Wind Loads on Rooftop Solar Panel Systems:

A Contribution to NBCC 2015

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ABSTRACT: A comprehensive wind tunnel study was conducted in a boundary layer wind tunnel to examine the wind-induced loads on solar panel systems. Several configurations were considered in order to assess the effect of several parameters on the pressure and force exerted on the top and bottom surface of the panels. Moreover, the most critical, net effect was evaluated by considering the simultaneous top and bottom pressure time histories recorded by the pressure taps. Review of previous studies explains clearly the lack of design provisions in wind loading standards and codes of practice. The results of the current study identified, among other, the effects of panel inclination, panel location and building height. Last but not least, the area-averaged net force coefficients were calculated for future codification purposes. The outcome of this study is intended to provide some guidance in NBCC 2015 re: solar collector wind loads.

KEYWORDS: Solar panel, photovoltaic, wind tunnel, wind load, low-rise building.

1 INTRODUCTION

The current tentative plans for the next (2015) of the National Building Code of Canada (NBCC) – wind section - are to: bring most of the commentary into the code itself, especially the information on pressure coefficients, gust factors and topographic effects; modify some of the low-rise Cp values based on accumulated data indicating some values may be too low; put in some guidance on solar collector wind loads; and consider the possibility of introducing ultimate return period wind pressures.

The evaluation of wind-induced loads applied on solar panels plays a very important role for design purposes. During the last decades, a strong interest has been developed towards renewable energy resources and to this end the utilization of solar panels has been expanded. However, the effect of a number of factors such as the upstream exposure, the landscape, the panel inclination and location, the building height for panels attached to building roofs and the like have to be carefully considered in all experimental and computational procedures. Experiments can be performed nowadays with more sophisticated and cutting edge technology resulting in more accurate results.

Scientists and engineers have already made many efforts to define wind loading with results not always compatible. The main objective of such studies is to produce data that will be used for the improvement of building code provisions which in turn can lead to a more sufficient, economical and overall safer design. Many cases of damaged panels have been observed when exposed to strong winds because of poor or non-available provisions related to this kind of structures in wind design standards or building codes of practice. Analysis based on simplifications or assumptions often lead to incorrect results and uneconomic design, which may result in poor safety and/or unreasonable construction cost. Although, there is a number of studies which have dealt with this issue, many of them are contradictive and many aspects of the problem still remain uncovered requiring more research in this field. Thus, a more detailed study based on experimental results is necessary to address this problem.

2 PREVIOUS STUDIES

Results of previous studies show significant differences even when they correspond to similar configurations. The data were organized separately for solar collectors on flat or pitched roofs and stand-alone panels, as Figure 1 shows. Also, the inclination of the collector as well as its location on the roof, have been taken into account. A summary of the studies considered is presented in Table 1 for solar panels attached on flat roofs and Table 2 for solar panels attached near roof corners and edges. A critical discussion can be found in Xypnitou (2012).

A representative comparison of force coefficients obtained from two different studies (Erwin et al. 2011 and Saha et al. 2011) is presented in Figure 2. Several cases for different inclinations have been included in this comparison and results are presented in terms of both mean and peak net force coefficients. As far as the Erwin et al. (2011) study is concerned, both mean and peak values follow the same pattern for 15 and 45 degrees panel inclination. The inclination of the panels has a minimal effect on the mean values. The absolute minimum and maximum net pressure coefficients reach their peak for the wind directions of 45 and 135 degrees respectively. It should be noted that for wind directions greater than 45 degrees, the minimum and maximum values are really close for the configurations of 15 and 45-degree panel inclination. On the other hand, Saha et al. (2011) maximum values show a different trend and are in relative agreement to those of Erwin et al. (2011) only for the case of 0-degree wind direction. This phenomenon can be attributed to the different geometries considered for the building and solar panel models.

