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Aerodynamic mechanisms for wind loads on tilted, roof-mounted, solar arrays

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ABSTRACT

A wind tunnel study has been performed on roof-mounted solar arrays of two different panel tilt angles. One of the arrays was also placed on the ground in order to distinguish array generated aerodynamic effects from building generated effects. It is shown that there are two main mechanisms causing the aerodynamic loads: (i) turbulence generated by the panels and (ii) pressure equalization. For higher tilt angles, significant array generated turbulence increases the net wind loads, while for low tilt angles, pressure equalization dominates. In addition, it is observed that the presence of the building changes the aerodynamic loads substantially compared to ground-mounted systems. There is a complex interaction between building generated vortices and the flow induced by the array, which depends on building height, the setback of the array from the roof edge, and other building parameters.

1. Introduction

Tilted solar arrays are becoming common on the roofs of large, industrial, low-rise buildings. One of the significant practical issues is determining the aerodynamic forces acting on such arrays, particularly uplift, which may govern the potential need for penetrations of the roof in order to mount the system safely. While there have been many proprietary studies to determine wind loads on roof-mounted arrays containing many rows, each row with many panels, there is actually very little information in the published literature. In contrast, there have been several studies of ground-mount arrays, such as the seminal wind tunnel studies by Poreh, Peterka and Cermak, which can be found in the Appendices of reports by Bechtel National Inc. (1980), Miller and Zimmerman (1981) and Franklin (1983). The published results for roof-mounted systems have focussed on arrays made of single rows of panels (Tieleman et al., 1980), or just a few panels placed in different locations around the roof (Guerts and van Bentum, 2006).

The aerodynamics of roof-mounted arrays have a complexity beyond that of building aerodynamics due their presence in a flow field containing vortices generated by flow separations at the roof edges, turbulence induced by the array and, of course, turbulence in the atmospheric boundary layer. For low tilt angle arrays on roofs of low-rise buildings (i.e., those where the panel is nearly parallel with the roof surface), Bienkiewicz and Endo (2009) have shown that pressure equalization plays a significant role in the aerodynamics, just like for roof pavers (Bienkiewicz and Sun, 1992b, 1997) so that net uplift on arrays could be substantially less than that acting on the roof. These authors also show that the building-generated corner vortices (Bienkiewicz and Sun, 1992a) are important for defining design wind loads, as are array geometric details such as the spacing between rows and the height of the panels above the roof. However, very little is known about the aerodynamic mechanisms for higher tilt angle arrays and the roles of both the building and the array geometry, in multi-row arrays. We do know, however, that relatively low profile arrays do not substantially alter the net roof loads (Wood et al., 2001).

Understanding the basic aerodynamic mechanisms is important for designing appropriate wind tunnel experiments to determine the loads for particular systems and also as a first step toward the development of wind load provisions in building codes. The objective of the current study is to examine the flow mechanisms for roof-mounted, tilted solar arrays made up of many panels and placed on large, low-rise buildings with flat roofs. In particular, the goal is to distinguish both the role of the building and the array on the wind loading, as well as the role of pressure equalization. Design loads will be examined separately in future work, as many parameters are required for such an analysis and there is not sufficient space herein.

2. Experimental set-up

2.1. Choice of model scale

Wind loads on low-rise buildings depend on many factors which can be most simply summarized as the building geometry and the

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characteristics of the wind. The same can be said for any element, such as solar arrays, placed on the roof of such buildings. For wind tunnel testing to yield accurate results, it is critical that the scale of the simulated atmospheric boundary layer and the building are the same, with the flow and geometric modeling both being sufficiently accurate. However, in practice, these may have conflicting requirements that can be challenging to overcome. Thus, wind tunnel testing of roof-mounted solar arrays, with modules which are relatively small compared to the building size, involves a balance of larger scale flow simulations than one would use for tall buildings and relatively large building models. There are also the constraints that the wind tunnel blockage be less than about 5% and that the integral scales of the turbulence (which are limited by the constraints imposed by the wind tunnel walls) be within a factor of roughly two (Surry, 1982). Keeping in mind this balance between a model size with reasonable resolution and the flow simulation, a length scale of 1:30 was used for the current study, consistent with some of our previous work (e.g., Visscher and Kopp, 2007). The model design is discussed first, followed by the terrain simulation. Note that all dimensions will be given in (equivalent) full-scale units, as is common practice in wind engineering.

