J. Wind Eng. Ind. Aerodyn. 160 (2017) 1–15

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Modeling of wind turbine wakes under thermally-stratified atmospheric boundary layer

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ARTICLE INFO

Keywords:
Wind turbine wakes
Actuator disk
Atmospheric thermal stratification
Atmospheric boundary layer
RANS
k-ε model
Wind power

ABSTRACT

In the present work, the wake behavior of wind turbines, operating under thermally-stratified atmospheric boundary layer (ABL), is numerically investigated. The steady state three dimensional Reynolds-Averaged Navier−Stokes (RANS) equations, combined with the actuator disk approach, are used in the simulation. The standard k-ε turbulence model as well as a modified one namely El Kasmi model are adopted. Two different methods are used and compared, for representing the atmospheric stratification flow conditions: In the first one (direct method), the energy equation is considered along with mass, momentum, and turbulence model equations. In the second one (indirect method), stratification is modeled by means of additional buoyancy production and dissipation terms. Such terms are added to the turbulent kinetic energy and dissipation rate equations, instead of solving the energy equation. The results obtained from both methods show a reasonable agreement with the experimental data available from the literature. Moreover, it is concluded that, there is no significant difference between the predicted results from both methods. Further, the effect of the atmospheric stability class on the wake deficit and the available wind power in the wake region has been also investigated using the indirect method. It has been found that, there is a significant influence of the different atmospheric conditions on the wake behavior. In particular, the wake region becomes smaller with the decreasing of atmospheric stability, and hence a higher wind power in the wake region is observed for unstable conditions.

1. Introduction

Wind turbine wakes have attracted a lot of attention of the research community in recent years because of their effect on power production of wind farms. These wakes are characterized by a reduction of wind speed which in turn reduces the available wind power, and an increase of turbulence levels that generate fatigue loads on downstream wind turbines. Therefore, the investigation of wind turbine wakes becomes important to construct a suitable wind turbines farm.

Wind turbines operate in the lowest region of the atmospheric boundary layer (ABL). Therefore, the evolution and recovery of wind turbine wakes are strongly affected not only by the turbine characteristics and complexity of terrain, but also, by the ambient wind speed and turbulence levels related to the different thermal stratifications of ABL. A proper modeling of all these factors becomes mandatory for detailed understanding and accurate prediction of wind turbine wakes and their effects on the performance of the whole wind farm. According to the thermal conditions, the atmospheric boundary layer can be classified into three types, which are neutral (NBL), stable (SBL), and unstable or convective (CBL). In NBL, the mean potential temperature is approximately constant with height, so that the generated turbulence is mainly due to the ground surface. It is observed only during windy weather with clouds. In SBL, the ground surface is colder than the ambient air, therefore the generated turbulence by wind shear is suppressed by negative buoyancy resulted from vertical downward heat flux. This atmospheric condition usually occurs at night time. The third type, CBL, occurs during day time when the ground surface is warmer than ambient air. The vertical upward heat flux generates a positive buoyancy, which in turn enhances the ambient turbulence. It is observed that, the turbulence level varies in descending order of magnitude in CBL, NBL and SBL, respectively.

Full-scale field measurements as well as wind tunnel experiments of small-scaled models of wind turbines showed significant effects of thermal stratification on wind power production and structure of wind-turbine wakes, as reported in Van den Berg (2008), Wharton and Lundquist (2010), Chamorro and Porté-Agel (2010), Zhang et al. (2013), Hancock and Pascheke (2014). Baker and Walker (1984) used a kite anemometer to measure wake deficits of two MOD-2, 2.5 MW, 91 m diameter wind turbines. The measurements were obtained at different ambient turbulence levels under stable condition at Goodnoe

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http://dx.doi.org/10.1016/j.jweia.2016.11.001
Received 29 April 2016; Received in revised form 31 October 2016; Accepted 5 November 2016
0167-6105/

Hills, Washington. The results indicated that the wake velocity deficits 9 diameters downwind are of the order of 15–18%, while these deficits decrease to less than 10% under more turbulent night-time flow. Magnusson and Smedman (1994) investigated the influence of atmospheric stability on the wake structure of wind turbines operating at Alsvik wind farm. Their results showed that the different atmospheric stratifications affect the velocity deficit and the largest wake velocity deficit was observed under stable condition. Iungo and Porté-Agel (2014) measured turbulence intensity and wind velocity field in the wake, produced by a 2-*MW* Enercon E-70 wind turbine, using Doppler wind lidars. The measurements were carried out at different atmospheric stratification conditions. It was observed that there is a significant reduction of turbulence activity within the atmospheric surface layer moving from CBL to NBL regimes, which in turn causes the wake to recover faster under convective regime compared with neutral one. Similar behavior of wake recovery was observed during wind tunnel measurements of Zhang et al. (2013). They used stereoscopic particle image velocimetry (S-PIV) and triple-wire anemometry to study the effects of CBL on velocity deficits, turbulence intensities and tip vortices of the wakes of a miniature wind turbine. Also, Hancock and Pascheke (2014) carried out wake measurements in the EnFlo stratified-flow wind tunnel operating under neutral and stable atmospheric boundary layer. Their measured data demonstrated that the wake recovery is slower in SBL compared with NBL condition. This behavior is qualitatively consistent with the field measurements reported by Magnusson and Smedman (1999).

