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A comparative analysis of wind pressure on flat and stair-step constructions of solar plant trackers

Yuri S. Chumakov [a,*], Valery D. Rumyantsev [b], Yuri V. Ascheulov [b], Alexander V. Chekalin [b]

[a] *Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya St., St. Petersburg 195251, Russian Federation*
[b] *Ioffe Institute, 26 Politekhnicheskaya St., St. Petersburg 194021, Russian Federation*

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Abstract

The paper presents comparative experimental research of the aerodynamic processes and forces occurring due to airflow moving past by concentrator photovoltaic (CPV) modules assembled on a flat and a stair-step frame. The subsequent analysis of the aerodynamic properties of these design schemes has revealed the significant advantages of stair-step arrangement of CPV modules over the flat ones concerning smaller wind loads affecting the platform. In order to calculate the value of the forces operating on full-size solar installations, values for aerodynamic resistance for different schemes of module arrangement have been obtained. Detailed research of various solar installation models utilizing a wind tunnel and aerodynamic scales is carried out for the first time.

Keywords: Experimental study; Wind loads; PV platform; Force coefficient; Air tunnel; Flow visualization.

1. Introduction

Efficiencies over 45% under the conditions of sunlight concentration have been achieved in multi-junction solar cells (SCs) based on III–V semiconductors [1,2]. The wide application of these SCs under terrestrial conditions is possible only with the use of industrially inexpensive integral optical concentrators capable of focusing the sunlight onto a small surface (2 × 2 mm) of multi-junction SCs [3,4]. To maximize the amount of energy generated, the optical axis of the concentrator photovoltaic cell pair must be precisely oriented towards the Sun. In practice, for concentration ratios of around 1000 suns and above, the accuracy of the mutual positions of the components of this pair and the accuracy of the orientation towards the Sun must be stable and relatively high (at least 0.1°) [5]. Due to these requirements, there is a certain lag in the progress of concentrator photovoltaic (CPV) compared to other approaches aimed at generating electricity from sunlight. However, it shows significant promise for further improving the efficiency. One possible option is enhancing the structure and the constructions of all components of power facilities such as SCs, concentrating modules, and solar tracker constructions (the latter ensure that the CPV system as a whole operates normally).

* Corresponding author.
E-mail addresses: chymakov@yahoo.com (Yu.S. Chumakov), vdrum@mail.ioffe.ru (V.D. Rumyantsev), yuriascheulov@yandex.ru (Yu.V. Ascheulov), chekalin@mail.ioffe.ru (A.V. Chekalin).

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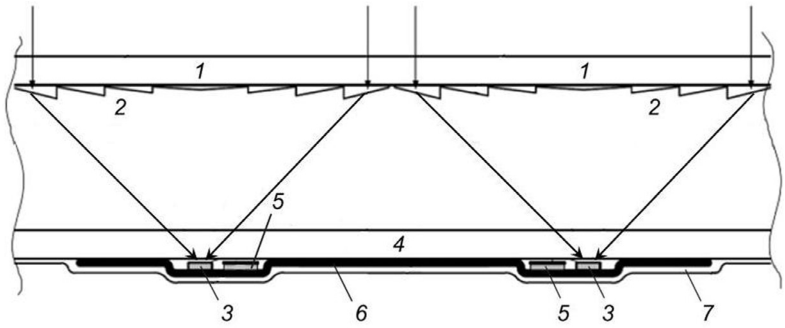

Fig. 1. A schematic cross-section of a SMALFOC-construction module: frontal glass plate (1), silicone Fresnel lenses (2), solar cell (3), rear glass plate (integral protective glass) (4), current-collecting busbar (5), heat-dissipation steel bar (6), laminating ethylene vinyl acetate (EVA) film (7). The arrows mark the path of the optical beams.

The conventional method of arranging the modules on the tracker's frame involves forming a photoreceptive surface of a solar installation as an integral flat panel. At the generated electric power of tens of kilowatts the flat panel consisting of separate CPV modules experiences significant wind loads. As a rule, once a certain wind speed is exceeded, the frame with the modules must be tilted horizontally in order to prevent installation failure. However, even with moderate but time-variable loads, there is, firstly, the risk of fatigue effects in the frame materials and in other mechanical parts of the tracker, and, secondly, such loads cause the error in the platform's orientation towards the Sun to increase [6], which ultimately leads to a significant decrease in the amount of the electric energy generated. Therefore, the problem of reducing wind loads on solar installations with sun-tracking systems is of high priority [7–10].

The goal of the present work is to experimentally establish the influence of wind loads on a platform with concentrating photovoltaic modules for two different schemes of arranging separate modules on the platform.

