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Computational evaluation of wind loads on sun-tracking ground-mounted photovoltaic panel arrays

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A B S T R A C T

Computational fluid dynamics is employed to evaluate the mean wind loads on sun-tracking ground-mounted solar photovoltaic panel arrays. Reynolds-averaged Navier-Stokes simulations are performed using a finite volume-based numerical method. The mean turbulent flow around the panel is simulated by following two different approaches, by considering either the full three-dimensional model or the reduced model with periodic boundary conditions in the spanwise homogeneous direction. The periodic model is demonstrated to well reproduce the aerodynamics of the panel with a considerable reduction of the computational cost. The wind loading history due to the continuous rotation of the system is directly simulated by means of the dynamic meshing technique, which allows for a further savings of computational resources with respect to static calculations.

1. Introduction

In recent years, solar power has been strongly emerging as the first source of alternative energy for industrial applications. Besides the relative simplicity of the electricity production process and the possibility of reducing the effect on global warming and air pollution, the main reason for such a trend lies in the continuously decreasing price of solar photovoltaic (PV) panels, whereas the cost of traditional energy sources has been increasing. However, the productivity of PV cells still represents a challenging issue, since the maximum efficiency reached by the large-area commercial cells is about 24% (Blakers et al., 2013). Furthermore, the highest performance of the PV system is achieved when the solar rays are approximately perpendicular to the given panel surface, and thus only for few hours per day.

In the industrial field, a widespread solution to the problem of low efficiency is the use of solar farms, which are large-scale PV power stations that are capable of generating large quantities of electricity. In these plants, even thousands of ground-mounted solar panels are connected to form systems of length equal to tens of meters and beyond. As to the panel surface orientation, recent studies have produced some smart solutions to this problem, such as the application of solar trackers, e.g. (Ghosh et al., 2010; Rohr et al., 2015). The latter are devices that allow the solar panels to rotate around one or two axes, while following the different inclination of the solar rays during the day, so as to extend the temporal period of maximum efficiency of the PV cells. This way, it was demonstrated that it is possible to increase the overall daily output power gain by more than 20% compared to a fixed mounted system, e.g. (Al-Mohamad, 2004).

One of the most important goals of the engineering research on PV systems, either fixed or mobile, is the analysis of the aerodynamic loads acting on the solar panels, and indirectly on the support structures. A large number of works on roof-mounted panels exist in the literature (Wood et al., 2001; Chung et al., 2008; 2011; Kopp and Banks, 2013; Pratt and Kopp, 2013; Banks, 2013; Browne et al., 2013; Cao et al., 2013; Aly and Bitsuamlak, 2014; Stathopoulos et al., 2014; Warsido et al., 2014), whereas studies on ground-mounted panels have been appearing only recently.

From the experimental point of view, the study of ground-mounted systems is very complex since the characteristic flow spatial scales that are involved require the realization of very small models for boundary layer wind tunnel tests. Nevertheless, among the others, important experimental findings were obtained by Stathopoulos et al. (2014), who studied the aerodynamic loads on a stand-alone PV panel for different configurations and inclinations. In particular, the maximum peak of the pressure coefficient for a ground-mounted panel was demonstrated for an inclination angle of 135° with respect to the wind direction. The pressure distribution on the upper and the lower surfaces of a single panel for four different wind directions was investigated by Abiola-Ogedengbe et al. (2015), while the effect of lateral and longitudinal spacing between

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panels on the wind loading of a ground-mounted solar array was studied by Warsido et al. (2014).

Also due to the difficulties encountered in wind tunnel testing, the Computational Fluid Dynamics (CFD) analysis has recently become an important predictive tool for ground-mounted PV systems. For instance, Aly and Bitsuamlak (2013) investigated the sensitivity of wind loads on the geometric scale of a stand-alone panel, by demonstrating that the mean loads are not significantly affected by the model size, while the peak loads are indeed varying. Shademan et al. (2014) performed three-dimensional Reynolds-Averaged Navier-Stokes (RANS) simulations to determine the effect of lateral spacing between sub-panels on wind loads in a PV system, as well as the influence of longitudinal spacing between solar panels in the arrayed configuration. Unsteady RANS models were also employed by Jubayer and Hangan (2014, 2016) to investigate the wind effects on a stand-alone panel as well as a solar panel array immersed in the Atmospheric Boundary Layer (ABL) flow, with a variable wind direction.

The main goal of this work is the computational evaluation of the mean wind loading on sun-tracking ground-mounted PV panel arrays, which are commonly used in solar farms. To fulfill the aim, two different numerical approaches are followed. First, the entire row is directly simulated in a fully three-dimensional computational domain. The alternative approach consists in the simulation of a small portion of the solar panel row by imposing periodic boundary conditions in the spanwise homogeneous direction. The present RANS solutions are examined by correlating the wind flow field past the obstacle with the panel surface pressure distributions. In addition, the dynamic mesh technique is applied to determine the history of the wind loading on the panel structures due to the action of a single axis sun-tracking device. The numerical simulations are performed using the commercial solver ANSYS Fluent, which is commonly and successfully employed in the industrial aerodynamics research, e.g. Liu et al., 2011; Moonen and Carmeliet, 2012; Tan et al., 2016.

