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On the evaluation of wind loads on solar panels: The scale issue

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ABSTRACT

Solar power can improve the quality of life and reduce dependency on traditional energies that are a significant source of pollution and global warming. Solar panels are common devices used for collecting solar energy. To balance between sustainability and resilience, it is essential to provide an accurate estimate of the design wind loads for the solar panels. Traditionally design wind loads for buildings and other structures are obtained using building codes and standards. The solar panels represent a relatively recent technology and indeed there is no complete guidance ready for codification of wind loads on these types of structures. Available wind tunnel data show discrepancies in wind loads on solar panels, owing to inconsistent model scales and test flows, among other factors. To eliminate such discrepancies in the test results and to allow for accurate wind load estimation, the current paper investigates the geometric scale and the inflow turbulence characteristics as potential causes of high uncertainties. Computational fluid dynamics (CFD) simulations are employed and results are compared with available wind tunnel data, as a complementary tool with a potential to simulate wind loads at full-scale. The results show that the geometric scale is a primary reason for the discrepancies in peak wind loads, which can be avoided by adapting the inflow turbulence and using a proper testing protocol. The results show an evidence of the correctness of a hypothesis that the lack of large-scale turbulence can dramatically affect peak wind loads on test objects. Consequently, recommendations are articulated regarding the best usage of the available wind load estimation tools. This is expected to lead to consistent and accurate results from wind tunnel testing and CFD simulations, a crucial step toward codification of wind loads on solar panels.

1. Introduction

1.1. Background

The importance of the solar power as a source of eco-friendly energy was documented early in 1911 (Shuman, 1911). With worldwide concerns regarding the impact that combustible fuels have on the increase in greenhouse gas emissions and climate change, sustainable development policies supporting the integration of renewable energies have started. Photovoltaic (PV) or solar panel systems are common devices used for collecting solar energy (Singh, 2013). Probably technology will lead to 'Covering the Planet with Solar Panels' (Webb, 2007). For large-scale solar energy production, PV panels are usually mounted on ground. The main concern regarding solar panels installation is their vulnerability to highly turbulent and gusty wind. Developing design standards is still in an incipient stage, and building guidelines are not clearly defined. Indeed there are no code guidelines available yet, that can support the evaluation of design wind loads for solar panels (Stathopoulos et al., 2012). This means that the designer may roughly estimate the loads with the consequences of either overestimation, which put obstacles on a technology that is supposed to be economic, or underestimation, which may lead to failure. For both scenarios the design is not feasible. It is worthy to mention that in the past decades, the solar cell industry has grown significantly, however, because of its relatively high cost, solar power accounts for a little portion of the U.S. electricity (Robert, 2003). According to Morton (2006), sunlight is a ubiquitous form of energy, but not as yet an economic one. This highlights the importance of building wind resistant solar panels in an economic way, which can be achieved by accurate estimation of the design loads. For large structures, e.g. high-rise buildings, wind loads are easier to be predicted by wind tunnel testing (at geometric scales ranging from 1:100 to 1:500) as the flow depicts all necessary turbulence content; however, for small structures, for example solar panels, testing in wind tunnels can be challenging. Aerodynamic testing of small structures, for instance ground-mounted solar panels, is typically carried out at scales larger than those usually used in boundary-layer wind tunnels (e.g., 1:30 scale). This is to alleviate potential technical problems; especially those related to pressure

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Nomenclature

A	tributary area
a_n, b_n, c_n, α_n	Fourier coefficients
C_{NF}	normal force coefficient
$C_{NF,peak}$	peak force coefficient
$C_P(t)$	time history of pressure coefficient
$C_{P,bottom}(t)$	pressure coefficient (bottom surface)
$C_{P,tot}(t)$	total pressure coefficient
$C_{P,top}(t)$	pressure coefficient (top surface)
c_E	turbulent kinetic energy constant
$E(\kappa)$	energy of wave number κ
$f(x)$	synthesized inlet fluctuations
k	turbulent kinetic energy
$P(t)$	instantaneous surface pressure
U	mean wind speed
u_{std}	root-mean square speed
v'_1, v'_2, v'_3	inlet fluctuating velocity fields
$\mathbf{v}'(x)$	turbulent velocity field
W	number of windows
β^n	velocity field calculation figure
ε	dissipation rate
κ_e	unscaled wave number
κ_η	Kolmogorov wave number
κ^n	wave number
$\hat{u}^n$	amplitude of Fourier mode
ρ	air density
σ^n	direction of Fourier mode
υ	molecular viscosity
ψ^n	phase of Fourier mode
N	number of samples per window
x	spatial coordinate
n	Fourier mode

resolution, interference effects from measuring instruments and falls in the uncertain flow regimes close to the tunnel floor. The problem is that, at such geometric scales, the flow lacks essential turbulence content.