2. Concentrating photovoltaic systems

The photovoltaics laboratory of the Ioffe Institute has been developing all the components of concentrating photovoltaic systems, including concentrating modules and solar trackers over the recent years [3,4]. The modules that are supposed to be placed on the trackers have the so-called SMALFOC construction [6] which has many similarities with the construction of ordinary flat modules without concentrators both in the type of main materials used and in manufacturing technology. A schematic cross-section of a fragment of such a module is shown in Fig. 1.

In world practice, Fresnel lens concentrators manufactured from a transparent acrylic material by hot stamping are most commonly used in solar concentrator modules. The acrylic is transparent in the visible region but has absorption bands in the near-infrared part of the spectrum. The researchers of the Ioffe Institute suggested using a transparent silicone compound [4] instead of the acrylic. A sheet of silicate glass (which is a cheap, highly transparent and abrasion-resistant material) serves in this case as a mechanical base of the lens panel. A thin layer of silicone is placed on the inner side of the glass for a Fresnel lens profile to be formed on it.

The module has a lens concentrator frontal panel 1, with the solar elements 3 combined into a photoreceptive panel that is distanced from a lens panel by a distance equal to the focal distance of the lenses 2 (see Fig. 1). A panel-type concentrator module with small-sized isolated submodules is thus formed. The photoelements 3 are hermetically sealed and protected from environmental exposure by a simple method using the laminating film *7*. The photoreceptive surface of a standard module measures 480 × 960 mm, while its output voltage is 48 V at a 2.5 A current. These parameters are maintained by 16 series-connected assemblies, each assembly having 8 parallel-connected SCs. Using SCs with efficiencies of about 43% potentially allows obtaining total efficiencies of about 34% for the whole module. To achieve such an efficiency, the image of the solar disk must be precisely focused on the receiving surface element of each photoconverter. For this goal, it is enough to maintain the standard assembling accuracy of each individual module, to keep all modules in fine adjustment on the common base to align their optical axes, to point the platform precisely at the Sun, and, finally, to preserve the stability of these technological parameters during the whole lifetime of a power plant

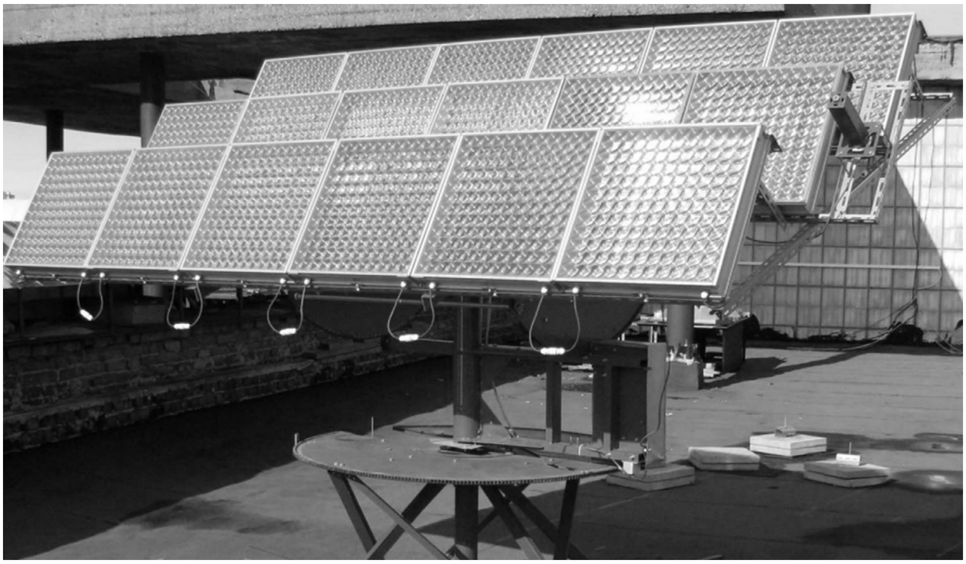

Fig. 2. A photograph of an experimental solar tracker developed at the Ioffe Institute. The total power of the concentrating modules is 1 kW.

(up to 25 years). We may thus deduce that to retain high efficiencies for the whole solar power plant it is necessary to take into account the wind loads causing the dynamic deformation of a platform with modules [7,11].

3. The analysis of the effect of wind loads

The researchers of the Photovoltaics laboratory of the Ioffe Institute developed a method of minimizing the effect of wind loads, which entails a stair-step arrangement of the modules on the solar tracker (see Fig. 2). A frame with CPV modules rotates around a vertical axis from the sunrise to the sunset orientation rotating through a limit angle of no more than ± 45º (relative to the horizon) around a horizontal axis. This allows manufacturing the frame as a stiff 3D construction with a trim capability. Supposedly, this method of module arrangement may allow to significantly reduce wind loads on photovoltaic installations.

