Journal of Wind Engineering & Industrial Aerodynamics 174 (2018) 210–224

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Effects of building parameters on wind loads on flat-roof-mounted solar arrays

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ARTICLE INFO

Keywords:
Wind load
Wind tunnel test
Flat-roof-mounted solar array
Side ratio
Aspect ratio
Parapet height

ABSTRACT

Roof-mounted solar panels play an increasingly important role in developing renewable energy. Wind loading is a major concern for these systems and is affected by parameters related to both building and array dimensions. The effects of building side ratio (D/B=0.4 to 1), aspect ratio (H/B=0.8 to 2) and parapet height (h_p/H=0 to 0.06) are investigated under the condition of a constant building height (H=20 m) in wind tunnel tests. The local wind pressure distributions and area-averaged net pressure coefficients of solar panels are examined. The results indicate that the most critical negative peak area-averaged net pressure coefficients considering all wind directions and all panels show an increasing tendency with increase in side ratio, but that the most critical positive peak values show no significant change. An increase in aspect ratio leads to decrease the most critical positive and negative peak net pressures. Curves fitting for the envelopes of equivalent values $(GC_{pn})_{eq}$ in the format of ASCE 7-10 are introduced based on all tested models. The most critical positive peak area-averaged net pressures decrease with increase in parapet height, and the most critical negative peak values of building models with a parapet are smaller than those without a parapet.

1. Introduction

Solar panels have been playing an increasingly important role in developing renewable energy in recent years. They have been widely applied on large, low-rise and mid-rise buildings. Wind loading is a major concern for these systems. Besides the approaching turbulence in the atmospheric boundary layer, aerodynamic characteristics of roof-mounted solar panels are also affected by parameters related to their dimensions and those of the buildings on which they are mounted (Kopp et al., 2012). These two groups of parameters have been examined mainly for low-rise buildings in previous studies. The effects of array parameters, such as tilt angle, array spacing, panel size, and panel location, have been sufficiently studied by Kopp et al. (2012), Saha et al. (2011), Cao et al. (2013), Pratt and Kopp (2013), Stathopoulos et al. (2014) and others. The effects of building parameters, including building height, building plan dimensions and the existences of local geometric features such as roof parapet, have been examined in previous studies shown in Table 1 (flat-roof-mounted solar panels with different building dimensions) and Table 2 (flat-roof-mounted solar panels with different parapet heights). But some of their views seem inconsistent due to different array parameters or approaching wind characteristics. Stathopoulos et al. (2014) examined the wind pressures on a single row of relatively large panels placed on 7 m- and 16 m-high buildings and found that the effect of building height was minimal. However, in Kopp (2014), small-size solar arrays in multi-row layout were examined and larger wind loads were observed for higher buildings with heights ranging from 7.3 m to 21.9 m. This discrepancy may be due to a lack of differences in their array geometries, tilt angles, and also the approaching turbulence intensities along with variations of building height as well as aspect ratio. For buildings of the same height but various plan dimensions, Banks (2013) and Kopp (2014) reached the fact that enlarging building sizes increased the wind loads on solar panels due to stronger vortices induced by building edges, but Cao et al. (2013) found that building depth did not significantly affect the wind loads on corner panels. Additionally, based on SEAOC (2012), Banks (2013) and Browne et al. (2013), parapets generally increased wind loads on solar panels. However, Cao et al. (2013) indicated that wind loads on corner panels showed a slightly decreasing tendency when parapet height increased. Thus, there are still

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https://doi.org/10.1016/j.jweia.2017.12.023
Received 10 June 2017; Received in revised form 29 October 2017; Accepted 25 December 2017

Nomenclature

B	building width
D	building depth
H	building height
h_p	parapet height
β	tilt angle of solar panels
h	height of solar panels
d	spacing between solar panels
s	setback from roof edge to panel edge
c	panel chord
K	shadow length factor
λ	latitude in earth
N	No. of panel rows
U_H	mean wind speed at building height
I_H	turbulence intensity at building height
α	power law exponent
Θ	wind direction
C_{pu}	wind pressure coefficient on upper surface
C_{pl}	wind pressure coefficient on lower surface
$C_{pm\text{-}u}$	module pressure coefficient on upper surface
$C_{pm\text{-}l}$	module pressure coefficient on lower surface
C_{pn}	net pressure coefficient
$C_{A\text{-}net}$	area-averaged net pressure coefficient
C_{fm}	module force coefficient
C_{fp}	panel force coefficient
$(GC_{pn})_{eq}$	equivalent peak net pressure coefficient
A_t	tributary area
$\overline{(*)}$	mean value of (*)
$\widehat{(*)}$	positive peak of (*)
$\check{(*)}$	negative peak of (*)
$\widehat{(*)}_{max}$	most critical positive peak of (*)
$\check{(*)}_{min}$	most critical negative peak of (*)

some differences among obtained effects of building parameters. Further systematic study is necessary in order to quantify the full range of effects for these parameters.

