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Velocity measurements around low-profile, tilted, solar arrays mounted on large flat-roofs, for wall normal wind directions

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ABSTRACT

An investigation of the wind field around roof-mounted solar arrays has been undertaken, utilizing synchronized time-resolved particle image velocimetry and pressure measurements, in order to better understand the flow structures and aerodynamic mechanisms which cause the peak wind loads. The study focused on wall normal wind directions, which result in critical loads on panels within the separation bubble. The mean flow is not significantly altered above the array as compared to that for a bare roof. However, the array has a significant effect on the turbulence above and around the panels in the separation bubble. When panels are installed on the roof, both Reynolds normal and Reynolds shear stresses are markedly reduced when compared to the flow over the bare roof in the region of the separated shear layer. Ensemble averaged flow fields, conditioned on peak panel uplift, were used to investigate the mechanisms associated with peak uplifts on the array. As the tilt angle of the solar array is increased, a progression from purely vortex driven suctions, which cause peak uplifts on a bare roof, towards local flow driven uplifts is observed. For small tilt angle (2°) arrays this local flow is established by large-scale building generated vortices, while for the larger tilt angle (20°) arrays the instantaneous reattachment of the (building generated) separated shear layer sets up the local flow. For the larger tilt angles, south wind peak uplifts are driven by large vertical gusts, while peaks for northern winds are the result of streamwise gusts. The interaction of these large-scale features with the panels, in the form of locally oriented drag, results in the peak uplifting loads.

1. Introduction

An investigation of the velocity field around roof-mounted photovoltaic (PV) arrays has been undertaken, with the goal of understanding the flow structures and mechanisms which cause the peak aerodynamic loads. The flow field which develops over roof-mounted PV arrays is complex. First, the flow is influenced by the building which causes flow separations at the building's edges, resulting in large scale building generated vortices. The panels themselves induce local separations and reattachments along the array. The structure of the incident boundary layer is, of course, also important, and the mean flow turbulence of the boundary layer must be accurately simulated in any wind tunnel testing. Finally, all these structures and features of the flow will interact with one another. To begin to understand these flow fields a series of experiments have been conducted using time-resolved particle image velocimetry (TR-PIV) with synchronized pressure measurements. The use of PIV allows the spatial development of the flow field to be examined in greater detail than is possible with pressure measurements alone.

An aerodynamic study of PV arrays is particularly relevant given the recent rapid increase in installed solar PV capacity (Ayoub et al., 2010; Masson et al., 2012). Despite the rapid increase there are currently no building standards in North America which explicitly cover the wind loading experienced by PV arrays on rooftops (ASCE 7-10, 2010; National Building Code of Canada, 2005), although some standards have been proposed in Europe (Geurts and van Bentum, 2006), Australia (AS/NZS 1170.2, 2011), and California (SEAOC, 2012). The practice of installing PV arrays on roof tops has become common in both new construction and retrofit projects, particularly in urban and suburban areas where access to undeveloped land is limited and expensive. Rooftops offer the additional benefit of having less shading from surrounding natural and built environments.

Roof-mounted PV panels are generally mounted in a light framing system and secured on flat roofs through two methods: mechanical fastening directly to the building structure or ballasting of the framing system. Penetrating the roofing system is often undesirable, and ballasting appears to be used most often to secure PV arrays. Since large flat roofs generally do not have the capacity for much additional loading, an understanding of the

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aerodynamics of loads on PV arrays is important to ensure systems are able to withstand wind loads without being over designed. A thorough understanding of the aerodynamics mechanisms that result in the peak wind loads on PV arrays also opens the opportunity to determine methods to minimize loads whether it be through optimal positioning of panels or through the use of designed features.

The published work available in the literature on the subject has been primarily focused on determining the aerodynamic loads on roof mounted PV arrays, such as the work by Radu et al. (1986), Wood et al. (2001), Geurts and van Bentum (2006, 2007) and Kopp (2013). Both Wood et al. (2001) and Kopp et al. (2012) provide summaries of the available literature on the subject of wind loads on roof-mounted PV arrays. There has been far less discussion on the aerodynamic mechanisms which are responsible for these loads, particularly the mechanisms which are driving the peak loads.

