with convergence of the simulation and more attention should be paid to the value chosen for this parameter.

Keywords:
Actuator disk; Atmospheric boundary layer; wake recovery; Wind turbine; CFD

1. Introduction

The inevitable shift towards a more sustainable and clean method of energy production is evident and urgent. An increase in wind power generation to much more marginal sources require increasing efficiency with advanced design tools. Computational fluid dynamics (CFD) will play a growing role in wind farm optimization. In this study a fast set of CFD simulations is implemented to investigate wake recovery using the actuator disk model. Traditionally, indirect rotor modelling techniques are extensively used to model the aerodynamics of wind turbines. The actuator disk (AD) model is among the simplest methods which is still in use today. The AD model assumes that the wind turbine can be replaced with a thin actuator disk that exerts force in the axial direction, extracting momentum and modifying the flow field. Simple in its implementation, AD models have proven to be fairly accurate for a wide range of applications [1, 2]. Basic AD models though, have several shortcomings: they are one dimensional, meaning they do not account for the rotation and swirl of the flow, and they also do not account for the geometric properties of the blade.

Blade element momentum methods (BEM) developed by Glauert [3] addressed some of the inaccuracies of AD models. The capabilities of the BEM method have made this method popular in wind turbine design. A LES and unsteady RANS simulation using AD and AD-BEM done by Lavaroni

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showed that the latter better represents the turbulence levels while under predicting the velocity deficit in the near wake [4]. The differences between these two methods are mostly limited to the near wake region, and the results of the two methods overlap as the flow moves to the far wake.

The goals of our study are twofold: firstly, to investigate the effects of different inflow parameters on the accuracy of CFD results. The choice of CFD inflow parameters has shown to greatly affect the results [5]. In order to recreate the atmospheric boundary layer profiles, two methodologies have been developed: 1. Logarithmic Profiles developed by Richard & Hoxey [6] , 2. Power law profiles developed by the Architectural Institute of Japan [7]. These two methodologies have entirely different formulations for the velocity, turbulence kinetic energy and turbulent dissipation profiles. Given the sensitivity of CFD results to inlet conditions, an inflow study using these two profiles will be conducted. A study of the recent papers has shown that most researchers prefer to use the logarithmic inflow profile with very few papers using the power law formulation. Logarithmic formulation is also the method of choice in CFD simulations of urban environment [8]. Although both methods have proven to be fairly accurate, slight discrepancy between the actual working condition and the imposed velocity profile can lead to inaccurate results. The second goal of this paper is to investigate the scantly investigated effects of actuator disk thickness on flow structure. A rigorous literature review of RANS and URANS studies has shown that few researchers report the value of their disk thickness, or simply only report the value without any further investigation [9, 10]. To this aim, first an overview of actuator disk formulations using the $k-\omega$ model will be presented. The model will be then validated using a set of atmospheric boundary-layer wind tunnel experiments gathered by Chamorro & Porte-Agel [11].

2. Methodology

2.1 Governing Equations

The incompressible Reynolds averaged Navier-Stokes and continuity equations are used to model the flow through a porous disk:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho u_i \frac{\partial u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) + F_t \tag{2}$$

where u is the averaged velocity, ρ is the density, p is the pressure, μ is the dynamic viscosity, u' is the fluctuation of velocity and F_t is the body force due to the presence of the turbine. In the actuator disk model, wind turbine is replaced with a thin permeable disc. By using this method, the thrust F_t is uniformly applied to the disk and no direct modelling of the rotor is needed.

$$F_t = 0.5\rho u_{hub}^2 c_t \tag{3}$$

F_t is calculated using equation 3. where c_t is the thrust coefficient and u_{hub} is the velocity at the hub height. c_t can be calculated using the wind turbine characteristic curve.

