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Comparison of the wake recovery of the axial-flow and cross-flow turbine concepts

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ABSTRACT

A detailed wake analysis of two different turbine concepts is conducted to gain a fundamental understanding of the main energy recovery processes at play in each case. An axial-flow turbine and a cross-flow turbine are considered. Both operate near their respective optimal efficiency conditions in a uniform oncoming flow and at a Reynolds number of 10^7. Three-dimensional Delayed Detached-Eddy Simulations (DDES) are carried out and the time-averaged Unsteady Reynolds-averaged Navier–Stokes (URANS) equations are used as a post-processing tool in order to assess the importance of the various contributions affecting the wake recovery quantitatively. It is found that the dominant mechanism is fundamentally different between the two turbine technologies. Indeed, while the axial-flow turbine's wake is strongly influenced by an instability phenomenon leading to a significant turbulent transport, the cross-flow turbine's wake recovery is found to be much more related to the mean spanwise velocity field. As a result, unlike the axial-flow turbine's wake dynamics which is highly dependent on the turbulent characteristics of the oncoming flow, the cross-flow turbine's wake is expected to be less sensitive to these turbulent characteristics but highly dependent on the geometric characteristics of the turbine such as the turbine's aspect ratio.

1. Introduction

Renewable energy sources, such as marine currents and winds, are diffuse compared to the energy coming from fossil fuels (Lago et al., 2010). Consequently, it is critical to densify the energy production of hydrokinetic and wind turbines by suitably placing them in farms for this energy sector to become economically competitive. In this context, the choice of a particular technology over another does not depend solely on the efficiency of a single machine but the interactions between the turbines must also be taken into account (Dabiri, 2011). Moreover, it has been found that, for very large turbine farms (several turbine rows), the amount of energy available for each turbine strongly depends on the vertical kinetic energy fluxes ($-\rho\, U_\infty(\overline{u'\, w'})$) from the flow passing above the turbines to the flow at the turbines' level (Abkar and Porté-Agel, 2014; Calaf et al., 2010; Chamorro et al., 2011). In an infinitely long turbine farm, these vertical energy fluxes necessarily balance the power extracted by the turbines. Since these fluxes are affected by the flow topology in the turbines' wakes, it is important to characterize the wake dynamics of different types of turbine, such as the axial-flow turbine (AFT) and the cross-flow turbine (CFT), as a specific turbine could become interesting in the context of a very large turbine farm even if it is not the most efficient one when it is considered individually, in isolation. It is also worth mentioning that some recent findings have shown that a turbine's farm performance could be increased by operating the turbines at non-optimum conditions (Kazda et al., 2016), therefore again demonstrating that the performances of turbines in isolation are not the only parameters of interest when optimizing a farm.

Several studies have been devoted to the analysis of the flow field in the wake of a single axial-flow turbine, with some of them focusing on the tip vortices' dynamics in the near wake (Chamorro et al., 2013b; Lignarolo et al., 2014; Zhang et al., 2012). Sherry et al. (2013) performed PIV measurements in the wake of an AFT facing a uniform oncoming flow and focused on the vortex instability occurring in the wake, which was found to be strongly dependent on the tip speed ratio. Lignarolo et al. (2014) minimized the ambient turbulence in their experimental facilities and their stereoscopic particle image velocimetry (SPIV) measurements have suggested that the enhanced mixing caused by the tip vortices' instability has a pronounced effect on the momentum recovery. However, their measurements were limited to the near wake, i.e., up to only 5 diameters downstream of the turbine, and they did not quantify the relative contribution of the tip vortices' instability in comparison with the other mechanisms affecting the momentum recovery.

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Owing to the fact that the AFT's wake dynamics is highly influenced by the turbulent characteristics of the oncoming flow (Chamorro and Porté-Agel, 2009; Chu and Chiang, 2014; Mycek et al., 2014a,b; Zhang et al., 2012) and in order to be as faithful as possible to realistic turbine operating conditions, several recent AFT wake studies have been performed on turbines operating in a turbulent boundary layer (Cal et al., 2010; Chamorro and Porté-Agel, 2009, 2010; Chamorro et al., 2013a,b; El-Askary et al., 2017; Hu et al., 2012; Porté-Agel et al., 2011; Wu and Porté-Agel, 2012; Zhang et al., 2012), either corresponding to the atmospheric boundary layer in the case of wind turbines or to the marine boundary layer in the case of hydrokinetic turbines. Among these studies, it is worth mentioning that Chamorro et al. (2013b) and Zhang et al. (2012) performed, respectively, detailed particle image velocimetry (PIV) and volumetric 3-component velocimetry (V3V) measurements of the three velocity components and the Reynolds stresses in an axial-flow turbine's near wake. Chamorro et al. (2012b) and Wu and Porté-Agel (2012) evaluated various terms of the turbulent kinetic energy budget in the wake of an axial-flow turbine operating in a boundary layer flow through experimental measurements and numerical simulations. A few works have also been devoted to the study of the energy transport in AFT arrays by carrying out a budget of either the mean kinetic energy equation (Abkar and Porté-Agel, 2014; Cal et al., 2010; Hamilton et al., 2012; Lebron et al., 2012; Newman et al., 2014; VerHulst and Meneveau, 2014) or the turbulent kinetic energy equation (Abkar and Porté-Agel, 2014). These studies have highlighted the importance of the radial turbulent transport in axial-flow turbines' wakes. Furthermore, Meyers and Meneveau (2013) visualized the energy transport in various configurations of turbine arrays using the concept of the energy transport tube. Lastly, the interested reader is referred to two recent reviews discussing the flow topology in axial-flow turbines' farms (Mehta et al., 2014; Stevens and Meneveau, 2017).

