Applied Energy 212 (2018) 33–45

Contents lists available at ScienceDirect

Applied Energy

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

Assessing compressibility effects on the performance of large horizontal-axis wind turbines

Chi Yan*, Cristina L. Archer

College of Earth, Ocean, and Environment, University of Delaware, Newark DE 19716, USA

HIGHLIGHTS

- Assessments of compressibility effects around large wind turbines are conducted.
- Compressibility effects in flow around large wind turbines are not negligible.
- Compressibility effects start near the blade tips and impact the wake.
- Compressibility effects increase as upstream wind speed and tip speed ratio increase.
- Power generation of wind turbines is lower when compressibility is considered.

ARTICLE INFO

Keywords:
Wind turbine
Computational fluid dynamics
Incompressible
Compressible
Blade element
Actuator line model
Wind power

ABSTRACT

The tips of large horizontal-axis wind turbines can easily reach high speeds, thus raising the concern that compressibility effects may influence turbine wakes and ultimately power production. All past studies have assumed that these effects are negligible. Compressibility effects are assessed here in terms of blade aerodynamic properties and variable density separately. Using the Blade Element Momentum (BEM) method, we find that under normal operating conditions (i.e., wind speed $<\sim 15\,\mathrm{m\,s^{-1}}$ and tip speed ratio TSR $< \sim 12$) aerodynamic corrections to the lift and drag coefficients of the blades have a minimal impact, thus the incompressible coefficients are adequate. To assess the variable-density effects, numerical simulations of a single turbine and two aligned turbines, modeled via the actuator line model with the default aerodynamic coefficients, are conducted using both the traditional incompressible and a compressible framework. The flow field around the single turbine and its power performance are affected by compressibility and both show a strong dependency on TSR. Wind speed and turbulent kinetic energy (TKE) differences between compressible and incompressible results origin from the rotor tip region but then impact the entire wind turbine wake. Power production is lower by 8% under normal operating conditions (TSR $\sim$ 8) and 20% lower for TSR $\sim$ 12 due to compressibility effects. When a second turbine is added, the front turbine experiences similar effects as the single-turbine case, but TKE differences are enhanced while wind speed differences are reduced after the second turbine in the overlapping wakes. These findings suggest that compressibility effects play a more important role than previously thought on power production and, due to the acceptable additional computational cost of the compressible simulations, should be taken into account in future wind farm studies.

1. Introduction

Modern wind turbines are being built with longer blades, taller towers, and higher capacities than ever before, to deliver more energy in a more efficient way. Turbine manufacturers all over the world are building wind turbine blades that exceed 70 m in length, e.g., the MHI Vestas V164-8.0MW (rotor diameter D = 164 m) [1], the Siemens SWT-8.0MW (D = 154 m) [2], the special two-blade wind turbine Ming Yang SCD-6.0MW (D = 140 m) [3], and the prototype Adwen AD-8.0MW (D = 180 m) [4]. The tip speed of these powerful wind turbines can easily reach Mach numbers in the range of 0.2–0.3 under normal operating conditions (and even higher under high-wind conditions). At these Mach numbers, treating the flow near the wind turbine as incompressible is questionable, as compressibility effects are expected to arise and can affect the flow field as well as the performance of the wind turbines. The incompressibility assumption has been the gold standard in past studies of flow around turbines but it has never been evaluated before at such high tip speeds as we see today. This study is the first to

* Corresponding author.
E-mail address: yanchi@udel.edu (C. Yan).

https://doi.org/10.1016/j.apenergy.2017.12.020
Received 5 August 2017; Received in revised form 10 November 2017; Accepted 1 December 2017
0306-2619/

systematically evaluate the limitations of incompressibility with respect to both aerodynamic coefficients of the blades and variable density.

The extraction of energy from the wind by a large wind turbine leaves a wake behind it, which propagates downstream and is characterized by lower wind speeds and higher turbulence than the ambient air. The behavior of the wind turbine wake and the possible interactions between different wakes in a large wind farm have been extensively studied for more than three decades [5] via wind tunnel studies and computational simulations.

Experiments have been successfully conducted in wind tunnels to study wind turbine aerodynamics using scaled-down versions of small-size [6–8] and medium-size [9–11] rotors. Only two wind tunnel experiments were performed for full-size rotors, the National Renewable Energy Laboratory (NREL) Phase VI rotor [12] and the Model Experiments In Controlled Conditions (MEXICO) rotor [13]. The main limitation of wind tunnel studies lies in the scale of the wind turbine models. Even the full-size rotors are much smaller than the turbine rotors used in the industry, which usually are O(100) m. When extending the wind tunnel measurements to real applications, scaling effects occur [14].