2.2 Validation data

In order to validate the results, the experiments done by Chamorro and Porte-Agel [11] at the boundary-layer wind tunnel of the Saint Anthony Falls Laboratory were selected. The set-up consisted of a wind turbine with a diameter of $d = 15cm$ placed $2m$ down the inlet with a crosssectional area of $1.55m \times 1.35m$. The friction velocity and aerodynamic surface roughness length of this configuration were $u_r^* = 0.16\ m/s$ and $y_{0r} = 1.2\ mm$ respectively

2.3 Inflow conditions

As mentioned, two set of profiles were used at the inlet. The logarithmic profile can be calculated by entering the experimental data into the Richard and Hoxey equations, Eq. 4 to Eq. 7 [6]:

$$U = \frac{u_*}{\kappa} \ln\left(\frac{y+y_0}{y_0}\right) \tag{4}$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \tag{5}$$

$$\varepsilon = \frac{u_*^3}{\kappa(z+z_0)} \tag{6}$$

$$\omega = \varepsilon / C_\mu k \tag{7}$$

where C_μ is the model constant, κ is the von- Kármán constant, u_* is the friction velocity and y_0 is the surface roughness length. Alternatively, the power law equations, Eq. 8 through Eq. 11, can be used to derive an expression for velocity and turbulence kinetic energy:

$$U = U_{ref}\left(\frac{z}{z_{hub}}\right)^{\alpha} \tag{8}$$

$$T_I = 0.1\left(\frac{z}{z_{hub}}\right)^{-\alpha-0.05} \tag{9}$$

$$k = \frac{3}{2}[U.T_I]^2 \tag{10}$$

$$\varepsilon = \alpha C_\mu^{0.5} / C_\mu \frac{U_{ref}}{Z_{hub}} \left(\frac{z}{Z_{hub}}\right)^{-\alpha-1} \tag{11}$$

where U_{ref} is the inlet velocity at the hub height, T_I is the turbulent intensity and α is the power law coefficient which is determined using the terrain roughness. The velocity and kinetic energy profiles can be seen in Figure 1.

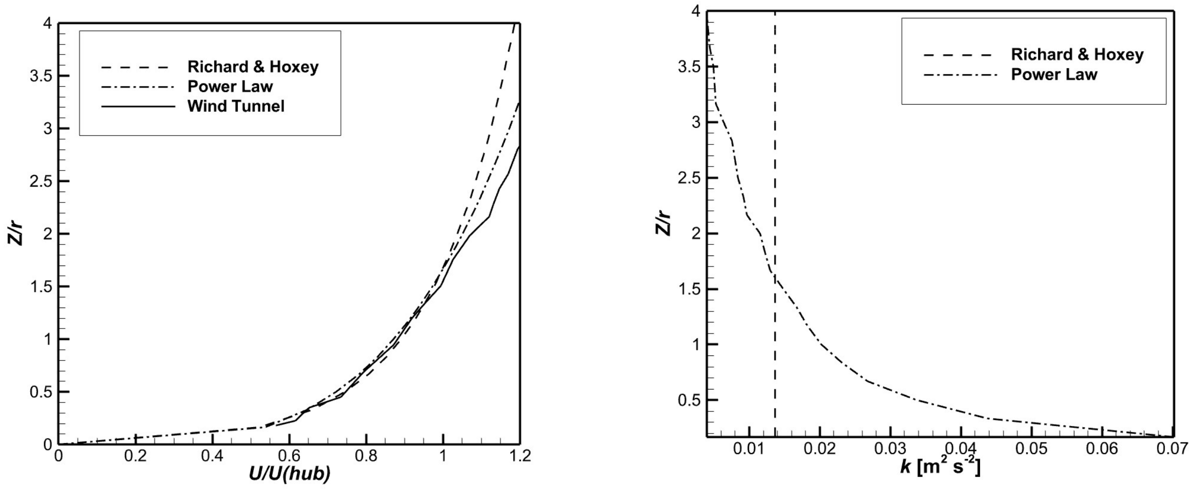

Fig. 1. Power law and logarithmic profiles velocity profile(left) Turbulence kinetic energy (m^2s^{-2}) (right)

3. Results and discussion

The experimental and numerical data are validated at four downstream locations. The rough wall velocity profiles in the near wake are depicted in Figure 2. Both profiles underestimate the velocity drop at the hub level in both $3D$ and $5D$ regions. The reason for this type of behaviour is because the simple actuator disk model does not account for the pressure drop that is associated with rotation of the flow in the wake. Another reason for the over-prediction of the velocity profile in the near wake is that the current model does not take the drag associated with the tower and hub into consideration, which causes an additional pressure drop in the wake. Both profiles do closely simulate the general behavior of the wake, but the power law seems to be the most appropriate in both cross sections.