The remainder of this paper is organized as follows. In §2, the overall computational methodology is described, with a particular focus on the inlet turbulent flow boundary conditions. After the preliminary validation of the proposed approach for a stand-alone panel, the results of the present numerical experiments for a sun-tracking ground-mounted panel array are presented and critically discussed in §3. Concluding remarks are provided in §4.

2. Computational modeling approach

In this section, the overall computational modeling approach is introduced. The geometry of the solar PV panel system under investigation and the numerical settings are presented, together with the free-stream turbulence conditions that are assumed.

2.1. Computational settings

The geometric model examined in this work corresponds to a ground-mounted solar panel array, on which a single horizontal axis tracker is installed. The sub-panel geometry is similar to that one described in Jubayer and Hangan, 2014, which represents the reference study that is used for validating the present approach, as discussed in the following section. In fact, the present PV system, which is typical of solar farms, consists of 36 panels arranged in portrait orientation to form a single row. The numerical simulation of more complex systems with multiple rows of panels will be the subject of our future work. Each panel has the chord length $C = 2$ *m*, the width of 1.2 *m* and the thickness of 0.007 *m*. It is worth noting that the low thickness of the present model does not represent the dimension of the frame of real panels, which is here not simulated. In fact, including the frame would cause a significant complication for the mesh generation, which is out of the scope of the present analysis. The transverse length of the whole system is $L = 43.2$ *m*. The existing gap between the single panels is actually neglected in the realization of the CFD model, because its effect upon the aerodynamics of the PV system is considered to be negligible, as suggested by Wu et al., 2010. Therefore, the row of panels is modeled as a single plate with an aspect ratio of $L/C = 21.6$. The PV structure is supported by six vertical columns that are equally spaced by 7.2 *m*. Each column is modeled as a bar with the height of 1 *m* and the square cross-section of side length 0.1 *m*.

The solar panel array is placed within a computational domain whose spatial dimensions are the following: 21.6 *C* (longitudinal length) along the *x*-axis, which is aligned with the wind direction, 6.3 *C* (vertical length) along the *y*-axis, and 32 *C* (spanwise length) along the *z*-axis. The upstream boundary is placed at a distance of 5 *C* from the obstacle, the downstream boundary at 16 *C*, the top boundary at 5 *C* and the lateral boundaries at 10.5 *C*. The shortness of the gap between the upstream boundary and the panel array reflects the fact that suitable profiles for the velocity and the turbulence intensity of the upcoming wind are explicitly imposed at the inlet boundary, as discussed in the following. This way, a substantial savings of computational resources can be yielded. In fact, the computational domain is created also following the practical guidelines provided by Franke et al. (2007). In Fig. 1, the domain is depicted for a given angle of inclination of the panel, which is $\theta = -60^{\circ}$, with respect to the oncoming wind direction. However, a number of three-dimensional

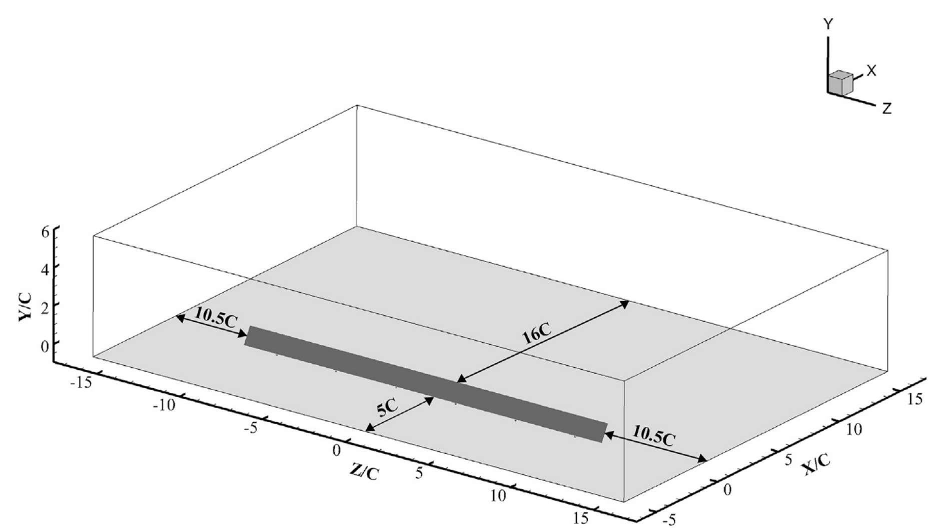

Fig. 1. Computational domain for the PV panel system: full model.

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