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Experimentos en túnel de viento sobre paneles fotovoltaicos montados en el suelo

Wind Tunnel Experiments on Ground-Mounted Photovoltaic Solar Panels

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Abstract

Over the last decades, renewable energy resources have gained an increasing interest for human development and, specifically, photovoltaic solar energy has shown a speedy and rising expansion. Several photovoltaic solar panel farms have been built in many countries to take advantage of this energy. Standards and codes for wind load action have not been an adequate tool for evaluating wind load on photovoltaic (PV) solar panels yet; thus, deeper studies on this subject are necessary. This paper presents an experimental study of wind load on a ground-mounted PV panel in a wind tunnel. The model was tested with inclinations of 15° and 23° for different wind attack directions in an open field. The detailed characteristics of pressure distribution of the mean and peak load coefficients on the panel surfaces were obtained. The shape coefficients from the peak loads were obtained using the 3-s (three-seconds) and area-average approach. Pressure coefficient increases are critical for 0° and 180° with an approximated total increasing percentage of 57% and 61% respectively when varying the angle from 15° to 23°.

Keywords: *Pressure coefficients, photovoltaic solar panels, wind directions, wind tunnel*

Resumen

En décadas recientes, el recurso de energías renovables suscita cada vez más interés para el desarrollo humano y la energía solar fotovoltaica ha mostrado una rápida y creciente expansión. Muchos países han construido parques de paneles solares fotovoltaicos para aprovechar esta energía. Las normas y códigos existentes para medir la acción de la carga de viento no son una herramienta adecuada para evaluar esta carga sobre los paneles FV, por lo cual se requieren estudios que profundicen en el tema. Este artículo presenta un ensayo experimental de las cargas de viento en túnel sobre paneles FV montados en el suelo. El modelo fue probado con inclinaciones de 15° y 23° con diferentes ángulos de ataque del viento a campo abierto. Con ello se obtuvieron las características de la distribución de la presión de los coeficientes máximos y medios de las carga sobre las superficies de los paneles. Los coeficientes de forma de las cargas máximas se obtuvieron mediante el enfoque de 3-s (tres segundos) y el promedio de áreas. Los incrementos de los coeficientes de presión resultan críticos para 0° y 180° con un porcentaje de aumento total aproximado del 57% y 61%, respectivamente, al variar el ángulo de 15° a 23°.

Palabras clave: *Coeficientes de presión, paneles fotovoltaicos, dirección del viento, túnel de viento*

1. Introduction

Renewable energy resource has an increasing interest for human development in the last decades and photovoltaic solar energy has become one of them in a speedy rising expansion. Several photovoltaic solar panels farms have been built to take advantage of this energy in many countries. Some areas of the planet with a good solar potential have also intense winds, which induce a great wind load on solar panels farms. Standards and codes for wind load action have not been an adequate tool to evaluate wind load on photovoltaic (PV) solar panels yet; thus, this is the main reason to carry out deeper studies on this subject. Many factors such as the panel inclination, panel dimensions, panel's height, upstream exposure and wind attack angles must be considered on the applied wind load design.

Studies of wind load on PV solar panels located on the ground or on the rooftop of the buildings have been reported in specialized literature. There are representative samples of these studies; some are presented in this article.

One of the first studies was performed by Miller and Zimmerman (1981); they analyzed the wind loading on photovoltaic array field through measures on wind tunnel models. These authors concluded that measure dimensionless pressure coefficients were independent of the Reynolds number. They also found considerable difference between normal force coefficients for uniform and non-uniform flow. Besides, they proposed the use of fence and barriers in order to reduce the wind forces on the PV panel located at the edge or at the corner of the PV field.

During the last decades, several studies of wind loads on PV panels on roofs-mounted have been developed through wind tunnel tests (Aly and Bitsuamlak 2013b, Bienkiewicz and Endo 2009, Bronkhorst et al. 2010, Ginger et al. 2011, Radu and Axinte 1989, Radu et al. 1986, Stathopoulos et al. 2015, Stathopoulos et al. 2014,

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Stenabaugh et al. 2015, Wood et al. 2001), full scale measurements (Geurts and Blackmore 2013) and numerical simulation (Banks 2013, Bienkiewicz and Endo 2009, Bronkhorst et al. 2010). Detailed features of some of these works can be found at the literature review conducted by Stathopoulos et al. (2012). However, few studies report the effect of wind loading on ground mounted PV panels through wind tunnel test (Abiola-Ogedengbe et al. 2015, Aly and Bitsuamlak 2013a, Stathopoulos et al. 2014), which is the aim of the present work.