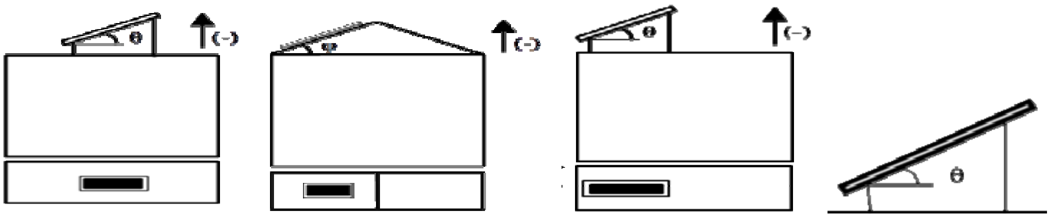


Figure 1. Configurations of photovoltaic systems considered for comparison to current study.

Table 1. Previous studies on solar panels attached on flat roofs.

	Country	Scale	Building Model Dimensions (m)	PV Model Dimensions (m)	Inclination Angle (deg.)
Radu et al. (1986)	Romania	1:50	0.3 x 0.43 x 0.3	0.04 x 0.02	30
Radu and Axinte (1989)	Romania	1:50	N/A	0.08 x 0.04	N/A
Wood et al. (2001)	Australia	1:100	0.41 x 0.27 x 0.12	0.41 x 0.027	0
Ruscheweyh and Windhovel (2011)	Germany	1:50	N/A	N/A	30
Saha et al. (2011)	Japan	1:50	0.45 x 0.45 x 0.4	0.02 x 0.04	0, 15, 30 & 45

Table 2. Previous studies on solar panels attached near roof corners and edges.

	Country	Scale	Building Model Dimensions (m)	PV Model Dimensions (m)	Inclination Angle (deg.)
Hosoya et al. (2001)	CO, USA	1:50	0.182 x 0.274 x 0.08	0.0244 x 0.0244 x 0.0244	N/A
Bronkhorst et al. (2010)	Nether-lands/ Ger-many	1:50	0.6 x 0.8 x 0.2	0.024 x 0.6	35
Bienkiewicz et al. (2009)	CO, USA	Variable			
Erwin et al. (2011)	FL, USA	Full-Scale	4.3 x 4.3 x 3.2	1.57 x 0.95 x 0.041	-45, -15, 0, 15, 45

Saha et al. (2011)	Japan	1:50	0.45 x 0.45 x 0.4	0.02 x 0.04	0, 15, 30, 45

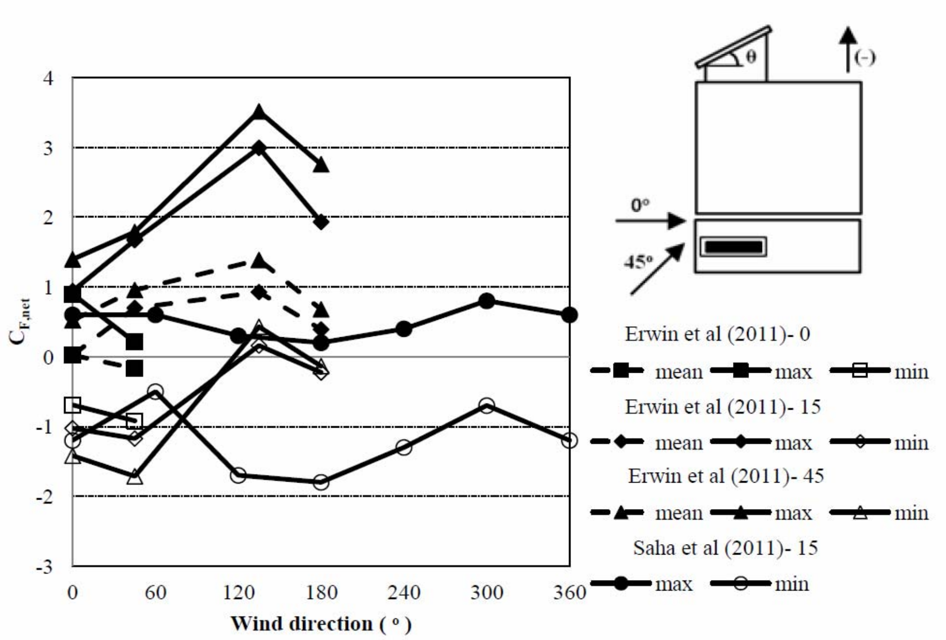


Figure 2. Comparison of results from Erwin et al. (2011) and Saha et al. (2011).