The present work has conducted an experimental investigation of two types of construction models with different CPV module arrangement on the tracker platform. The model of the studied object was placed into an operating part of a wind tunnel, with model loads arising from the airflow measured by a tunnel balance for varying air speeds and model positions relative to the air velocity vector. For comparative analysis of the results, all wind-tunnel tests of the models with flat and stair-step module arrangements were carried out under absolutely identical conditions (i.e. position in the tunnel, air flow homogeneity, air temperature and humidity). The resistance coefficient c_x was used as a criterion of assessing the efficiency of a model in minimally resisting the airflow; it is usually introduced in the following way:

$$F = c\frac{\rho V^2}{2}S, \tag{1}$$

where F is the resistance force determined using the tunnel balance; c_x is the resistance coefficient (for unstreamlined bodies it may reach values over 1); S is the area of the midsection (the area of the module panel projection on the plane perpendicular to the velocity-vector direction); ρ is the air density; V is the wind speed.

The focus of the attention during the tests was the influence of the angle between the direction of the incident flow velocity vector and the normal to the module plane on the magnitude of the resistance force. Let us denote this angle as β (hereinafter referred to as the angle of attack); it varies within a range from 0° to 90°. In this case, $\beta = 0°$ corresponds to the module orientation towards the horizon line at sunrise/sunset, while $\beta = 90º$ corresponds to the orientation for the zenithal position of the solar disk, i.e. for the situation that happens at noon for solar tracker located in the Earth's equatorial belt. Fig. 3 schematically shows the possible options of the orientation of a stair-step and a linear construction of a solar tracker relative to the wind velocity vector.

A preliminary analysis of the configuration of the velocity field that forms as a result of the airflow interacting with the stair-step construction was conducted using numerical simulation (based on the solution of the full Navier–Stokes equations in a two-dimensional approximation). We should note that substantial computation

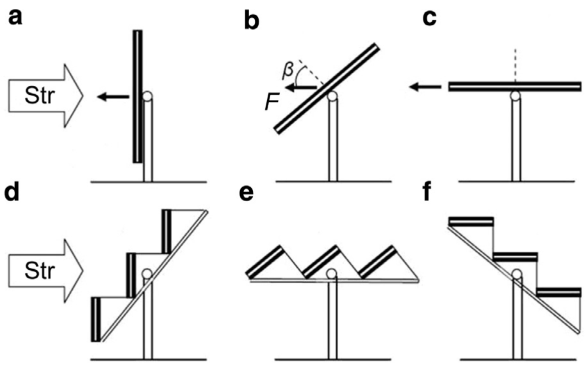

Fig. 3. The possible options of the orientation of the CPV modules on the platform relative to the wind stream (Str) during the light day (for various values of angle β): as a flat panel (*a*, *b*, *c*) and as stair-steps (*d*, *e*, *f*); $\beta = 0^o$ (*a*, *d*), 45º (*b*, *e*), 90º (*c*, *f*);. *F* is the force of resistance to the airflow.

times are required even for this problem statement which is significantly simplified. Therefore, it would seem more efficient and perhaps more accurate to experimentally study the solar tracker models using a wind tunnel to compare the forces of wind resistance in models of different configurations.

Models of solar trackers on a scale of 1 to 20 with the modules arranged on the tracker as a 6 × 6 m flat panel and as stair-steps (see Fig. 4) were made for laboratory experiments. The thickness of the material imitating the concentrator models was 8 mm, which corresponds to the thickness of SMALFOC modules and the longitudinal elements fastening them to the tracker frame.

The wind-tunnel tests of the models were carried out at a laboratory of Peter the Great St. Petersburg Polytechnic University. The open-jet working section was of 2 m in diameter and 3 m in length; the tunnel airstream speed ranged in value from 4 to 12 m/s. The chosen range matches the actual working conditions of solar power plants with CPV modules. The angles of attack β, i.e. the slope angles of the models, were varied in this experiment. The force *F* arising from the interaction of the airflow with the model was measured by the tunnel balance. Models were air-blown from both the frontal and the rear sides (the range of the angles of attack was 0–180°), perpendicular to the horizontal axis of model rotation. A panoramic photograph of a fragment of the wind tunnel with the solar tracker model positioned in the center is shown in Fig. 5.