Aly and Bitsuamlak (2013a) analyzed the wind load of ground mounted solar panels at different geometrical scales through experimental tests in a wind tunnel and numerical analysis using CFD. Full scale dimensions of the panel were 1.336 m x 9.144 m. It was tested with scales 1:50, 1:30, 1:20, 1:10, 1:5 with 25° and 40° of angles inclination for four wind profiles and 0° wind direction at wind tunnel. Results from these tests show that mean load coefficients are not significantly affected by the model size, while standard deviation and peak load coefficients vary according to model size and the spectral content of the test flow. However, these investigators pointed out that 3-s (three-seconds) peak values of the normal force coefficients were similar for all used model scales (1:30, 1:20, 1:10, 1:5), except for 1:50 scale model because its configuration was very close to ground.

Stathopoulos et al. (2014) compiled several wind tunnel experiments performed on PV panels located on the ground and attached to flat building roof in 2014. The dimensions of the panel model were 129 mm x 28 mm using a 1:200 geometrical scale for its construction. The model was tested with different angle inclinations (20°, 30°, 40° and 45°) for a range of 0° to 180° wind direction with 15° intervals. They concluded that the wind direction that produces the greatest values of pressure coefficients is 135° (wind attacking to the higher corner of the panel). In relation to the variations on inclination of panels located on the ground, their research (Stathopoulos et al. 2014) remarks that increasing panel inclination results in higher suction, that means higher values of pressure coefficients. In their work, it is mentioned that the effect of panel inclination is significant only for critical wind direction. Furthermore, they provided simplified net pressure coefficients for the design of solar panels.

Abiola-Ogedengbe et al. (2015) conducted wind tunnel experiments on a 1:10 PV panel model located on the ground for four different wind directions. Dimensions of the model were 730 mm x 249 mm and they ware was tested with 25° and 40° of angle inclinations at uniform and open terrain exposures of wind. The results from this study show symmetric pressure distribution about the mid-plane on the surface model for 0° and 180° wind directions and asymmetric at 30° and 150° wind directions. These researchers found higher values of magnitudes pressure with the increasing panel inclination. They also observed higher values of mean pressure magnitudes under smooth wind exposure than those under open terrain exposure.

The numerical simulation has been an alternative to obtain pressure coefficients on stand-alone ground mounted PV panel (Bitsuamlak et al. 2010, Shademan et al. 2014). Even when this technique is not used in the present work, the results of these studies (Bitsuamlak et al. 2010, Shademan et al. 2014) are interesting in order to deepen in the behavior of pressure distribution of PV panel. Bitsuamlak et al. (2010) investigated the wind effects of stand-alone ground mounted PV panel with 40° of inclination for three incident angles of attack (0°, 30° and 180°). Full scale experimental measurements were used to validate the Computational Fluid Dynamics (CFD) results. The authors who worked on this investigation (Bitsuamlak et al. 2010) reported that the highest values of overall wind loads correspond to 180° wind angle of attack. Shademan et al. (2014) performed CFD simulations to predict the wind loads on stand-alone and array PV panels. It was studied the effects of lateral gap spacing between sub-panels and the ground clearance on the wind loading of the stand-alone panel, which presents 45° of inclination. The simulations were carried out for a range from 0° to 180° wind direction with 30° intervals. Their results showed that the maximum aerodynamic forces for stand-alone panel were at wind direction of 0° and 180°.The authors (Shademan et al. 2014) also reported that introducing the gap between the sub-panels changes significantly the flow structure in the wake region. They pointed out that when the ground clearance is increased, it results in a lager mean wind loading on the structure.

