Revue des Energies Renouvelables Vol. 19 N°4 (2016) 517 - 524
DOI: https://doi.org/10.54966/jreen.v19i4.590

Analytical investigation of wind loads on heliostats

Hichem Bendjebbas [1,2 *], Mohamed Abbas [1] and Abdellah Abdellah-El-Hadj [2]

[1] Unité de Développement des Equipements Solaires, UDES
Centre de Développement des Energies Renouvelables, CDER
42004, Tipaza, Algeria
[2] Laboratoire de Mécanique, Physique et Modélisation Mathématique, LMP2M
Université de Médéa, 26000 Médéa, Algeria

(reçu le 10 Décembre 2016 - accepté le 20 Décembre 2016)

Abstract - *Applications of Heliostats for solar power tower plants increased in the recent years. Most of the solar power tower plants installed are on flat terrain and they may be subjected to wind loads. In the present study, a refined method for calculating the wind loads on heliostats is presented, here called the Sandia 92-method. The first step in the Sandia-92 method is to adjust the required wind speed value to the wind speed at the center of the mirror array at a height H above ground. Hence, the performance of heliostats with different pedestal heights can be compared. The design of heliostat must be calculated in-field and the calculation of isolated heliostat wind loads should not be taken as a reference. Also, the presence of well studied fences reduces considerably wind loads on heliostats placed in the front rows.*

Résumé - *Les applications des héliostats pour les centrales solaires à tour ont augmentées dans les dernières années. La plupart des centrales solaires à tour installées sont sur des terrain plats et ils sont soumis à des charges de vent. Dans la présente étude, une méthode raffinée pour le calcul des charges de vent sur les héliostats est présentée, appelée la méthode Sandia-92. La première étape de la méthode Sandia-92 est d'ajuster la valeur de la vitesse du vent requise pour la vitesse du vent au centre du miroir de l'héliostat à une hauteur H au dessus du sol. Par conséquent, la performance des héliostats avec différentes hauteurs de socles peuvent être comparés. La conception d'héliostats doit être calculée sur le terrain et le calcul des charges de vent sur les héliostats isolés ne doit pas être pris comme référence. En outre, la présence de clôtures bien étudiées réduit considérablement les charges de vent sur les héliostats placés dans les premiers rangs.*

Mots clés: Héliostat - Charges de vent - Méthode analytique - Sandia-92.

1. INTRODUCTION

Heliostats are the most important cost element of a solar power tower plant. Since they constitute ~50 % to the capital cost of the plant, it is important to reduce the cost of heliostats to as low as possible to improve the economic viability of power towers [1]. Actually, the cost of heliostats is estimated in the range of 150 and 200 USD/m^2 and the cost of target generally varies between 75 and 120 USD/m^2 [2].

A goal of 100 USD/m^2 is necessary for heliostat cost since at that the power towers levelized cost electricity (LEC) production may be competitive on the open market [1].

One of the design requirements of a heliostat is the ability to withstand three types of wind loads [3]:

- Storm winds: in discrete, infrequent storm loads of up to 40m/s free stream wind speed, heliostat in *stowed* position must survive (figure 1) (no static failure or low cycle fatigue failure),

* hbendjebbas@gmail.com

- Moderate winds: at wind speeds up to 22 m/s free stream, a heliostat in *any* position must survive (no static failure or low cycle fatigue failure), and the actuation mechanisms must be able to move the heliostat to the stow position in preparation for possible storm winds, and

- Operational winds: at more frequent oscillating wind speeds up to 15 m/s free stream, the actuation mechanisms must be capable to allow a heliostat in *any* position to track the sun accurately, and the resultant loads should not lead to high cycle fatigue failure.

In the above, free stream values are measured at 10 m above ground. To design a heliostat, therefore, one must be able to predict the mean and oscillating wind loads on the heliostat for all elevation angles of the heliostat and all wind directions relative to the heliostat coordinate system.

Fig. 1: Heliostat in stow position

In the Sandia report Wind load design methods for ground-based heliostats and parabolic dish collectors by Peterka and Derickson, published in 1992 [4], a refined method for calculating the wind loads on heliostats is presented, here called the Sandia 92-method.

The first step in the Sandia-92 method is to adjust thre required wind speed value to the wind speed at the center of the mirror array at a height H above ground. Hence, the performance of heliostats with different pedestal heights can be compared.