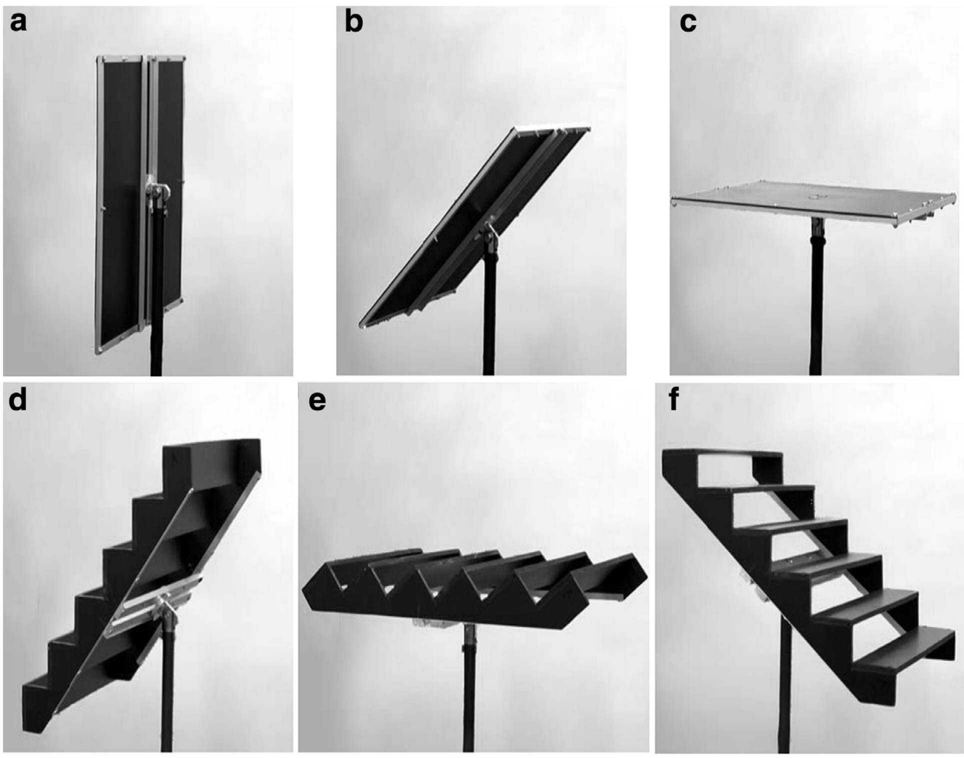

Fig. 4. Photographs of models of solar trackers, made on a 1:20 scale, with the modules arranged as a flat panel (*a*–*c*) and as six stair-steps with the same total module area (*d*–*f*) (see Fig. 3).

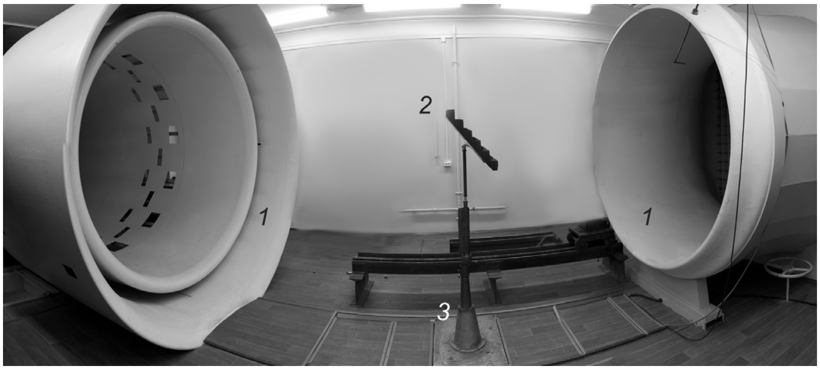

Fig. 5. A panoramic photograph of the setup for the wind-tunnel tests: fragments of the wind tunnel (1), a model of the solar tracker (2), a tunnel balance (3).