As the flow evolves to the far wake $(z/r > 4D)$, the agreement between the modelling and experiments significantly increases; from Figure 3 the power law exhibits the best fit with the experiments. We expect a better fit downstream as the flow adjusts to the effect of the rotor. Any lack of realism regarding interaction with rotor, namely the wake rotation, is ``forgotten''. The accuracy of the logarithmic profile does surpass the power law when it comes to simulating the turbulence intensity. Both sets of profiles do underestimate the turbulence intensity in the regions near the ground and disk. This inaccuracy is due to multiple reasons including the absence of rotation in the model and the absence of hub structure, but the main reason for this inaccuracy is probably the viscous interaction of the flow with the rotor and the anisotropic nature of turbulence in the near wake. This would mean that isotropic turbulence models, including the two-equation eddy viscosity models, fail to predict the turbulence intensity. The same type of behavior as observed with velocity is seen for the turbulence intensity further downstream away from the disk in Figure 3. The accuracy of results increases rapidly with the distance from rotor. This is partly due to wake recovery but another reason for the increase in the accuracy is the overall decrease of turbulence intensity and anisotropy of the flow. The increasing isotropy of the flow indicates that flow evolves to near zero stream-wise gradient. As a result, the logarithmic profile shows a greater agreement with the experimental data in $Z > 5D$. Overall, the power law shows better fit to experiments in the velocity profile while the logarithmic profiles are better suited to capture the turbulence quantities, especially in the far wake.

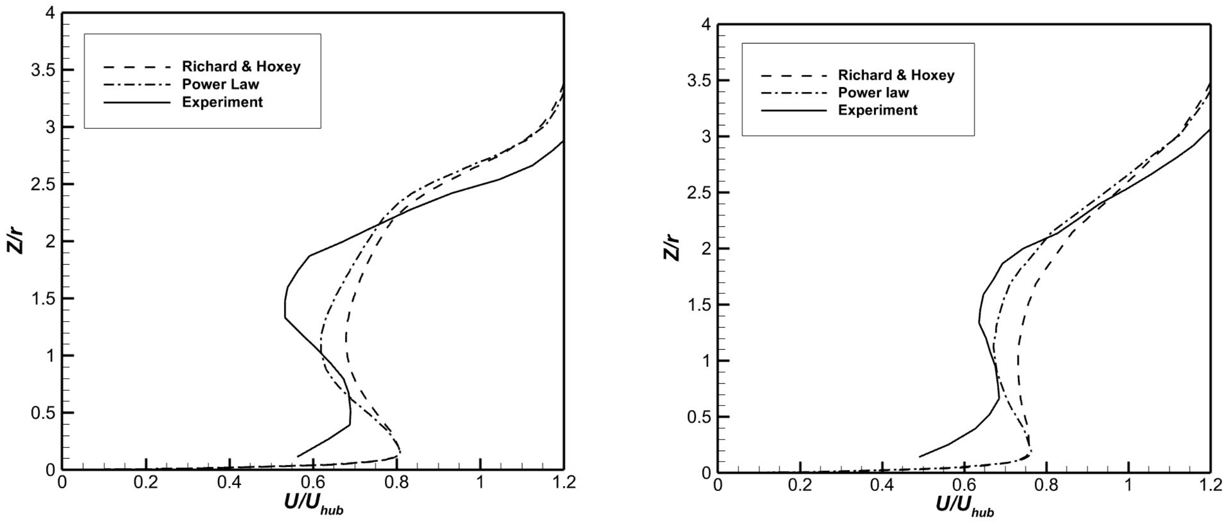

Fig. 2. Power law and logarithmic velocity profile in the near wake at $3D$(left) $5D$(right)