2. IN-FIELD HELIOSTATS PERFORMANCES

The dynamic wind pressure is multiplied with the surface area of the mirror assembly, which gives the force. The moments M are obtained by multiplying the force F with the moment arm r, according to:

$$M = F \times r \tag{1}$$

The loads are then multiplied with their respective load factor, which takes the influence of turbulence into account. Peterka obtained the factors from wind-tunnel experiments with miniaturized heliostat models. The methodology with load factors from the wind tunnel experiments are still used in more recently done works, for example the research presented in the article Fluctuating wind pressure characteristics of heliostats by Bo Gong *et al.*, 2012 [5].

An extra feature is also included in the Sandia-92 method: It is possible to calculate the wind loads for a heliostat located in a heliostat field on a specific row. The heliostat field can either be unprotected or protected by external fences. Values can be obtained for both cases. External fences give effect to the 3-4 most outer rows of heliostats – which otherwise experience the highest loads – and gives radically reductions in wind loads. Internal fences can also be taken into account, i.e. fences between heliostats.

Notably, the wind loads may increase on the heliostats in the most outer rows when the heliostats are located in a field, due to turbulence, compared with the case with a single isolated heliostat. The heliostats on the inner rows are in some extent protected by the surrounding heliostats.

The heliostat's in-field performance is calculated using simplified General Blocking Area (GBA). The GBA is defined as follows:

$$\text{GBA} = \frac{\text{Solid area of upwind blockage projected to wind direction}}{\text{Area of ground occupied by the blockage objects}} \tag{2}$$

Following assumptions are made for the model:

- Square shaped mirrors
- The pedestal area is neglected
- Forces in the trusses are neglected
- Equal spacing between heliostats in a field situation; arranged in a regular pattern.
- The hinge point about which hinge moments are defined is centered on the collector geometry and is 0.062·h from the rear surface (downwind side when ß = 0°, and α = 90°), h = heliostat chord length.

If the gaps between the mirror facets are resulting in an area smaller than 15 % of the total mirror assembly area, the gaps should be neglected in the analysis and the total solid surface area is calculated as the square of the mirror assembly chord length (i.e. $A = L_2$) (Peterka, 1992) [4].

The error of the model is estimated to 15-20 % (Peterka, 1992) [4]. However, Peterka gives no justification for this estimation, and the report does not clarify if any systematic research has been conducted that investigates the model's precision and applicability on full scale heliostats.

The figure 2 shows the layout for a simplified GBA calculation.

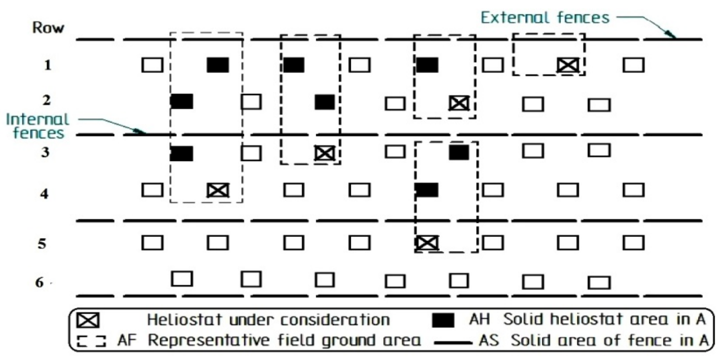

Fig. 2: Layout for simplified GBA calculation. Inspired from (Peterka, 1992) [4]

3. FORMULAS FOR WIND LOAD CALCULATION

Generalized Blockings Area-

$$GBA = \frac{(K) \times (AH) + AS}{AF} \tag{3}$$

AH , actual surface area of the heliostat mirror-array (m^2) = h^2
AF, representative ground area occupied by the heliostat.
AS, solid area of the fences within AF
K , correction factor for azimuth angle, resp. elevation angle, according to **Table 1**

Table 1: K-factors (Peterla *et al.*, 1992) [4]