The present work follows an extensive series of wind tunnel pressure studies conducted at the University of Western Ontario's (UWO) Boundary Layer Wind Tunnel Laboratory (BLWTL) by Kopp et al. (2012) and Kopp (2013). These multi-parameter studies aimed to investigate wind loads on low profile, tilted PV arrays mounted on large flat roofs and determine the effect of panel tilt angle, inter-panel spacing and roof offset on these loads. Furthermore, the results were compared to the wind loads for similar arrays mounted on the ground in order to determine the effect of the building on the loads. Kopp et al. (2012) found that three critical wind directions (those which resulted in the largest panel uplifts) existed for roof mounted systems: Northern (0°), northern-cornering (30°–60°) winds and southern winds (180°) (bearing in mind that for PV arrays installed in the northern-hemisphere will face south to achieve the highest solar efficiency). The peak uplifts for southern winds most often occurred on the first two southern rows. These rows were located within the separation bubble that forms when the flow separates from the southern edge of the roof. The flow in the separation bubble at the height of the array travels opposite to the freestream velocity, resulting in uplift on the panels. Peak uplifts for northern winds occurred downstream of the separation bubble once the flow had reattached along the roof. For northern cornering winds, the peak loads were found to be due to interaction of the corner vortex with the array. The peak loads for this wind direction typically occur in the NE corner of the roof, and not necessarily on the perimeter of the array. Peak events were characterized by peak factors approaching values of 10, indicating the rarity of these events.

While the work of Kopp et al. (2012) did locate the peak loads on a roof mounted PV array and where on the roof they occur, the details of the flow field and mechanisms that resulted in these peak loads are still unclear. Thus, the objective of the present work is to examine the flow and mechanisms resulting in the peak uplifts on the panels.

2. Experimental setup

A series of experiments were conducted using time resolved, particle image velocimetry (TR-PIV) with synchronized pressure measurements. While there have been several studies which have utilized pressure measurements to investigate roof-mounted PV arrays, the use of TR-PIV allows the flow field to be analyzed directly. The focus of this study is on the flow-field that develops at the leading edge of the building during southern and northern winds. By focusing initially on the northern and southern winds it is possible to avoid the complications that would be associated with performing PIV for the cornering winds, which would likely necessitate the use of either stereoscopic or dual-plane PIV to resolve the three dimensionality of the flow. Similarly, this work will focus on the model north-south centreline to minimize any error associated with out of plane velocity components; the mean velocity in the cross-stream direction is zero due to symmetry, although turbulence is, of course, always three-dimensional. As summarized in Section 1, the south wind direction is critical for panels located in within the separation bubble—see, for example, Figs. 9 and 10 in Kopp (2013).

2.1. Wind tunnel facility

Experiments were conducted in Boundary Layer Wind Tunnel (BLWT) II at the UWO's Boundary Layer Wind Tunnel Laboratory (BLWTL). The high-speed test section of BLWT-II has a working cross section 3.4 m wide with a variable height, nominally 2.4 m high at the test section. The length of the upstream fetch to the centre of the turntable is 39 m. The tunnel floor is lined with a series of pneumatically controlled roughness elements which can be raised up to 200 mm above the tunnel floor. Additional turbulence generating elements including trips and spires were used to achieve the desired boundary layer profile.

2.2. Model details

The models used in the present experiments are the same as those used by Kopp et al. (2012). The 1:30 length scale of the models was selected so as to balance the constraints of accurately simulating the boundary layer flow while maintaining a large enough model size so as to be able to accurately resolve the flow field (Kopp et al., 2012). Two tilt angles have been examined in the present study: 2° and 20°. The 2° case represents a flow regime which is largely dominated by pressure equalization effects, while in the 20° case the local flow around the panels becomes increasingly important (Kopp et al., 2012). A bare roof building was also investigated to provide a base line comparison. Note that in the following discussion of the model details all units are given in (equivalent) full-scale, as is common practice in wind engineering.

The building height, $H = 7.3$ m, was common across all the models and is a typical value for a low-rise building. The PV array in the present study covered the entire roof (with roof edge setbacks and inter panel spacing identical to those in Kopp (2013)). The array consisted of 12 rows of 12 modules, which were mounted on the roof such that the rows ran parallel to a roof edge. Since solar panels normally tilt towards the south in the northern hemisphere, we use this to establish the N-E-S-W directions. The chord of the modules is 1.00 m, and the length is 1.65 m. Rows were modeled without gaps, hence each row was 20 m long and the total size of the array was 240 m^2. The roof setback, defined as the distance from the roof edge to the panel edge, represents a typical minimum distance solar panels would be installed from the roof edge in North America (Kopp et al., 2012). The spacing between rows of the arrays was selected so as to minimize the total roof area utilized by the array while still minimizing the shading which occurs at lower solar elevation angles. As such, the length of each building was different depending on the roof edge setbacks and inter-row spacings. Full geometrical details are given in Table 1.

Experiments were conducted at a wind tunnel reference speed of approximately 15 m/s. The reference speed was measured above the boundary layer at a height of 1.5 m above the tunnel test section floor. The Reynolds number, based on the model height and roof height mean velocity was 1.9×10^5. As noted by Kopp et al. (2012), the full-scale Reynolds number would larger by a factor of the length scale multiplied by the velocity scale. Thus, the experiments were conducted at a Reynolds number approximately two orders of magnitude too low; however, this is still one order of