1.2. Review

In order to obtain realistic wind loads by wind tunnel testing, fundamental laws of similitude should be employed. These are mainly the similarity of the test model and the approaching flow to full-scale (Plate, 1982). Wind loads on solar panels depend on wind speed, terrain characteristics, shape, which includes inclination angle, and installation type, among other factors. The majority of solar panels installations are either roof-mounted or ground-mounted. Although the literature has a number of studies concerning wind loads on roof mounted solar panels (Radu et al., 1986; Radu and Axinte, 1989; Wood et al., 2001; Kopp et al., 2002; Chung et al., 2008; Meroney and Neff, 2010; Banks, 2013; Browne et al., 2013; Cao et al., 2013; Aly and Bitsuamlak, 2014; Stathopoulos et al., 2014; Warsido et al., 2014), a paucity of papers address ground mounted solar panels (Bitsuamlak et al., 2010; Kopp et al., 2012; Abiola-Ogedengbe, 2013; Aly and Bitsuamlak, 2013; Stathopoulos et al., 2014; Warsido et al., 2014; Shademan et al., 2014a,b; Jubayer and Hangan, 2014). Pfahl et al. (2011) presents wind loads on heliostats and photovoltaic trackers of various aspect ratios, with a model scale of 1:20. The study suggests that higher aspect ratios are advantageous for the dimensioning of the foundation, and the pylon and the elevation drive but disadvantageous for the azimuth drive. Blackmon (2014) investigates the effects of wind load on projected fatigue life and safety factor for heliostat drive unit. The study shows that having heliostats fully stowed at bottom wind speeds than legacy specifications of 50 mph increase life and reduce safety factors required.

Complimentary to the wind tunnel studies (Kopp et al., 2002, 2012; Aly and Bitsuamlak, 2012, 2013), a limited computational fluid dynamics (CFD) studies on wind loads for the solar panels are reported in the literature. Shademan and Hangan (2009) carried out CFD simulations to estimate the wind loads on stand-alone and arrayed solar panels. They observed that at a specific distance between two sets of panels the drag coefficient for the downstream panels reaches a minimum. Shademan et al. (2014a, b) carried out Detached Eddy Simulations (DES) to analyze the influence of ground clearance on solar panels. The study shows that an increase in the clearance produces stronger vortex shedding fluctuations, and larger mean and unsteady wind loading. However, at a relatively small clearance, the vortex shedding effects are minimized which suggests a reference value for minimizing the unsteady wind loading on ground-mounted solar panels. Bitsuamlak et al. (2010) carried out full-scale testing and CFD simulations on stand-alone solar panels. The results show similar patterns of pressure coefficient distribution when compared to full-scale measurements, but the magnitude of the pressure coefficients was generally underestimated by the numerical calculations when compared to the experimental results. Aly and Bitsuamlak (2013) presented wind tunnel test data along with CFD simulation results on ground-mounted solar panels at different scales and under different wind flow characteristics. They concluded that the mean wind loads on the solar panels obtained from CFD simulations are in a good agreement with the wind tunnel results at different geometric scales.

Warsido et al. (2014) carried out a boundary-layer wind tunnel tests to investigate the effects of different spacing parameters on the wind loading of ground-mounted solar arrays. The study shows that the magnitude of force and moment coefficients on the ground mounted array decreased across panel rows as a result of the sheltering effect from the neighboring upwind panels. Meroney and Neff (2010) presented the results of a hybrid numerical and physical model program to predict wind loads on PV collector arrays. The hybrid numerical and physical model was developed to perform rapid and cost-effective comparisons of alternate PV design configurations. Some of the advantages of the CFD simulations include generation of continuous wind load information over the structural elements as well as whole-flow field at the possibility of executing full-scale simulation studies without geometric scale constraints. However, one primary shortcoming of a CFD based approach is being computationally costly to predict peak loads on structures under turbulent flows. When a relatively accurate turbulence closure, for example Large Eddy Simulations (LES), is incorporated into the numerical modeling at high Reynolds numbers, CFD simulations require a very high performance computing capabilities. This coupled with the costly commercial CFD license for parallel computing is limiting CFD for design wind load evaluation in practice. Wind tunnel experiments still remain an economic choice compared to CFD simulations, for wind load applications. However, concurrent CFD studies provide additional opportunities to explain/augment wind tunnel studies. In any case, Stathopoulos et al. (2012) carried out a review on wind loads on solar collectors, in which they conclude that results show significant differences among different studies, some of which correspond to similar configurations. The discrepancies in the results