Loads	K
F_x	1.0
F_z	0.5
M_{Hy}	0.5
M_z	0.5

Drag force- $$F_x = C_{F_x} Q A \tag{4}$$

Lift force- $$F_z = C_{F_z} Q A \tag{5}$$

Hinge moment- $$M_{Hy} = C_{MHy} Q AH \tag{6}$$

Azimuthal moment- $$M_z = C_{M_z} Q AH \tag{7}$$

Base overturning moment- $$M_y = C_{My} Q AH \tag{8}$$

Where $$C_{My} = C_{F_x} + C_{Mhy} \times (h/H) \tag{9}$$

Table 2: Definitions for wind loads calculation

Sym	Unit	Description	Formula or value
Q	$[P]=[N/m^2]$	Dynamic pressure of the mean approach wind.	$Q=\frac{\rho.U^2}{2}$
ρ	[kg/m^3]	Density of air.	$\rho \approx 1.229\, kg/m^3$
U	[m/s]	Mean approach wind at elevation H .	$U=U_{mean}(H/Z_{ref})^n$
n		Power law exponent for the approaching wind.	For glass and open terrain- $n=0.15$
U_{mean}	[m/s]	Mean approach wind at elevation Z_{ref} .	$U_{mean}=U_{gust}/1.6$
U_{gust}	[m/s]	2-3 second gust wind speed at height Z_{ref} above ground.	
Z_{ref}	[m]	Height between ground and wind speed measurement device.	
A	[m^2]	Solid surface area of heliostat. Include openings in the solid area if they constitute less than 15% of the total area.	
h	[m]	Chord length of the heliostat.	
H	[m]	Height of the center of the heliostat area from ground.	
Z_0	[m]	Effective surface roughness length	Typically 0.01-0.05 m in open country.

For in-field performance, the C- factors for peak loads are obtained with the following formulas.

$$C_{F_x} = -13.6 \times GBA_{Fx} + 6.52 \quad (10)$$

$$C_{F_z} = -10.6 \times GBA_{Fz} + 4.52 \quad (11)$$

$$C_{Mhy} = -3.2 \times GBA_{Mhy} + 0.9 \quad (12)$$

$$C_{Mz} = -4.6 \times GBA_{Mz} + 0.92 \quad (13)$$

$$C_{My} = C_{F_x} + C_{Mhy} \times (h/H) \quad (14)$$

For calculating the peak and mean loads acting on a single isolated heliostat, the dynamic pressure can be multiplied with the factors C from **Table 1**.

The **Table 3** also lists the 04 extreme cases where load components reach their maximum values, as well as the stow-position case. Note that F_x and M_y respectively F_z and M_{Hy} reaches their maximums at the same angles.

Table 3: Wind load coefficients C - on a single isolated heliostat
One component is a maximum.

	$\alpha = 90°$ $\beta = 0°$	$\alpha = 30°$ $\beta = 0°$	$\alpha = 90°$ $\beta = 65°$	$\alpha = 0°$ $\beta = 0°$
Load at their maximum	F_x , M_y	F_z , M_{hy}	M_z	Stove load
Peak Loads				
C_{Fx}	4.0	2.1	3.7	0.6
C_{Fz}	10	2.8	0.5	0.9
C_{Mhy}	0.25	0.6	0.15	0.2
C_{Mz}	0.29	0.06	0.7	0.02
Mean Loads				
C_{Fx}	2.0	1.0	1.6	0.1
C_{Fz}	0.3	1.35	0.3	0.1
C_{Mhy}	0.02	0.25	0.02	0.02
C_{Mz}	0	0	0.25	0

4. WIND LOADS CALCULATION

An Excel sheet was prepared that calculates the wind loads on the heliostat, based on the formulas presented in the previous section, two heliostats sizes of $49m^2$ and $25m^2$ was studied. Following cases were explored in work:

- Wind loads on a *single isolated heliostat* for gust wind speeds 35 m/s, which is the speed that causes maximum wind loads. In the 40 m/s case, the heliostat is in stove position; hence the loads are lower than the 30 deg case.

- Wind loads on a *heliostat in-field*, on row 1; 2; 3; 4; 5 and above, for wind speed 35 m/s. (Row number is counted from outer row, inwards to the tower) – With and without *external fence.*

- The input values used for the wind load calculation are shown in **Table 4**.