Wind load on solar panels are not a particular case in standards and wind codes, then they could be designed as canopies. The study of several standards and codes (AS/NZS1170.2 2011, ASCE7-10 2010, CIRSOC-102 1992, EN1991-1-4 2004, NBR6123 1988, NC-285 2003) evidences a wide spread of pressure distributions and pressure coefficients for this case. The American (ASCE7-10 2010) and Australian (AS/NZS1170.2 2011) standards recommend two values of pressure coefficients for the panel, one for the lower side of the panel and the other for the upper side of the panel. Eurocode (EN1991-1-4 2004) proposes to divide the area of the panel into three zones: the center and the sides of the panel, each one with different values of pressure coefficients. Cuban (NC-285 2003), Brazilian (NBR6123 1988) and Argentina (CIRSOC-102 1992) standards recommend a trapezoidal distribution of pressure. Besides the different pressure distributions, the values of pressure coefficients are also different among standards conducting to great imprecision for panel design (López Llanusa et al. 2014).

The lack of design provisions in wind loading standards and codes and the few studies in the specialized literature indicate the need of more studies of wind loading on ground mounted PV panels. This paper presents an experimental study of the wind load on a stand-alone ground mounted PV panel in a wind tunnel. The model was tested with inclinations of 15° and 23° for different wind attack directions in an open terrain. It was obtained the detailed characteristics of pressure distribution of the mean and peak load coefficients on the panel surfaces. The peak loads were obtained using 3-s (three-seconds) and an area-average approach are also presented.

2. Description of the experimental test

In this study, the experimental test was performed following the requirements defined by Kopp and Banks (2012) even when they are presented specifically for roof mounted solar-arrays, they can be applied for PV panels on the ground.

2.1 Model

The reduced model of the PV panel was built according to data collected of a full-scale PV module (prototype), it is a repetitive form used at Cuban solar farms installed on the ground. General dimensions of PV module are 5.1 x 5.3 meters, composed by 20 individuals PV panels of 1.00 m x 1.325 m in a 4x5 array. The prototype is a four legs structure with braced elements of steel channels of 80 mm as support of panels as shown in Figure 1.

Figure 1. *Photovoltaic solar farm in Cuba (prototype)*

Model of PV panel was built in a geometrical scale of 1:10 considering the independence of pressure coefficients of Reynolds number, appropriate materials for model's construction, wind tunnel blockage and allowing an appropriate system of pressure taps in order to detail the pressure distributions. Dimensions of reduced model are shown in Figure 2. Maximum blockage ratio calculated for model is equal to 2%, then no corrections were made. The model allows the inclination of the panel for 15° and 23°. Materials employed in the construction of the model were aluminum and acrylic ensuring the adequate stiffness for the test. The PV model was erected with four acrylic plates of 10 mm thick inside which the flexible pressure tubes were inserted. Structure of the model was designed considering that all pressure tubes could be installed without a modification of the wind flow. Tubes were conducted inside the legs and the braced members as can be seen in Figure 3a. The surface of the panel were sectioned in four symmetric divisions where 28 pressure taps of 1 mm internal diameter were spread in the upper and under face as shown in Figure 3b. Each pressure taps on the upper side and in the lower side are over the same normal line to the face. Pressure taps were incremented at the panel corners in order to capture the effects of the vortices produced in this area.

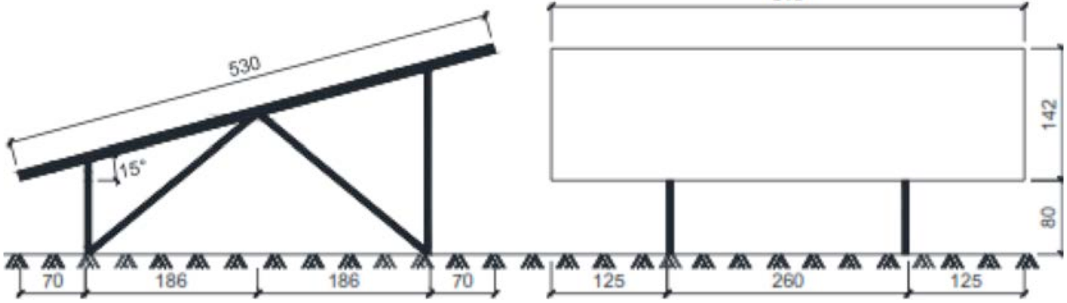

Figure 2. *Reduced model at geometric scale of 1:10 with 15° inclination (dimensions in mm)*