3 WIND TUNNEL EXPERIMENTS

3.1 *General description*

The main scope of this study was the systematic examination of wind-induced pressures applied to the surface of solar panels, placed on the ground or on the roof of buildings. The experiments for this study were carried out in the Building Aerodynamics Laboratory of Concordia University. A geometric scale 1:200 was selected and the tests were performed for open terrain exposure. The model consists of a rectangular flat-roof building on top of which three identical panels were attached – see Figure 3. The external dimensions of the building model are 15.3 cm (length) x 9.8 cm (width) and the height corresponding to the two different cases examined is 3.5 cm and 8 cm respectively.

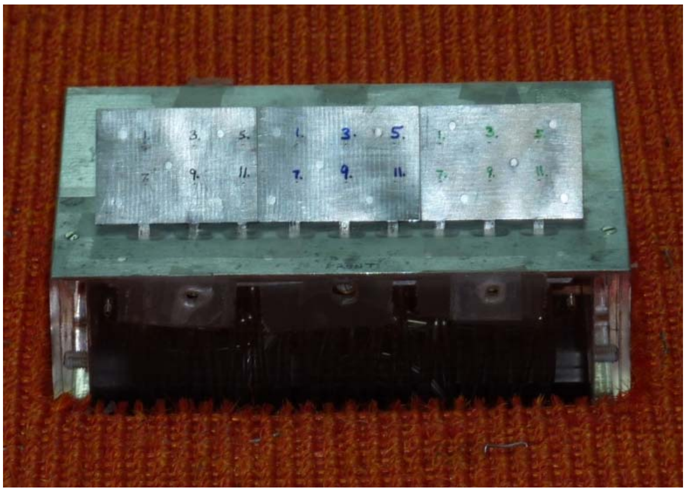
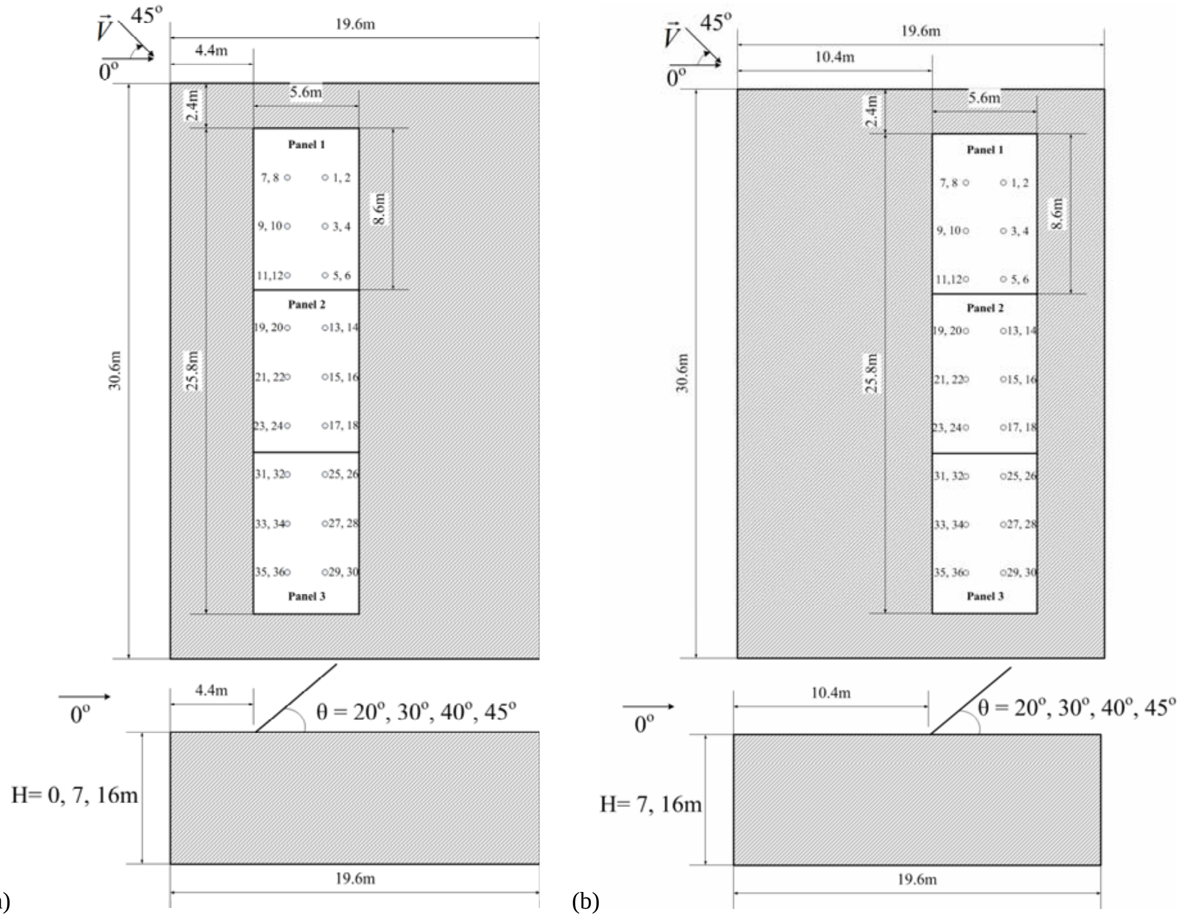