Table 4: Input values

Description	Symbol	Unit	25 m²	49 m²
Heliostat height (ground to center support)	H	[m]	3.5	5
Mirror assembly size, one cant, chord length	h	[m]	5	7
External fence, height	h_{ext}	[m]	2.5	3.5
Heliostat spacing (parallel to the fence), (rows)	*deltax*	[m]	10	14
Heliostat spacing (perpendicular to the fence), (columns)	*deltay*	[m]	10	14
Gust wind speed at height z_wind above ground (2-3 sec)	U_{gust}	[m/s]	35	35
Elevation of wind speed measurement above ground	Z_{ref}	[m]	10	10
Power law exponent, based on surface roughness	n	[-]	0.15	0.15
Density of air	ρ	[kg/m³]	1.229	1.229

5. RESULTS AND DISCUSSION

The use of fences for heliostat wind loads reduction is very important. The Sandia-92 method is a analytical method based on experimental measurements in wind tunnel.

According to the results, the design of heliostat must be calculated in-field.

The calculation of isolated heliostat wind loads should not be taken as a reference. Figure 3 to figure 7 illustrates a difference between heliostat In-field and isolated heliostat wind drag pressure, lifting pressure, Base overturning moment, Hing moment and azimuthal moment where a significant difference is noted.

In-field heliostat is affected by wind flow turbulence created by a multitude of heliostat rows of a non-symmetrical manner which results in turbulent zones.

Wind loads are maximums in the first and the second field row. Beginning with the third field row, wind loads begin to diminish because of obstacles effect of heliostats in the first and second row.

The comparison between wind loads on 49 m^2 and 29 m^2 shows that the heliostats of large sizes are more sensitive to wind loads. Figure 5, figure 6 and figure 7 show that augmentation of heliostats sizes greatly increases with loads on heliostats especially the Base overturning moments, the Hing moments and the azimuthal moments when the difference is significant between-two sizes of heliostats.

This method is not the ideal way to calculate wind loads on heliostats but can be as a preliminary method of calculation that helps to make decisions.

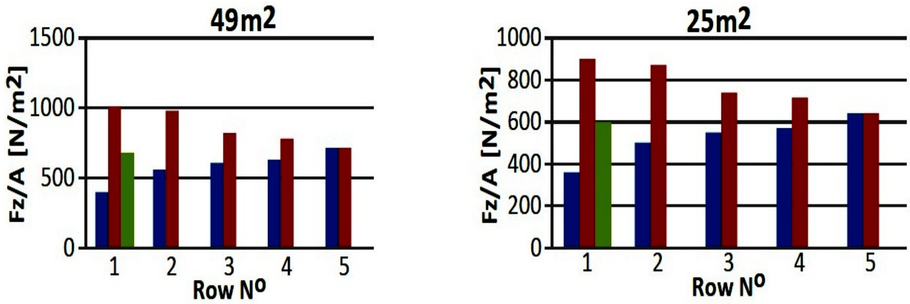

Fig. 3: Drag pressure on isolated heliostat,
in field without fence and in field with fence

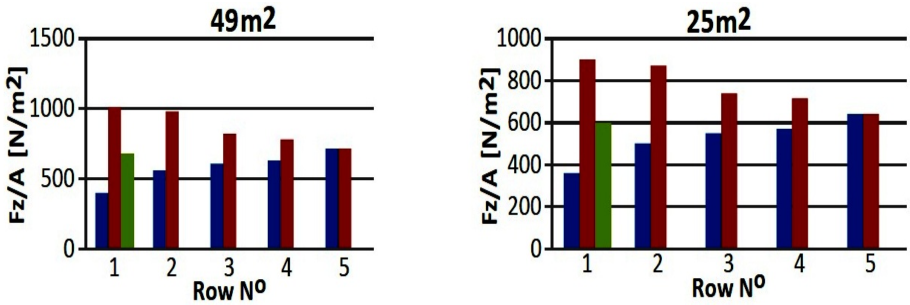

Fig. 4: Lifting pressure on isolated heliostat, in field without fence and in field with fence

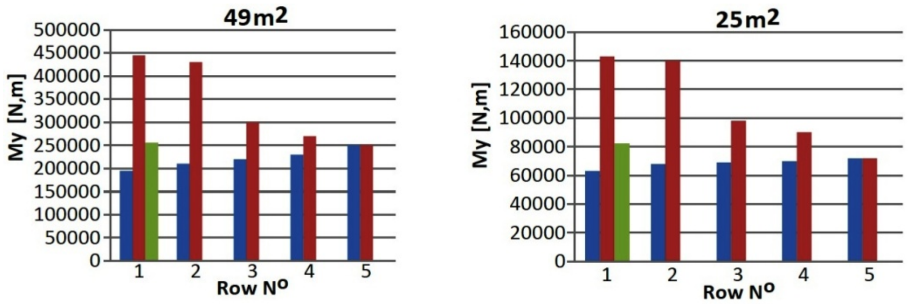

Fig. 5: Base overturning moment on isolated heliostat, in field without fence and in field with fence