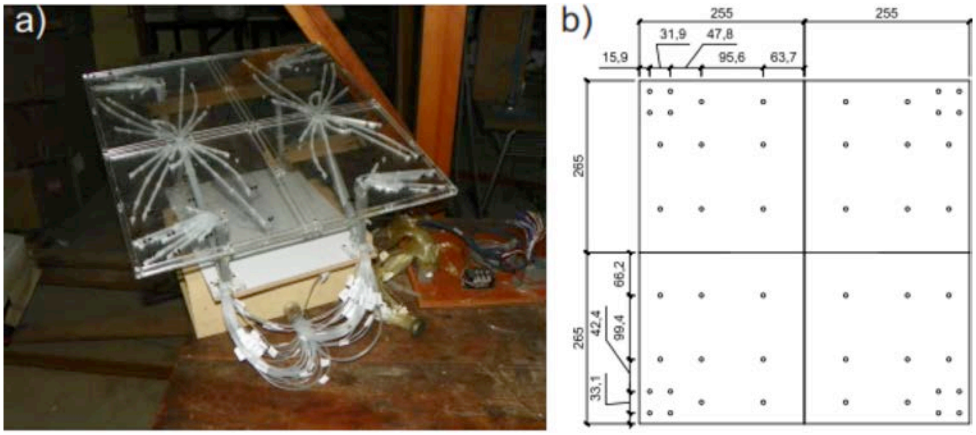

Figure 3. *a) Photograph of pressure taps on the PV pane model, b) Sketch of pressure taps on the upper side of the panel, there are 56 taps on each surface of the model shown by the open circles*

2.2 Testing facilities and procedure

The atmospheric boundary layer tunnel used for the test bellows is located at the Institute of Fluids Mechanics and Environment Engineering (IMFIA) of University of Republic (UDELAR), Montevideo, Uruguay. The tunnel has a 17 m length test section with a cross area 2.25 m wide and 1.8 m high. Other features of this tunnel can be seen at reference (Cataldo and Durañona 1998).

The instrumented model was installed above the tunnel floor on a turntable circular plate at the downstream wind tunnel test section and it was connected to the pressure scanners devises SCANIVALVE ZOC33/64 Px. The scanner was connected to two separate channels on the data acquisition system; each channel obtains the pressure data from 56 pressure tubes. The pressure measurements were recorded at a sampling frequency of 120 Hz and a time step of 8.22 μs. A total of 27 000 frames were collected and digitally processed.

The tests were performed for the wind profile representative of the open terrain exposure. Figure 4a shows that the measured profile was well approximated with the mean wind profile described by the logarithmic law (Davenport 1967) represented by (1).

$$\bar{U}(z)=\frac{u^{*}}{K}\ln\left(\frac{z}{Z_{o}}\right) \qquad (1)$$

Where $\bar{U}(z)$ represents the mean wind velocity at height z, u^{*} is the friction velocity, K is the von Kármán coefficient approximate 0.4, $Z_0 = 0.5\ cm$ is the roughness for open terrain exposure at model scale. The intensity of turbulence was between 19% and 23% along the panel height (see Figure 4b). Wind velocity and turbulence intensity profiles were measured using a hot wire anemometer IFA100 from TSI Company U.S. Test wind velocity was set at 20 m/s. Figure 4c shows the velocity fluctuation frequency spectra at *the mean height of the panel and the spectrum is to be target von Kármán. In all tests, the measurements were collected along 3.7 minutes. This situation was supposed the model of a full scale storm of about 10 minutes with a wind speed of 45 m/s at 10 m height. A pitot-tube device was used to measure the free stream velocity at an undisturbed height above the model during the tests. A schematic representation of the experiment at wind tunnel for the present study is shown in Figure 5. The tests were implemented from 0° to 180° at 45° intervals due to the symmetry of the PV model as shown in Figure 6.*

At prototype scale this flow correspond to a rural terrain exposure with a roughness length of 5 cm and with a velocity scale of 33,29 m/s.