Figure 3. Building and solar panel wind tunnel model.

The panels were located in two different positions on the roof, the one closer to the side facing the 0-degree wind direction (front location – see Figure 4a) and the other closer to the opposite side (back location – see Figure 4b). For the front location, the distance between the panel base and the front edge is 2.2 cm and 1.2 cm from the side edge. For the back location, the base of the panel is found at a distance 5.2 cm from the front edge of the building and 1.2 cm from the side edge. The model allows the inclination of the panels to vary from 20 to 45 degrees. In order to measure the wind loads applied to the solar panels, 36 pressure taps in total were placed on the panels measuring the pressure on the upper and lower surface of the panel. The building model with the panels attached is symmetrical and for this reason the tested wind directions ranged from 0 to 180 degrees while a total number of 13 wind attack angles were tested with 15-degree intervals.



(a) (b)

Figure 4. Solar panel and building model plan and side views indicating (a) front and (b) back panel configuration.

The results in the following sections are presented in terms of dimensionless pressure and force coefficients. The following formulas have been used:

$$c_{p,mean/peak} = \frac{P_{mean/peak} - P_a}{1/2 \rho U^2} \quad (1)$$

$$c_{p,net} = c_{p,us} - c_{p,ls} \quad (2)$$

$$c_f = \frac{F}{1/2 \rho U^2 A} \quad (3)$$

$$c_{p,area-averaged} = \frac{\sum_{i=1}^{n} c_{p,net} a_i}{\sum_{i=1}^{n} a_i} \quad (4)$$

3.2 *Experimental findings*

As previously mentioned, a number of different parameters were considered in this study. Representative results from Xypnitou (2012) will be presented and discussed here.

Panel inclination effect

In order to investigate the effect of panel inclination, several configurations were considered. Measured pressure coefficients are given as a function of the panel inclination for the critical 135 degree wind direction. It should be noted that only the extreme values have been considered for the cases of stand-alone panels and panels attached to building roofs; for the latter, both building heights (i.e. 7 m and 16 m) and both panel locations (i.e. front and back) are presented.

The net values of the pressure coefficients referring to the whole solar panel appear in Figure 5. The maximum Cp values decrease somewhat with increasing panel inclination (from -0.5 to < -1.0). On the contrary, the minimum values show smaller suction with increasing panel inclination for both 7 m and 16 m building height and front location. The trends for back location show that increasing inclination results in higher suction for every building height and the stand-alone case as well. The different behavior for front and back panels comes from the fact that different panel locations affect differently the wind flow. Panel inclination also contributes to this phenomenon and a different pressure field is created for different panel inclinations.