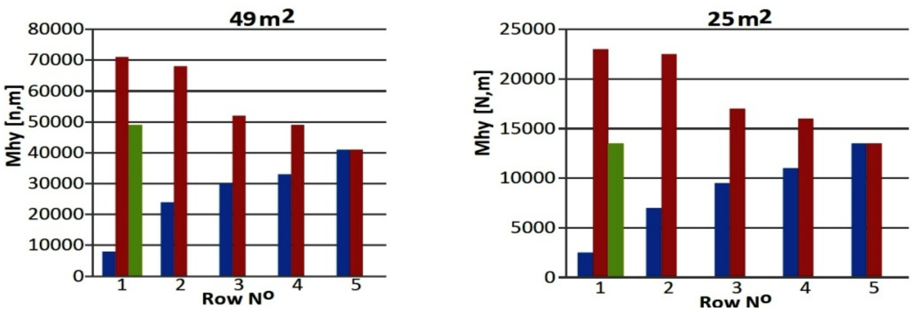

Fig. 6: Hing moment on isolated heliostat, in field without fence and in field with fence

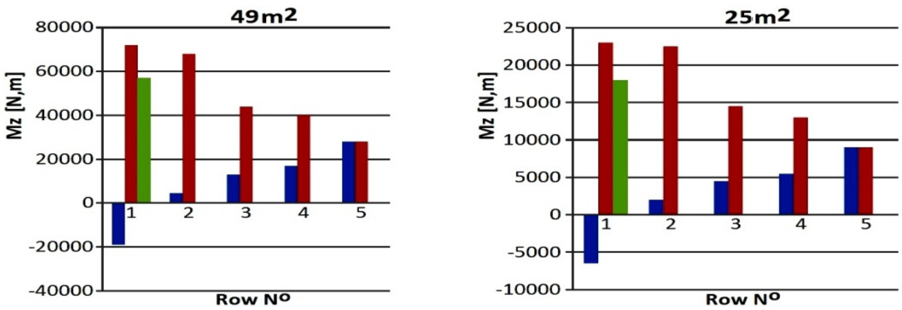

Fig. 7: Azimuth moment on isolated heliostat, in field without fence and in field with fence

6. CONCLUSION

Sandia-92 analytical method was used to compute wind loads on isolated heliostat and in-field heliostats. According to the results shown in figures 3 to 7, the design of heliostat must be calculated in-field and the calculation of isolated heliostat wind loads should not be taken as a reference. Also, the presence of well studied fences reduces considerably wind loads on heliostats placed in the front rows.

Large size heliostats are very sensitive to wind loads in contrast to the small sizes heliostats. but for better economic efficiency, it is suggested to use large size heliostat while seeking the best ways to reduce the effects of wind that affects their stability.

REFERENCES

[1] G.J. Kolb, S.A. Jones, M.W. Donnelly, D. Gorman, R. Thomas, R. Davenport, and R. Lumia, '*Heliostat Cost Reduction Study*', Sandia National Laboratory, USA, 2007.

[2] H. Sun, B. Gong and Q. Yao, '*A Review of Wind Loads on Heliostats and Trough Collectors*', Renewable and Sustainable Energy Reviews, Vol. 32, pp. 206 - 221, 2014.

[3] J.W. Strachan, '*Testing and Evaluation of Large-Area Heliostats for Solar Thermal Applications*', Sandia National Laboratories, USA, 1993.

[4] J.A. Peterka and R.G. Derickson, '*Wind Load Design Methods for Ground-Based Heliostats and Parabolic Dish Collectors*', Colorado State University, USA, 1986.

[5] B. Gong, Z.N. Li and Z.F. Wang, '*Wind-Induced Dynamic Response of Heliostat*', Renewable Energy, Vol. 38, N°1, pp. 206 - 213, 2012.