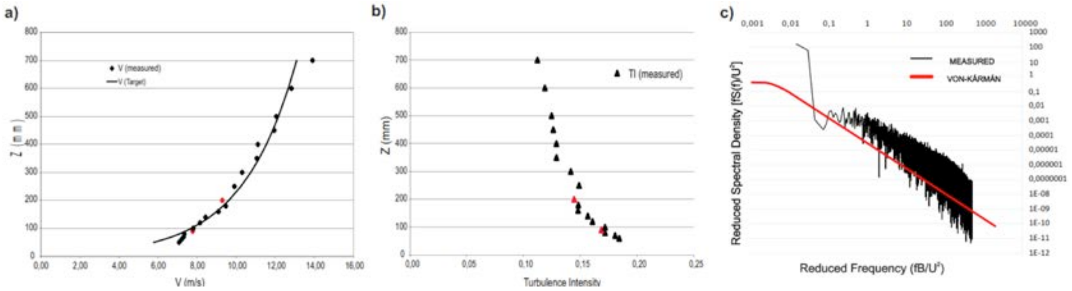

***Figure 4**. a) Wind velocity profile, b) Turbulence intensity profile, c) Spectral frequency the wind tunnel*

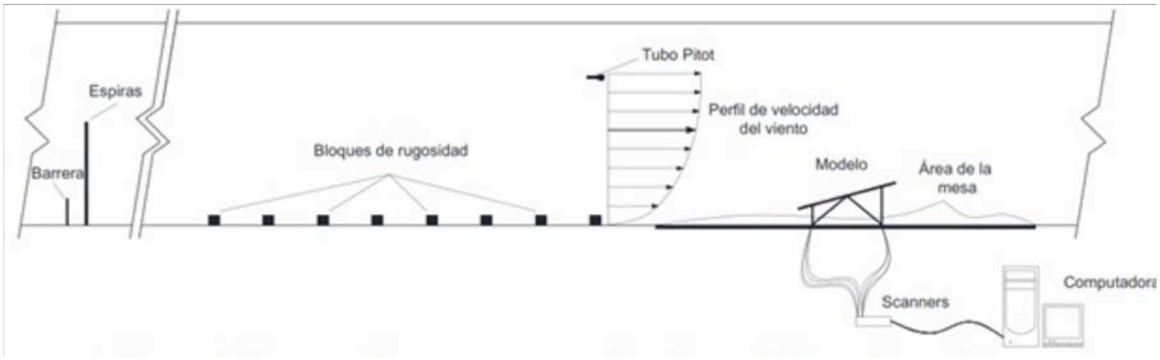

***Figure 5.** Schematic representation of the experiment at the wind tunnel*

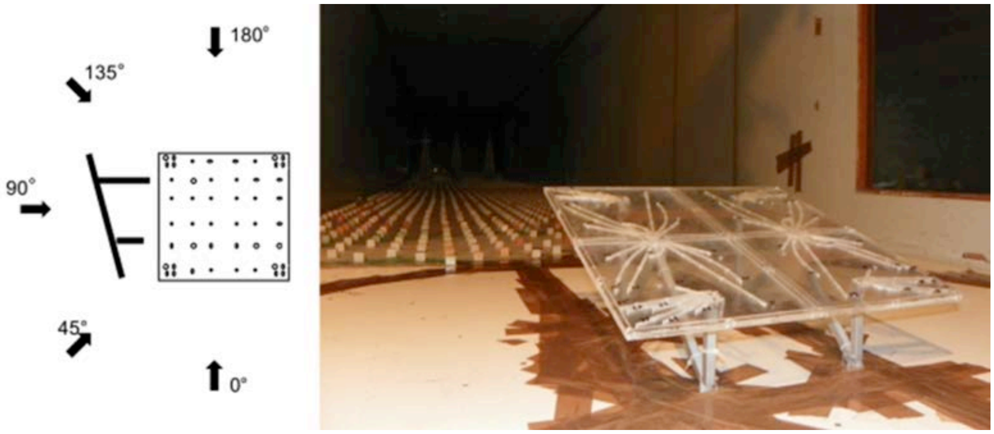

Figure 6. *PV panel tested with five wind attack angles in the wind tunnel*

We guess the turbulence small scale for this structure about 0.2 m at prototype scale, let say 1/10th of the height. At model scale these scale would present a frequency of 450 Hz. This value is inside of the inertial sub range of the spectrum.