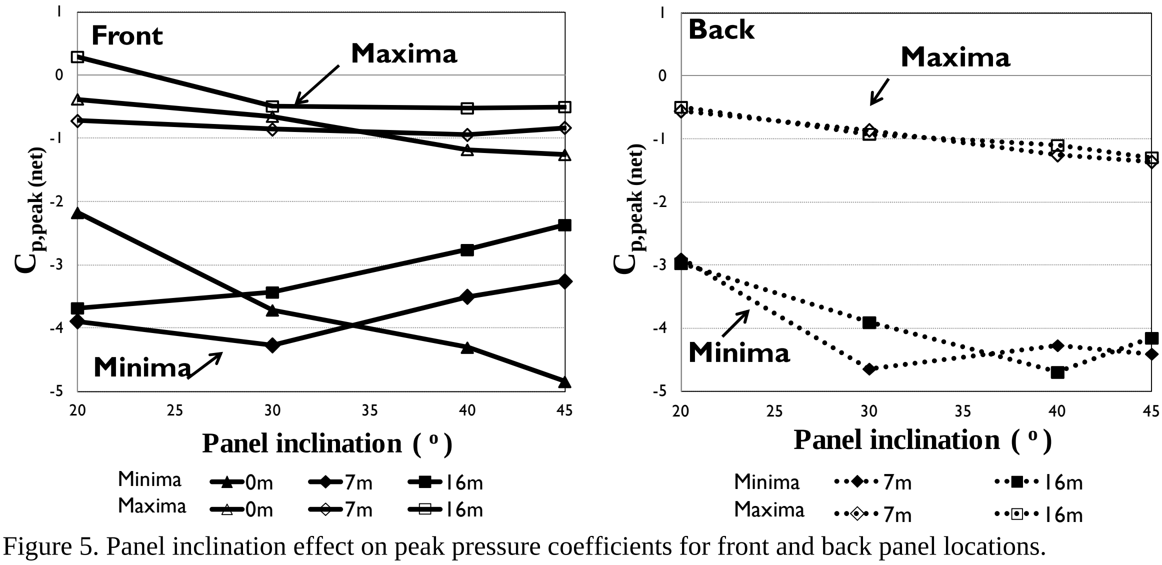


Figure 5. Panel inclination effect on peak pressure coefficients for front and back panel locations.

Building height

Different model configurations were tested in order to evaluate the effect of building height on the wind-induced load on solar panels. Figure 6 shows how the local peak pressure coefficients from all pressure taps corresponding to different panel inclinations vary with building height for the most critical case of 135-degree wind direction. Figure 6 depicts the net values of peak pressure coefficients as a function of building height. Maximum values range from -1.2 to -0.2, whereas the 16 m high building results in lower suctions for every panel inclination compared to those appearing for 7 m high building. For panels at the ground level, suction takes its greatest value for 40 and 45-degree panel inclination, while the lowest suction appears for the 20-degree panel inclination. The trend of 30-degree panel inclination ranges from -4.2 to -3.7; thus, no significant building height effect is observed.

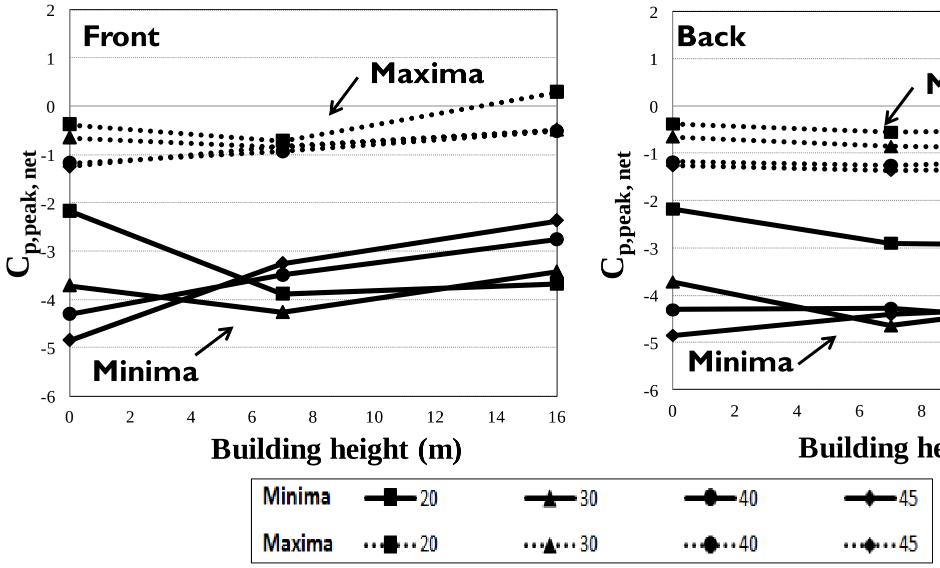


Figure 6. Building height effect on peak pressure coefficients for front and back panel locations.