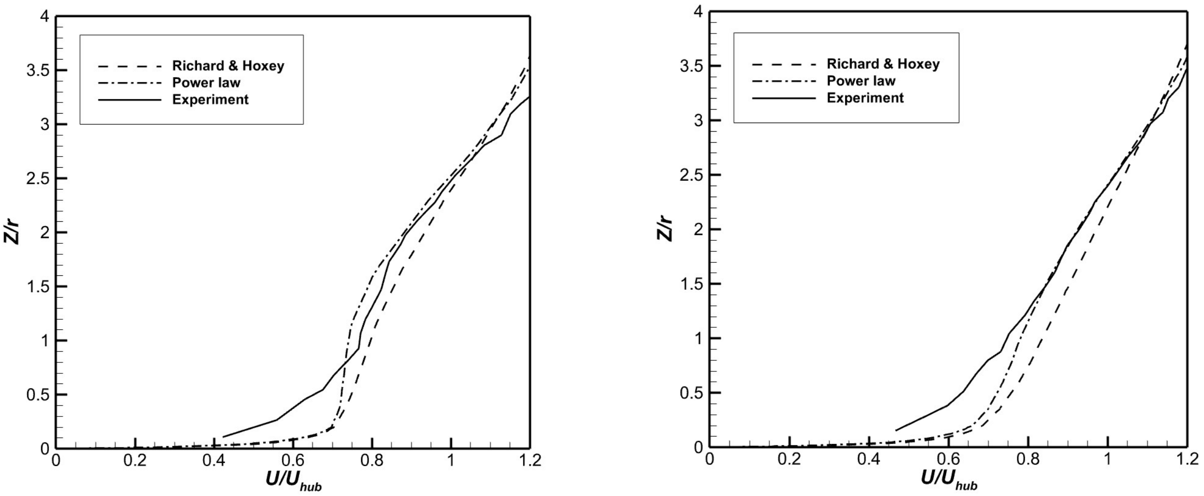

Fig. 3. Power law and logarithmic velocity profile in the near wake at $10D$(left) $15D$(right)

3.2 Actuator disk thickness

To investigate the sensitivity of the results to the disc thickness, three values of thickness ratio of *T/r = 0.0032 ,0.0064, 0.0016* were chosen. A detailed investigation of the turbulence intensity and turbulent kinetic energy, shown in Figure 4, show great agreement for the 3 different thicknesses. Aside from a slight discrepancy, all three thickness ratios show near identical behavior in both 1D and 2D regions. This implies that the final results of actuator disk simulations have little dependence on the value of the disk thickness.