3. Results and discussion

3.1 Pressure coefficients

Pressure measurements of the upper and lower surfaces of the panel were processed to calculate the time history net pressure coefficients ($C_{pi(net)}(t)$) at each pressure taps by means of equation 2.

$$\mathbf{C_{pi(neto)}(t)} = \frac{\mathbf{P_i^U(t) - P_i^L(t)}}{\frac{1}{2}\rho \mathbf{V_{ref}^2}} \tag{2}$$

where $P_i^U(t)$ and $P_i^L(t)$ are pressures measured at upper and lower surfaces at the tap i respectively, ρ is air density, V_{ref} is mean wind speed at reference height, which was taken at the mid height of the inclined model. The net pressure coefficients are defined as negative when they are acting in the upward direction and they are positive when they are acting in the downward direction. It was obtained the mean $C_{p\ (mean)}$ and peak $C_{p\ (peak\ 3s)}$ load coefficients from the time history net pressure coefficients. To obtain the 3-s peak load coefficients, the time history of the net pressure coefficients was divided into several intervals of 3 seconds size, at full scale time, with W number of samples for each interval where can be observed a maximum and a minimum value of net pressure $p(max\ o\ min)3\ s$ respectively. The 3-s peak value of the pressure coefficients can be calculated as the sum of the maximum or minimum of each interval divided by the total number of intervals.

$$(\mathbf{C_{p(máx)3s}}) = \frac{\mathbf{p(máx\ o\ mín)3\ s}}{\frac{1}{2}\rho \mathbf{V_{ref}^2}} \tag{3}$$

$$\mathbf{p(máx)3s = máx\ o\ mín\left\{\langle p(neto)\rangle_{3\ s,i}\right\}_{i=1\ a\ N}}$$

Graphics on Figure 7 show mean and (3-s) peak values of net pressure coefficients distribution for 15° and 23° panel inclination for each tested wind direction. It is observed that pressure distributions are similar for both panel inclinations, however highest values of net pressure coefficients were found for 23° panel inclination in agreement with previous studies (Abiola-Ogedengbe et al. 2015, Stathopoulos et al. 2014) which reported that with increased panel inclination results in higher values of pressure coefficients.

As can be seen in Figure 7, net pressure distribution varies with wind angle attack. For 0° and 45° wind angle attack, the panel is totally under downwards pressure, while for 135° and 180° the panel is totally under uplift pressure. Graphics for 0° and 180° wind direction show symmetric pressure distribution about mid axis which correspond with the wind direction, these results are consistent with the studies developed by Abiola-Ogedengbe et al. (2015) and (Shademan et al. 2014). Net pressure coefficients distributions for 0° wind direction show the highest values at the lowest part of the PV panel and the values decrease towards the upper edge. The opposite phenomenon occurs for 180° wind direction as shown in Figure 7e. It is observed at Figure 7c that net pressure coefficients are almost zero for 90° wind direction, due to the same pressure distribution at lower and upper panel surfaces. At oblique wind direction 45° and 135° the highest values of net pressure coefficients are present on the panel corner and they decreased toward the opposite corner of the wind attack direction as can be seen in Figure 7b and Figure 7d.