Besides field measurements and wind tunnel experiments of wind turbine wakes, analytical and numerical models have also addressed the effect of atmospheric stability on wind turbine wake behavior, see (Crespo and Hernandez, 1996; El Kasmi and Masson, 2008; Rados et al., 2009; Sanderse et al., 2011; Prospathopoulos et al., 2011; Churchfield et al., 2012; Keck et al., 2014). Bastankhah and Porté-Agel (2014) proposed a new analytical model based on self-similar Gaussian wake velocity distribution to predict the velocity deficit downstream of wind turbines operating under neutrally-stratified flow condition. The model was tested against wind tunnel measurements of Chamorro and Porté-Agel (2010) and Large-Eddy Simulation (LES) data for real-scale wind turbine wakes of Wu and Porté-Agel, (2011, 2012). The results showed an acceptable agreement with the aforementioned test cases. However, Bastankhah and Porté-Agel (2014) recommended performing more research to consider the effect of inflow conditions on the wake growth rate. Recently, Abkar and Porté-Agel (2015) used LES frame work combined with the actuator disk model with rotation to investigate the effect of atmospheric thermal stability on wind turbine wakes produced by Vestas V80-2*MW* wind turbine. Their results indicated that, the spatial distribution of the wake characteristics is strongly affected by the different atmospheric stratifications. In particular, the wake recovers faster under convective conditions compared with the other two conditions due to higher turbulence level of incoming wind in CBL. In addition, they used the results to calibrate the model of Bastankhah and Porté-Agel (2014) and proposed a developed one assuming an elliptical (instead of axisymmetric) Gaussian distribution for the wake deficit, taking into account the different thermal stratification of ABL.

To the best of our knowledge, simulation of the wind turbine wakes under thermally-stratified atmosphere using Reynolds-Averaged Navier–Stokes (RANS) technique is not well documented in the literature. The present paper aims to test this technique in order to investigate the wake behavior at different ambient stability conditions. Two different methods, described in the next section, which are direct and indirect methods, are adopted and compared for representing the buoyancy effect produced by ambient stratification. The standard k-ε model of Jones and Launder (1972) as well as the modified k-ε model of El Kasmi and Masson (2008), referred to hereafter as El Kasmi model, are used for turbulence modulation. The Monin-Obukhov similarity theory is used for describing the atmospheric conditions under the influence of heat transfer, see Arya (2005).

2. Mathematical modeling

In the present work, the numerical simulation of wind turbine wakes under different thermally-stratified conditions of ABL is based on RANS equations. The flow is considered as steady ideal gas. Also, the buoyancy effect due to atmospheric thermal stratifications is taken into account. In the direct modeling of atmospheric stratification, the complete set of continuity, momentum and energy equations are considered according to Alinot and Masson (2005), and solved.

The continuity and momentum equations are given by,

$$\frac{\partial \rho u_j}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+S_m \tag{2}$$

where, ρ is the air density, u_i is the i$^{\text{th}}$ velocity component, p is the presure,$S_m=\rho g_i$ is the momentum added source term to represent the gravity force, and τ_{ij} is the Reynolds stress tensor of eddy viscosity model that is given by

$$\tau_{ij}=\mu_e\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

where, $\mu_e=\mu+\mu_t$ is the effective viscosity, in which μ is the laminar viscosity and μ_t is the turbulent viscosity, calculated from the adopted turbulence closure.

The energy equation is written as

$$\frac{\partial}{\partial x_j}\rho c_p u_i T=\frac{\partial}{\partial x_j}\left[u_j\tau_{ij}+\frac{c_p\mu_t}{\sigma_T}\left(\frac{\partial T}{\partial x_i}-\Gamma\right)\right]+S_E \tag{4}$$

where, c_p is the specific heat, T is the air temperature, σ_T is the turbulent prandtl number, $S_E=\rho u_i g_i$ is the added source term to the energy equation to account for gravity effect (g is the gravitational acceleration), and $\Gamma=g_i/c_p$ is the dry adiabatic laps rate added to the energy equation in order to reformulate the temperature gradients based on potential temperature θ.

The potential temperature is related to the temperature (T) by

$$\frac{\partial\theta}{\partial z}=\frac{\theta}{T}\left(\frac{\partial T}{\partial z}+\Gamma\right)\cong\frac{\partial T}{\partial z}+\Gamma \tag{5}$$

2.1. Modeling of wind turbine

The actuator disk approach is used to represent the effect the turbine rotor on the flow. The rotor is simulated as a momentum sink to be applied on the surface of the actuator disk according to Prospathopoulos et al. (2011),

$$F=0.\ 5\rho C_T A U_{hub}^2 \tag{6}$$

where, A is the scanned surface area of the turbine rotor, and C_T is the thrust coefficient that is obtained from the thrust coefficient curves against wind velocity for the modeled turbines at the given hub height velocity U_{hub}. The selected C_T is assumed to be constant across the whole actuator disk. As a result, the calculated thrust force is uniformly distributed over the disk. The assumption of constant C_T is used because the non-uniform calculation of C_T over the rotor disk would require the coupling of the Navier–Stokes solver with a Blade Element Momentum (BEM) theory solver. Also, it requires detailed data of the blade geometry and the lift coefficient (C_L) and the drag coefficient (C_D) distributions of the airfoils along the span of the blades, which are usually not available.