Wind direction

The case where the panels are attached to a 7 m high building, located at the front and back of the roof is shown in Figure 7. For wind directions 120 and 135 degrees, the extreme values do occur for 45 and 30-degree panel inclination respectively, when the panel is back located. The maximum positive pressure can be observed for 30-degree wind direction when the panels are located at the front position and are inclined by 45 degrees.

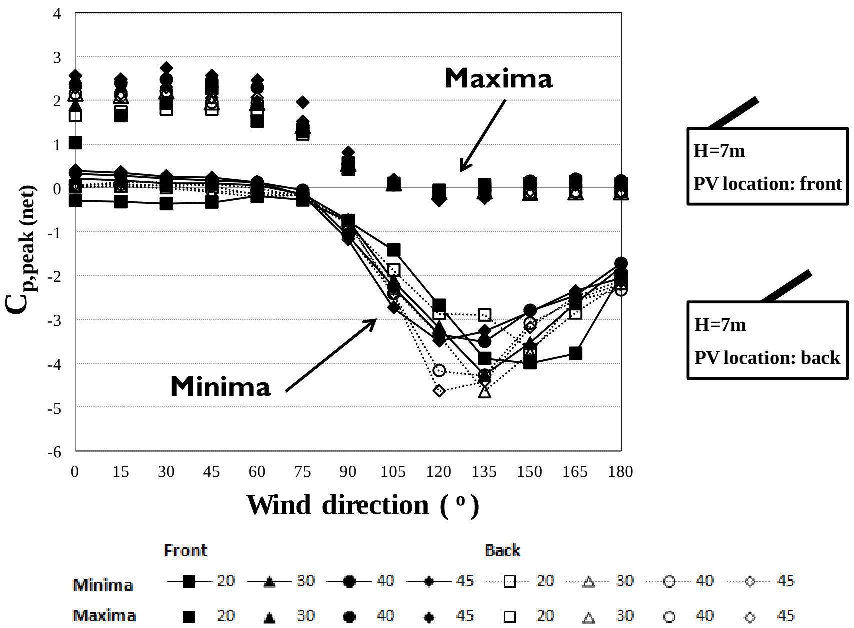


Figure 7. Wind direction effect on peak pressure coefficients for front and back panel locations; building height is 7 m.

Area-averaged pressure coefficients

Area-averaged pressure coefficients are depicted in this section as a function of the area when the wind direction is 135 degrees for panels inclined by 20, 30, 40 and 45 degrees – see Figure 8. The extreme values occur for a 30-degree panel inclination at the back location. Greater suction is detected on back-located panels for both building heights with only exception being the 20-degree panel inclination case. For the case of front-located panels, when attached to the 16 m high building, the suction experienced becomes smaller compared to that experienced by back-located panels. The gradient of minimum values results in smaller suction overall, which can be reduced to almost half of the initial value. Maxima for both building heights range from -1 to 0 with slight differences among the trends, which have a very small gradient with respect to the area.