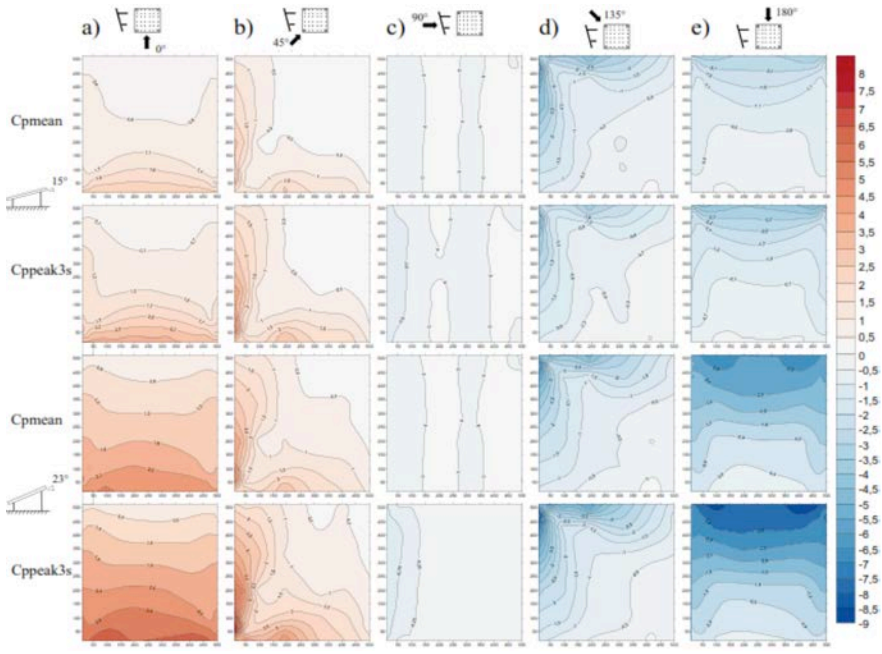

Figure 7. *Mean and peak net pressure coefficients distribution for 15° and 23° inclination PV panel at five wind angle attack*

The variation of the panel inclination from 15° to 23° caused an increasing of 2.48 to 2.83 of the greater value of the average pressure and a variation in the pressure tap where these values are obtained; however, they are always achieved on the edge of the wind attack. For wind angle attack of 0° and 180°, the increments on the pressure raise when the inclination angle varies from 15° to 23°, between 1% and 14% while for the wind angle attack of 45° and 135° they are found between 30% and 54%. When it is raised to 23°, a greater blockade is locally provoked; the flowing presents a greater curvature, a greater increment of the local speed and a greater reduction of the pressure of the end of the panel.

In the cases of variation of wind angle attack from 0° to 45°, the peak pressure increases from 3.70 to 5.92 for 23° of inclination and from 3.47 to 3. 87 for 15°. In the case of wind attack from 180° to 135° the suction values vary from -4.20 to -8.76 for 23° and from -4.15 to -5.96 for 15°. As it can be observed, there is a meaningful increasing of the pressure values when the wind angle attack is changed independently of the panel inclination. Although the greatest values are obtained for the angle attacks of 45° and 135, they are located on the attack edge. On the other hand, for 0° and 180° the values are found in a greater area.

3.2 Local shape coefficients

Local shape coefficients are used to calculate wind loads on full-scale structures. It can be calculated by summing several individual pressure coefficients which are multiplied by tributary areas (see Equation 4). Aly (2013) defined tributary area as the area surrounding to a pressure tap where the pressure is assumed to be equal. Figure 8 displays the tributary areas selected for each tap on the PV panel model at the present work.

$$\boldsymbol{Cf} = \frac{\sum_i^n \boldsymbol{C}_{\boldsymbol{p}(\text{máx o mín})3s} * \boldsymbol{A_i}}{\sum_i^n \boldsymbol{A_i}} \qquad (4)$$

Where Cf is the local shape coefficient for each local area, $C_{pi,peak3s}$ is peak 3-s net pressure coefficient of the tap i, n is the total number of pressure tap of each local area, A_i is tributary area for each tap i.

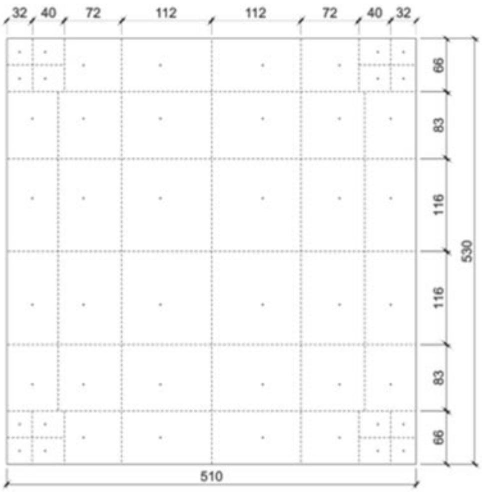

__Figure 8.__ Tributary areas for PV panel model. Dashed line represents tributary barriers and circles represents pressure taps (mm)