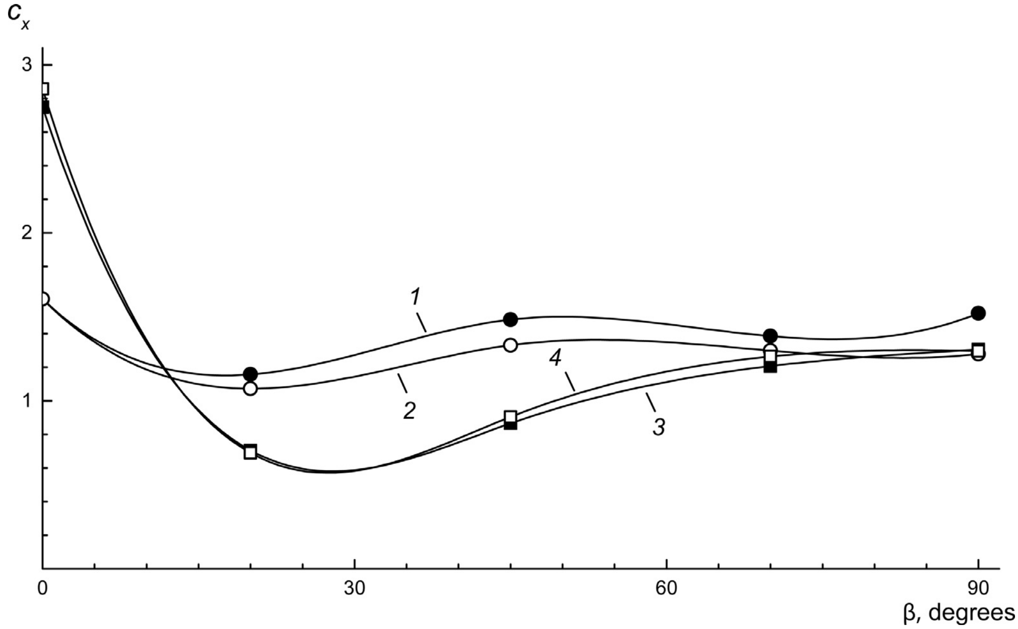

Fig. 6. The plots of the resistance coefficients versus the angle of attack for models of solar tracker with flat (1, 2) and six-step (3, 4) module arrangements for two values of air stream speed V, m/s: 8.2 (1, 4) and 11.5 (2, 3).

Fig. 6 presents the experimental results of the wind-tunnel tests for two different types of module arrangement. The dependences of the resistance coefficient c_x on the angle of attack were measured for different values of tunnel air stream speed V.

A comparative analysis of the results allows to conclude the following: the maximum value of resistance coefficient c_x is reached for both models at a zero slope angle ($\beta = 0$), i.e. when the modules are oriented towards sunrise/sunset, with factor values being roughly equal for both configurations. When the angle of attack is increased, the resistance coefficient decreases faster for the model with the stair-step arrangement of the modules, reaching its minimum for slope angles of about 30° and then increasing insignificantly up to the zenithal position of the modules. As for the model with the flat module panel, resistance coefficient decreases almost monotonously up to the zenithal position of the frame, and exceeds the respective resistance factor for the stair-step model practically over the entire range of angle variation. The most significant difference in resistance coefficients (up to 20%) is observed for the mid-positions of the modules (the angle of attack of 20–60°) which amount to up to 70% of all operating time of the power plants during a light day. This result highlights a significant advantage of the stair-step module arrangement over the flat type.

Table 1
The calculated values of the force of the models' resistance to the air flow for two values of the wind-stream speed.

V (m/s)	F (N)	
	Flat model	Stair-step model
8.2	1546	274
11.5	2594	547

Note. The calculation is made for existing platforms with CPV modules with dimensions of 6 × 6 m and an angle of attack $\beta = 45°$.

To illustrate the obtained results, Table 1 lists the comparative values of the resistance forces F calculated for the existing platforms with CPV modules for two wind-stream speeds. Experimental values obtained in the present work were used for the ratio (1) as the resistance coefficient c_x. The coefficient was assumed to be weakly dependent on the Reynolds number, which is normally the case for unstreamlined bodies.

It follows from the analysis of the table data that the stair-step model is highly superior to the flat one when it comes to reducing aerodynamic loads.

4. Conclusion

The conducted comparative experimental studies of the aerodynamic performance data of models of platforms with CPV modules revealed that the stair-step type of module arrangement on the platform has significant advantages over the model that is an integral flat panel. The reduction in the resistance coefficient c_x for a stair-step construction is observed for mid-positions of the modules that are characteristic for the longest operating conditions of solar power plants during a light day. The decrease in the resistance coefficient c_x (up to 20%) and the reduction in the mid-section of a model with a stair-step CPV module arrangement leads to a several-fold reduction in wind loads. The obtained result allows to predict a significant increase in the operating lifetime of a solar power plant with the highest possible efficiency on days with unfavorable wind conditions, and also to decrease the risk of fatigue effects in the materials of the frame and other mechanical parts of the tracker. This is a reason to recommend the proposed stair-step construction of solar tracker as preferable to the commonly used models with concentrator modules arranged as flat panels.

Additionally, we should note that modern aerodynamics methods make it possible to study the peculiarities of the wind-stream interaction with various models of CPV module arrangement on the solar tracker platform, and to conduct an objective qualitative and quantitative assessments of the advantages of various types of models.

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