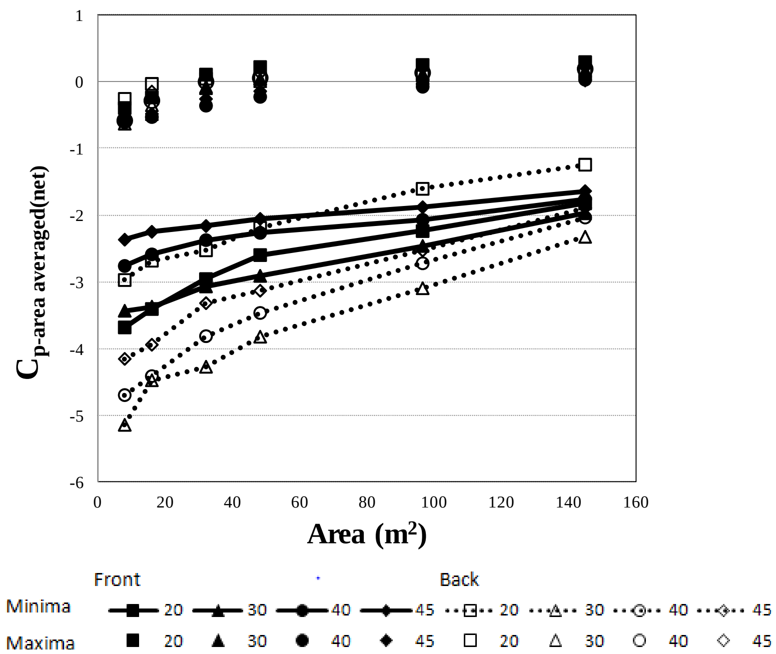


Figure 8. Area-averaged peak pressure coefficient for front and back panel locations.

4 COMPARISON WITH PREVIOUS STUDIES

A comparison between the experimental findings of the current study and those of previous studies was made in order to investigate how the results coming from different studies are related. The outcome data of these studies are referred to mean and peak values of pressure and force coefficients when the panels have the same or very close values of inclination and are located centrally at the roof, at the front corner or at central back position.

A representative case, which includes the Saha et al. (2011) study, is presented in Figure 9 and demonstrates the net mean force coefficients for panels attached to building roofs and inclined by 30 and 45 degrees. These values follow similar patterns for both studies for wind direction ranging from 0 to 135 degrees, and in general, there is a good agreement in the results. However, the current study shows that when the wind direction ranges from 135 to 180 degrees, mean force coefficients remain almost constant.

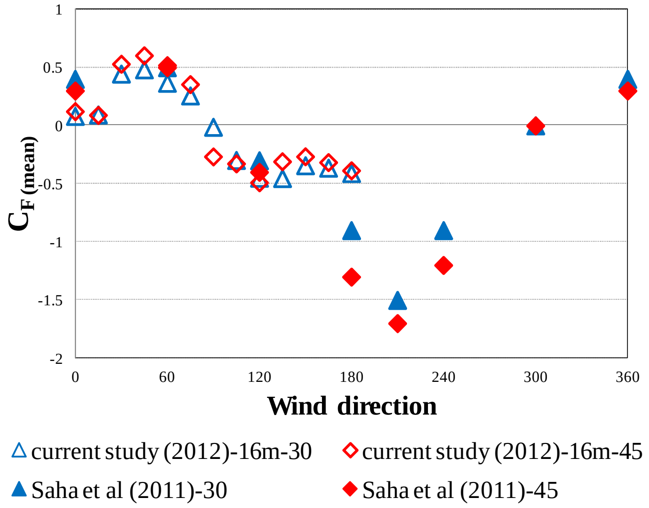


Figure 9. Force coefficient comparison of current study findings to Saha et al. (2011).

5 CONCLUSIONS

The scope of this study was to better understand the wind pressure distribution on stand-alone panel surfaces and panels attached to flat building roofs. For this purpose, sophisticated physical models of solar panels of different configurations were constructed and appropriate instrumentation was used during the experimental process in the boundary layer wind tunnel in order to evaluate relevant wind-induced loads.

Some of the most important findings of this study can be summarized as follows:

The wind direction of 135 degrees can be considered as the most critical since the highest peak pressure coefficients occur for this wind direction.

The net values of pressure coefficients corresponding to different configurations are affected by the panel inclination for the critical 135-degree wind direction. For panels located at the ground level, increasing panel inclination results in greater suction, as well as for panels attached to 7 m and 16 m high buildings, located at the back of the roof. On the contrary, for front-located panels attached to 7 m and 16 m high building roofs, suction becomes smaller with increasing panel inclination.

The increase of building height for panels located at the front position of the building roof results in slightly smaller suction, while for panels located at the back, the suction remains almost constant for 135-degree wind direction.

As far as the panel location is concerned, clearly back located panels suffer higher suction than front located panels, at least for the critical 135-degree wind direction.

Comparison of the experimental results of the current study with those of previous studies show that net mean force coefficients are in good agreement, while discrepancies are observed for the net peak force coefficient values.

6 ACKNOWLEDGEMENT

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