Studying individual and clustered real-size wind turbines has been made possible by computational fluid dynamics (CFD). With CFD, representing large wind turbine rotors with high fidelity, i.e., fully resolving the geometry, rotation, and effects of the turbine blades, is possible in principle, but remains nearly impossible in practice because it is too computationally intensive, as reviewed in [15,5]. For high Reynolds number flows, the length scale of the boundary layer that forms around the turbine blades is $O(10^{-3})$ m, while the length scale of the atmospheric boundary layer (ABL) domain is $O(10^3)$ m. The number of grid points required to properly simulate such a range of scales is enormous, although some parts of the domain can be resolved at coarser resolution. To overcome this computational impediment, parameterizations of the aerodynamic forces on the turbine have been therefore developed to reduce grid requirements. In general, the turbine rotor or blades can be represented by the Actuator Disk Model (ADM) or the Actuator Line Model (ALM). For both, the aerodynamic forces are obtained with the Blade Element theory [16]. The original ADM uses a circular disk to simulate the rotor and the thrust force induced by the wind turbine is imposed to the flow [17–19]; however, the rotational effects of the rotor are not taken into account. This limitation was overcome by another version of the ADM, in which both thrust and tangential forces are imposed to the flow [20–22]. The disadvantage of the ADM is that the aerodynamic forces imposed on the fluid are averaged over the rotor area whereas the actual location of the blades changes with time. With the ALM, drag and lift forces are calculated along actuator lines that represent the rotating blades, therefore the rotational effects and movements of the blades are taken into account [23–25]. The ADM and ALM can be integrated with either the unsteady Reynolds Averaged Navier-Stokes (RANS) framework [21,26] or the Large Eddy Simulation (LES) framework [19,27]. Finite Element Method (FEM) [28], Finite Difference Method (FDM) [27] and Finite Volume Method (FVM) [29,30] have been used to solve the URANS and LES systems of equations, using the incompressible assumption.

Some efforts have been made to account for compressibility effects when modeling wind turbines and the flow around them, but either for small regions confined near the turbine blades or using certain simplifications or corrections. Wood [31] assumed that compressibility effects, being due primarily to the rotation of the blades, would be confined to the region near the blades and performed calculations of aerodynamic properties at various wind speeds using BEM theory. He found that, when the wind speeds were of the order of $30\,\mathrm{m\,s^{-1}}$, significant reductions in the wind turbine performance occurred due to compressibility. Leishman and Beddoes [32] proposed a semi-empirical stall model in which compressibility effects were simply represented with a constant correction coefficient. Duque et al. [33] performed successful simulations of compressible flow around a wind turbine blade (the NREL phase II rotor) but using the so-called "thin-layer" Navier-Stokes equations. Later Duque et al. [34] simulated the flow around blade of the NREL phase VI rotor using both CAMRAD II (a lifting-line code with a free wake model) and OVERFLOW-D (a compressible solver with low Mach-number preconditioning capability); the power prediction with OVERFLOW-D showed good agreement with measurements while CAMRAD II did not and modifications were needed. Xu and Sankar [35] solved the viscous compressible flow equations over a small region around the rotor and the other part of the domain was modeled using an inviscid free-wake method. Pape and Lecanu [36] performed 2D and 3D simulations of a two-bladed wind turbine with a compressible solver, developed by ONERA [37], over a domain restricted to one 180° azimuthal sector by using periodic boundary conditions. Their 2D simulations showed good agreement with experiments whereas the 3D computations did not, especially in the high speed region. In summary, no information can be found in the literature about assessments of the compressibility effects around large wind turbines in a realistically-sized domain.

The most widely used, averaged or filtered, governing momentum equation for wind turbine and wind farm simulations is the incompressible, Boussinesq form of the Navier-Stokes equation as follows:

$$\frac{\partial}{\partial t}(\rho_0\overline{u}_i) + \frac{\partial}{\partial x_j}(\rho_0\overline{u}_j\overline{u}_i) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{t_{ij}}) + \overline{\rho} g_i + \rho_0 f_i, \tag{1}$$

where $\overline{u}_i$ is the averaged or filtered velocity, τ_{ij} is the mean or resolved laminar stress tensor, $\tau_{t_{ij}}$ is the turbulent stress tensor, g_i is the gravitational acceleration, f_i is the body force from the turbine blade model (ADM/ALM), and, from the Boussinesq approximation, air density is assumed constant everywhere (ρ_0) except in the gravity term ($\overline{\rho}$). Next, the buoyancy term can be linked to temperature to give the final form of the three governing equations (continuity, momentum, and temperature equations):

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{2}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_j\overline{u}_i) = -\frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial x_i} + \frac{1}{\rho_0}\frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{t_{ij}}) + [1-\beta(\overline{\theta}-\theta_0)]g_i + f_i, \tag{3}$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_j\overline{\theta}) = -\frac{\partial q_j}{\partial x_j} - \frac{\partial q_{t_j}}{\partial x_j}, \tag{4}$$

where $\overline{\theta}$ is the averaged or filtered potential temperature, θ_0 is the reference, constant, and uniform potential temperature, q_j is the mean or resolved heat flux, q_{t_j} is the turbulent heat flux, β is the coefficient of volume expansion.

Two problems arise when compressibility effects are taken into account. First, the body force f_i on the flow is equal and opposite to the force exerted by the ADM/ALM, which is calculated using tabulated airfoil lift and drag coefficients based on the incompressible assumption. Thus, these tabulated aerodynamic properties of each blade section can be safely used when the Mach number is small because the incompressible assumption is valid. However, the Mach number at blade sections near the tip of large wind turbines can easily reach up to ~0.2–0.3. Based on linearized, compressible, subsonic flow analysis, as the Mach number increases, both lift and drag coefficients of the airfoil will increase [38], thus compressibility corrections need to be applied to these coefficients when modeling large wind turbines. This will be explained in more detail in Section 2.

Second, the body force f_i in the incompressible framework is a density-normalized force. However, to calculate torque, thrust, or power output of the turbine, the body force needs to be multiplied by air density, which in principle is different at each point and at each time. Because of the incompressible and Boussinesq assumptions, air density is treated as a constant and therefore the body force is simply multiplied by a constant reference density ρ_0 (Fig. 1a). Choosing the