2.2. Pressure model configurations

In order to design the experiments, both the array layout and building layout have to be chosen. The array must be large enough, i.e., have sufficient numbers of rows, each of sufficient length, so that all aerodynamic effects, and the critical loads, can be identified. If roof and/or array zoning are to be considered, both should be large enough so that there are regions without any edge effects. Since little is known about aerodynamic loading, we considered that the array, and building, should be reasonably large, given the constraints of blockage in the wind tunnel. For this, we chose an array of 12 rows, with each row made up of 12 modules of chord (i.e., the width in the north–south direction when mounted on the roof; noting that the modules normally tilt towards the south in the northern hemisphere), $c=1.00$ m and length of 1.65 m (in east–west direction). Thus, the length of each row of 12 modules was 20 m since the rows were modeled without gaps between modules. In total, the array had 144 modules with a total area of 240 m^2. Array geometries vary in tilt and row spacing in order to optimize use of roof space and to minimize shading. Two module tilt angles, 2° and 20°, are considered in the current study, and the associated row spacing values are given in Table 1, along with other geometric details of the array. Note that this array has no aerodynamic treatments except the northernmost row, which had a non-instrumented shroud.

Roof-mounted arrays are typically mounted with some setback from the edge of the roof. For the 20° tilt angle array, two setbacks, $s=1.2$ m and 2.9 m were chosen. The lower value represents a typically minimum distance from the edge. The larger value of s was chosen as being equal to $0.4H$, which is the nominal width of the "edge zone" for roof Components and Cladding (C&C) loads in ASCE 7-10 (2010); notwithstanding the $0.1L$ clause which is not likely of aerodynamic relevance for the current problem since roof pressures are much more dependent on roof height than building length (e.g., Lin and Surry, 1998). In other words, for the larger setback, the entire array was within the "interior zone", as defined by ASCE 7, for the roof height, $H=7.3$ m.

With the size of the array and the distance from the edges defined, the building sizes are defined. These are given in Table 2. The roof height, H, was chosen as being a typical value, but keeping in mind the requirement that the blockage be less than about 5%. Since the inter-row spacing depends on tilt angle, the buildings for the 2° and 20° tilt angles had slightly different lengths, and different building models were constructed for each case. Fig. 1 shows photographs of the array and building models in the wind tunnel.

Since one of the objectives of this work is to determine the effects of the building on the array aerodynamics, the 20° tilt angle array was also placed on the ground. A photograph of the model in this configuration can also be seen in Fig. 1(a).

The pressure models of the arrays were designed to be as modular as possible so that they could be easily used in a wide range of configurations. The models were made in panels three modules long, each panel having 16 pressure taps (12 on the upper surface and 4 on the lower, with the expectation that the pressure gradients are reduced on the underside (Bienkiewicz and Sun, 1992b) for a total of 576 taps. Fig. 2 shows the tap layout on the 144 modules. Each panel was connected to a single, 16-channel pressure scanner. Thus, once the panels are connected to a scanner, they can be quickly reattached into alternative configurations allowing for quick change-overs during wind tunnel testing. Note, however, that different support structures are required for the different tilt angles, as well as different building models (which are simple to build and change out during tests). Fig. 1(c) shows close-up photographs of the panels and their supports in the 20° tilt angle configuration. The tubes for the pressure taps can be seen passing through an opening in the building model roof, designed to accommodate them. The model was carefully sealed prior to testing each configuration.

In addition, for the current experiments, the roof surfaces of the two basic models were instrumented, each with about 400 pressure taps. The number of roof taps on each model varied slightly due to the different plan dimensions.

The maximum blockage for the models was less than 3%, while the minimum roof height based Reynolds number was 1.9×10^5. Full-scale Reynolds numbers would be larger by the length scale multiplied by the velocity scale, so the present experiments are about two orders of magnitude low, although the current experiments are about one order of magnitude higher than the minimum allowed in the ASCE No. 67 (1999), and other low-rise building experiments.

2.3. Terrain simulation

The experiments were designed to match the terrain used for the NIST Aerodynamic Database for Low-Rise Buildings, described in Ho et al. (2005), with an open country terrain characterized by a roughness length, z_0, of 0.03 m. The intent of these experiments

Table 2
Details of the low-rise buildings (in equivalent full-scale dimensions).

Array tilt angle (deg.)	Array setback, s (m)	Building width (east–west), W (m)	Building length (north–south), L (m)
20	1.22	22.5	23.5
20	2.93	25.9	26.9
2	1.22	22.5	15.9

Table 1
Details of the solar array (in equivalent full-scale dimensions).

Module chord, c (m)	Module length, l (m)	Tilt angle (deg.)	Ground clearance, h (m)	Distance between rows, x (m)	x/c (dimensionless)	Setback, s (m)
1.00	1.65	20	0.16	1.68	1.7	1.22; 2.93
1.00	1.65	2	0.10	1.12	1.1	1.22