Regarding the cross-flow turbine concept, numerous experimental measurements have been taken in the wake of the straight-blade H-Darrieus turbine concept (Bachant and Wosnik, 2013, 2015, 2016; Battisti et al., 2011; Brochier et al., 1986; Hofemann et al., 2008; Ryan et al., 2016; Simão Ferreira et al., 2006, 2007, 2009, 2010; Tescione et al., 2014). Battisti et al. (2011) performed hot-wire measurements on a plane normal to the upstream flow located 1.5 diameters downstream of such a CFT in open and closed wind tunnel configurations. They presented time-averaged and phase-averaged results and showed the importance of the tip effects on the turbine's performances and on its wake topology. Other studies focused on the evolution of the shed vorticity and the tip vortices in the wake of the H-Darrieus turbine and highlighted the fact that the tip vortices ejected from the CFT blades tend to convect toward the wake center in the spanwise direction (Hofemann et al., 2008; Simão Ferreira et al., 2006, 2007, 2009, 2010; Scheurich et al., 2011). The same observation was also made more recently by Tescione et al. (2014) who used the PIV technique to observe in detail the flow field in the near wake of an H-Darrieus CFT turbine. However, their measurements only covered the first three diameters downstream of the turbine's axis of rotation. Measurements up to seven and ten diameters downstream have been taken by Ryan et al. (2016), who showed the effects of the tip speed ratio on the wake dynamics, and by Peng et al. (2016), who investigated the wake of a five-blade cambered-airfoil turbine, respectively. Based on the results of full-scale field tests, Dabiri (2011) suggested that an array of closely spaced and relatively small cross-flow wind turbines could extract up to an order of magnitude more power per land area than conventional AFT farms. He attributed the quick energy recovery observed to the significant vertical turbulent transport occurring in the CFTs' wakes. This point was also affirmed by Kinzel et al. (2012, 2015) who conducted more detailed measurements in a similar field test, but an erratum later pointed out that this turbulent transport contribution had been overestimated (Kinzel et al., 2013). Finally, Bachant and Wosnik (2015) used the acoustic Doppler velocimetry (ADV) technique to make detailed measurements on a plane normal to the freestream flow located at one turbine diameter downstream of the turbine's axis of rotation. They showed that the mean spanwise velocity field actually contributes more to the wake recovery than the turbulent transport in the case of a CFT wake. However, they performed their analysis on a single plane, thus preventing them to evaluate the contributions of the streamwise pressure gradient and the streamwise derivatives of the Reynolds and viscous stresses.

The present work aims to shed more light on the flow dynamics in the wakes of both the axial-flow turbine and the cross-flow turbine by conducting a quantitative analysis of all the different physical mechanisms affecting the wake's recovery. This is done by using the streamwise component of the time-averaged Unsteady Reynolds-averaged Navier–Stokes (URANS) equations and by comparing the contribution of each term appearing in this equation. Such a budget provides a direct evaluation of the rate at which the mean streamwise velocity is recovered in the turbines' wakes, unlike the more popular method based on the mean kinetic energy transport equation (Abkar and Porté-Agel, 2014; Cal et al., 2010; Hamilton et al., 2012; Lebron et al., 2012; Newman et al., 2014; VerHulst and Meneveau, 2014). The results of this study are therefore of great interest in an engineering point of view because the mean streamwise velocity is directly related to the energy available for a subsequent turbine in a turbine cluster. Moreover, solving the complete three-dimensional flow field allows us to evaluate all the terms affecting the wake recovery, which is usually not done experimentally due to the fact that some measurements are especially difficult to make without affecting the flow, such as is the case for the pressure field for example. Furthermore, many previous wake studies were restricted to the very near wake either because of the restrictions related to the available laboratory facilities or to the high computational costs in the case of numerical studies. In the current work, the wakes of the two turbine technologies are analyzed up to 12 diameters downstream of their center. Finally, our knowledge based on the axial-flow turbine's literature should be used carefully when studying cross-flow turbines because the conclusions drawn from the study of the former do not necessarily directly apply to the latter. Studies that compare the wakes of these two turbine concepts are very useful in that regard.

Information about the turbines' operating conditions, the turbines' geometry, the turbulence modeling approach and the numerical methodology are given in Section 2. The wake dynamics of the two turbine technologies are then analyzed in Section 3, the importance of all the mechanisms involved in the wake's recovery is evaluated in Section 4 and a discussion on the findings stemming from this work is presented in Section 5. The results of the present study provide novel and very valuable quantitative information about the detailed three-dimensional flow field in the wake of the AFT and the CFT concepts operating at a high Reynolds number.

2. Methodology

2.1. Description of the turbine cases investigated

The axial-flow turbine (Burton, 2011; Sørensen, 2011) is characterized by blades rotating at a constant velocity around an axis aligned with the direction of the oncoming flow while the cross-flow turbine concept (Paraschivoiu, 2002), also known as the vertical-axis turbine or the Darrieus turbine, involves blades that are rotating around an axis which is perpendicular to the flow. Outlines of both concepts are shown in Fig. 1.

The instantaneous power coefficient of these two turbine concepts is defined as:

$$C_p(\theta) = \frac{P(\theta)}{\frac{1}{2}\rho\, U_\infty^3\, A}, \tag{1}$$