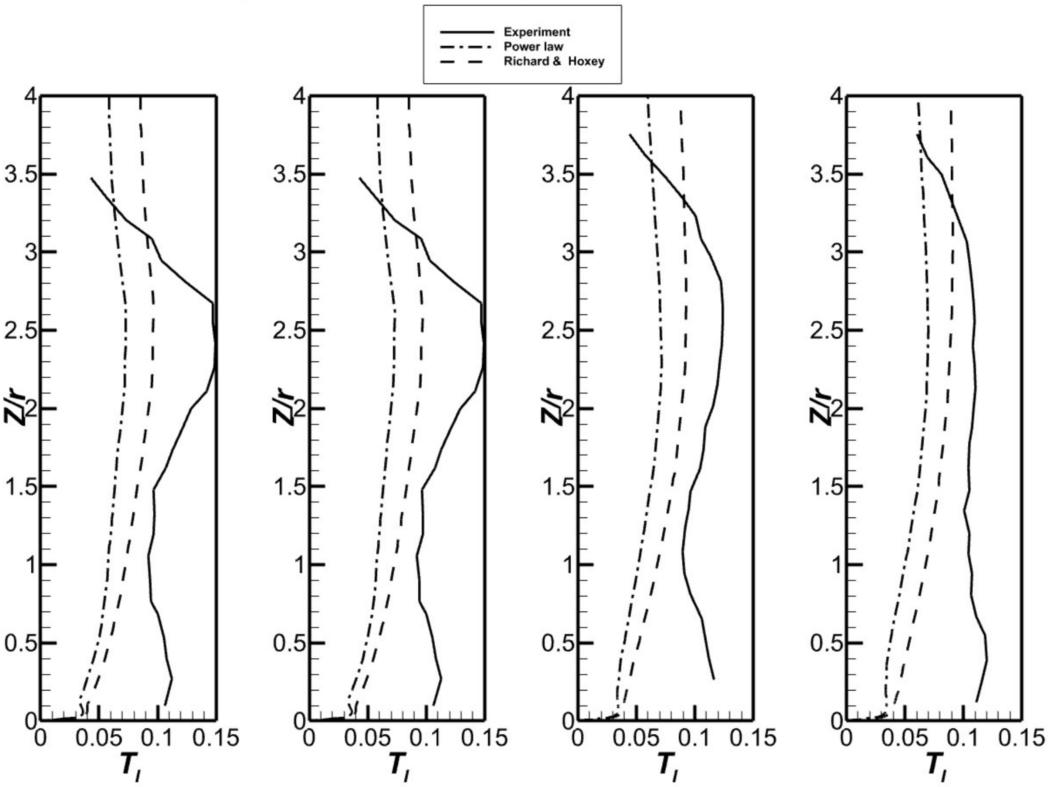

Fig. 4. Turbulence Intensity at $3D$ $5D$ $10D$ $15D$ (from left to right)

Nevertheless, there are two parameters that do vary from one thickness to the other. The first is the mesh refinement required for different thickness values. The second is the computation time. The smaller disks require a finer grid to better model the sudden rise in the pressure because as the disk gets smaller, the momentum source reaction on the flow takes place in a thinner region. The thinnest disk struggled with convergence with the normalized residuals capping at *1e-6* while the other cases did reach a lower residual at half the time of the thinnest case with the *T/r = 0.0064* having the fastest convergence rate of all. This all indicates that even though the exact value of the actuator disk thickness does not dramatically affect the results, a choice of *T/r> 0.0032* does help with the convergence and computational time, and thickness values smaller than *0.0016* should be avoided.

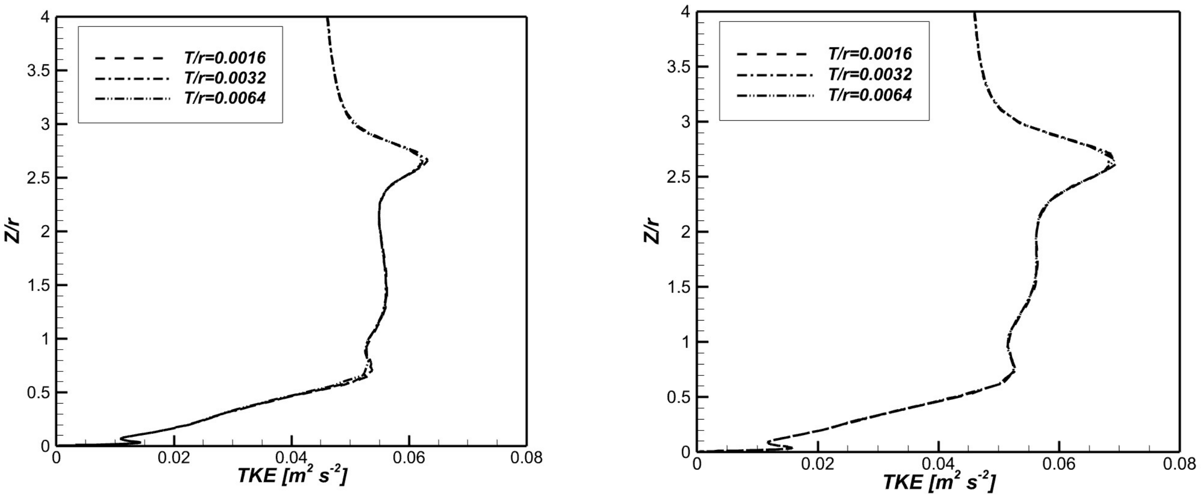

Fig. 5. Turbulence kinetic energy m^2s^{-2} at $1D$(left) and $2D$(right)

4. Conclusions

In this paper a study of logarithmic and power law inflow parameters along with an investigation of the effect of actuator disk thickness on the results were conducted. The wind turbine was modelled using the actuator disk concept and the result showed that even though the logarithmic formulation is most popular, the power law profile is the better all-round inflow profile. The accuracy of the power law was noticeably higher for the velocity profiles. The logarithmic profile based on the work of the Richard and Hoxey [6] did better simulates the turbulence intensity profile. As for the effect of the actuator disk thickness on the results, it was seen that the implementation of small thickness not only requires a finer mesh but also increases the run-time of the simulations.

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