Figure 9 shows the peak local shape coefficients at 0°, 45°, 135° and 180° wind directions. They were calculated for assigned areas which were defined from the shapes of the peak net pressure coefficients distributions. The maximum positive (downwards) Cf values are 2.83 and 3.78 for 15° and 23° panel inclinations respectively; they correspond to 0° wind direction. The maximum negative (upwards) Cf values are -3.43 and -5.03 for 15° and 23° panel inclinations respectively; they correspond to 135° wind direction.

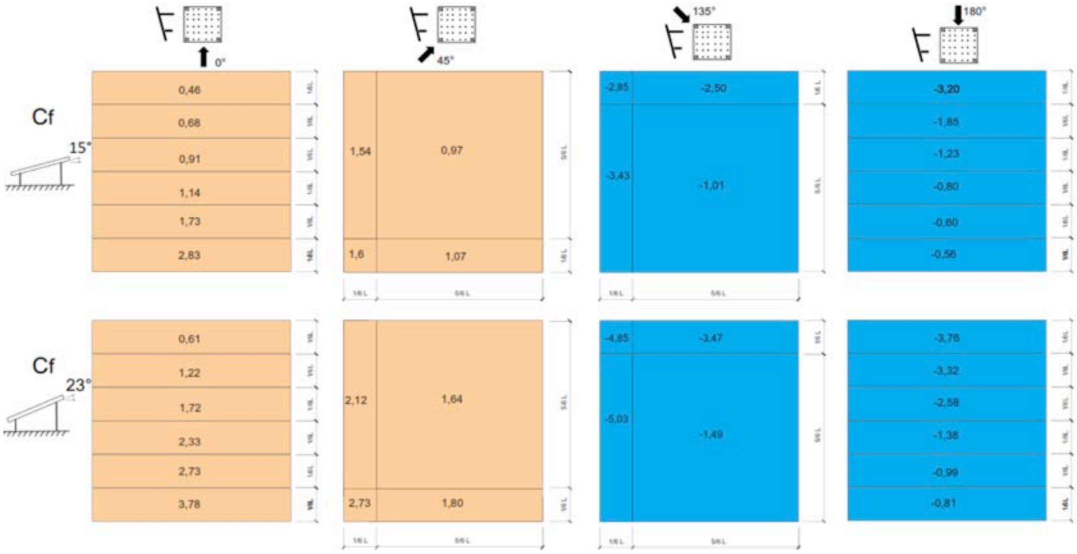

__Figure 9.__ Peak local shape coefficients at 0°, 45°, 135° and 180° wind directions

In the consulted bibliography, it is possible to find diverse research work (Ginger et al. 2011, Stathopoulos et al. 2014) which propose a value of shape coefficient for this type of structures.

The present work proposes to divide the solar panel into different zones taking into account the behavior of the gradient of net pressure on its surface.

To propose only one shape coefficient for the wind direction; for example, of 180°, it would imply underestimate the pressures on the higher part of the panel, and at the same time, overestimate the lower part

Furthermore, it should be carried out an analysis of the different wind directions because the patterns vary, and in the case that only one value were assumed, the attack edges, which are the ones that undergo the greatest pressures, would not be included in this kind of analysis.

All this would imply that in supporting the panel, diverse forces are undoubtedly generated and they should be considered as part of the general design.

4. Conclusion

This study investigates wind loads on PV panel. The main conclusions are summarized as follows:
Net pressure distribution patterns are similar for both 15° and 23° panel inclinations allowing the panel being divided into several sections in order to obtain the shape coefficients.

According with previous studies, before mentioned, increasing the panel inclination results in higher values of pressure coefficients whether for uplift pressure or downward pressure. Increments of pressure coefficients are critical for 0° and 180° with an approximated total increase percentage of 57% and 61% respectively when varying the angle from 15° to 23°.

Greatest values of coefficient pressure are located at the boundary of panels in a very small area. These maximum values of pressure coefficients were found for 45° and 135° wind direction attack. It should be take into consideration for possible local damage.

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