The objective of the paper is to systematically study the effects of building side ratio D/B, aspect ratio H/B and parapet height h_p/H through a series of wind tunnel tests. The focus is mainly on solar panels mounted on mid-rise flat-roof buildings, whose heights are comparative with or even larger than their horizontal dimensions. In order to clearly identify the effect of one particular parameter, the other parameters are kept constant. Therefore, a set of array parameters is adopted for all tests. And the building height H is fixed to avoid the effects of turbulence intensity I_H at building height. The aspect ratio H/B is kept the same to study the effect of side ratio D/B, and vice versa. Local and area-averaged pressure coefficients acting on solar panels are analyzed comprehensively. Finally, some proposals are made for codification purposes.

2. Wind tunnel experiments

2.1. Model configurations

As solar panels are relatively small compared with buildings, a larger model is usually preferred to accurately reproduce the geometric features of solar panel systems and more pressure taps can be installed to capture local wind pressures more precisely. However, a too-large model scale is not appropriate for reproducing the corresponding turbulence scale in a general boundary layer wind tunnel. The geometrical scale of 1/50 was adopted in this paper, which was consistent with Saha et al. (2011), Cao et al. (2013) and Kopp and Banks (2013). The largest blockage ratio in this study was 4.9%, which met the requirement of ASCE/SEI 49-12 (2012).

Fig. 1 shows an example of test models. Model dimensions are depicted in Fig. 2. The smallest unit of solar arrays was called a "module", which was 1 m × 2 m (in full-scale, as hereafter appears) in plan. Seven modules composed a "panel", and each panel was 7 m × 2 m in plan and was supported by frames at both ends. Panels were mounted on a flat roof with a tilt angle, β, of 15°. The height of a panel, h, was 0.52 m. In order to keep solar panels unshaded, the spacing between arrays, d, should satisfy $d \geq hK$ (Appelbaum and Bany, 1979), where K is the shadow length factor depending on the latitude, λ. Here, the array spacing was set to $d = 1.2$ m with $K = 2.3$ assuming a mid-latitude region with $\lambda = 35°$. According to JIS C 8955 (2011), a setback, s, should be taken from the roof edges to avoid excessive wind loads and for maintenance purposes, and was set at 10% of the largest side length for each model in this study.

To obtain reliable local wind pressure characteristics, each module had 8 uniformly distributed pressure taps on both upper and lower surfaces, as shown in Fig. 2. Accordingly, each panel had 56 taps on both

Table 1
Previous studies on flat-roof-mounted solar panels with different building dimensions.

	Exposure	Scale	Building dimensions $H \times B \times D$ (m)	Panel chord c (m)	Tilt angle β (°)	Array spacing d (m)	No. of rows N
Stathopoulos et al. (2014)	Open, α=0.16	1:200	7(16) × 19.6 × 30.6	5.6	20,30,40,45	N/A	1
Kopp (2014)	Open, z_o=0.03 m	1:30	7.3(14.6) × 22.5 × 17.4	1	5	1.21	12
			7.3(14.6,21.9) × 22.5 × 27.1(32.2)	1	30	1.94(2.35)	12
Banks (2013)	Open, α=0.14	1:50	10 × 20(60) × 20(60)	N/A	8	N/A	N/A
Cao et al. (2013)	Open, α=0.16	1:50	20 × 25 × 10 (17.5,25)	2	15	0.55	2(5,8)

Table 2
Previous studies on flat-roof-mounted solar panels with different parapet heights.

	Exposure	Scale	Building dimensions $H \times B \times D$ (m)	Panel chord c (m)	Tilt angle β (°)	Array spacing d (m)	No. of rows N	Height of solar panels h (m)	Parapet height h_p (m)	Normalized parapet height h_p/B
Banks (2013)	Open, α=0.14	1:25~1:100	10 × 20(60) × 20(60)	N/A	5~45	N/A	N/A	N/A	0~2	0~0.06
Browne et al. (2013)	Suburban, z_o=0.3 m	1:25	10 × 36 × 30	1.05	10	0.51	16	0.49	0.49, 1.47, 2.45, 3.68, 4.9	0.01, 0.04, 0.07, 0.10, 0.14
Cao et al. (2013)	Open, α=0.16	1:50	20 × 25 × 25	1	15	0.55	8	0.52	0.25, 0.5, 1, 1.5	0.01, 0.02, 0.04, 0.06