THEORETICAL AND EXPERIMENTAL STUDY OF SOLAR CELL TEMPERATURE CONDITION IN SPACE PV MODULE WITH LINEAR FRESNEL LENSES

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ABSTRACT: The results of theoretical and experimental study of solar cell temperature condition in a linear lens concentrator PV module are presented. The theoretical approach was based on a set of a heat-balance equations for heat-spreading plane as well as for a lens panel and accounted for the radiation heat transfer between module elements and with environments. For numerical solution of the thermal conductivity equation describing the three-dimensional field of a heat sink the finite difference method was used. Experimental study of the PV module temperature condition has been carried out on a specially designed test bench on the basis of a vacuum chamber with an inner nitrogen cryogenic screen and a steady-state solar simulator.
Keywords: Concentrator Cell , PV Module, Characterization

1. INTRODUCTION

Actuality of the problem of correct temperature determination of the space concentrator PV module main components, first of all concentrator solar cells arranged on the heat sink, is caused by the effect of heating on the output electrical characteristics of solar cells and a PV module as a whole.

In the work presented are the results of theoretical and experimental study of solar cell temperature condition in a linear lens concentrator PV module.

The theoretical approach was based on a set of heat-balance equations for heat-spreading plane as well as for a lens panel and accounted for the radiation heat transfer between module elements and with environments. For numerical solution of thermal conductivity equation describing the three-dimensional field of a heatsink the finite difference method was used.

The PC software for theoretical simulation based on the developed theoretical approach allows calculating the thermal field of heat-spreading plane and operation temperature of solar cells.

Experimental study of the PV module temperature condition has been carried out on a specially designed test bench on the basis of a vacuum chamber with an inner nitrogen cryogenic screen and a steady-state solar simulator with a 100 mm dia. test area .

To investigate the PV module temperature conditions in vacuum a module fragment with linear lens concentrators and III-V heterostructure solar cells have been fabricated. Temperatures of the heat-spreading plane and of solar cells were measured by means of miniature chromel-capel thermocouples. To avoid any heat abstraction via module fixing tools the latter ones were made of thermal insulating material. An accuracy of temperature determination was ±1 ^{o}C. During the tests temperature distribution across the heat-spreading board have been monitored at different module electrical loads with the purpose to compare experimental results with the calculated data.

2. THEORETICAL CONSIDERATION

When a lens concentrator photovoltaic module is located in a space vacuum, sunlight is the main external factor determining the temperature regime of its elements (such as lenses, solar cells (SC), etc.) and hence influenced on the shape of the cell I-V curves which essentially depend on temperature and define the output photoelectrical characteristics of the module.

However, the possibilities to simulate in the laboratory the space operation conditions of the module to investigate its output characteristics are very limited. To carrying out correct thermo-vacuum tests of concentrator solar array it is necessary to illuminate the module under test with the use of a solar simulator, which reproduce not only spectrum (AM0) and irradiance (1367 W/m^2) but also the angular divergence of rays (32 min. of arc). Besides, the simulator must operate in continuous mode with good stability and uniformity of the flux on the area larger than the module size to ensure the steady thermal condition. Unfortunately, as we know, at present there are no solar simulators satisfying to above mentioned requirements and allowing to test a full-scale solar array. However, the temperature dependences of the solar cell I-V curves can be obtained indoors by means of a flash solar simulator with temperature-controlled stage for SC under test [1]. Using the experimental data obtained in such a way in the mathematical simulation model one can determine real operation temperatures of SCs and the output electrical characteristics of a full-scale module, if the model is correct enough.

A rated scheme of a concentrator module is presented in Fig.1. The module consists of a lens panel of four linear Fresnel lenses of a_x width and a_y length each and $a_x a_y$ in size thermoconductive board with printed circuits. SCs are mounted on the insulating bases and arranged in four linear photoreceivers. A rigid frame fixates the lens panel and the board in parallel to each other at a distance f.

The following assumption has been accepted for simulation model:

1. Concentrated irradiance is uniformly distributed over the SC surface with the average concentration ratio of K_{av}. Temperature is one and the same for all SCs.
2. Reflectance is absent from the SC surface with antireflection coating, from module frame elements, from the lens panel and the thermoconductive board faced to each other.
3. The lens panel and thermoconductive board have diffusely irradiating surface.

4. Conductive heat exchange between the lens panel, the thermoconductive board and the frame is absent.

5. Temperature gradient between the top and bottom surfaces of the lens panel is absent.

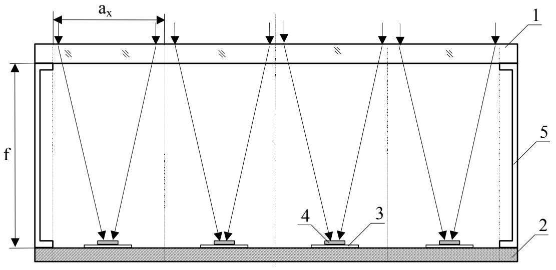

Figure 1: Rated module scheme: 1 – linear Fresnel lens panel; 2 – heat-spreading plane; 3 – flexible printed circuit card; 4 –solar cell; 5 – rigid frame.

Taking into account the mentioned above assumptions one may consider that only the lens panel and the thermoconductive board are participated in the heat exchange inside the module and between the module and environment. For this reason, on the first stage of mathematical simulation it is sufficient to restrict ourselves by consideration of only these elements. A rated module scheme corresponding to this description is presented in Fig. 2.

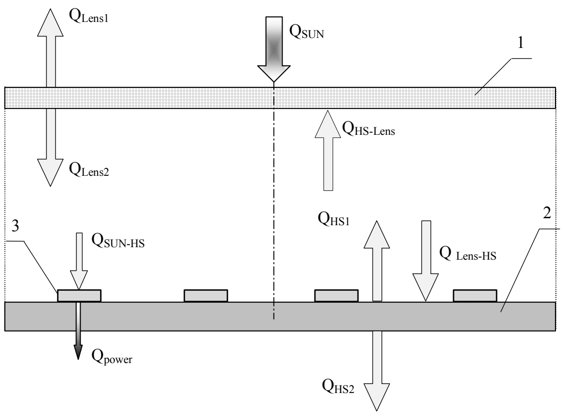

Figure 2: Scheme for calculation of heat abstraction from the module elements: 1 – lens panel; 2 – heat-spreading plane; 3 – solar cell; Q_{SUN} – thermal flow towards the lens panel from the Sun; Q_{Lens1}, Q_{Lens2} – thermal flows removed by irradiation from the top and bottom surfaces of the lens panel, correspondingly; Q_{HS1}, Q_{HS2} – thermal flows removed by irradiation from the top and bottom surfaces of the heat-spreading plane; $Q_{Lens\text{-}HS}$– thermal flow towards the heat sink from the lens panel resulted from a multiple diffusion reflection of the Q_{HS1} and Q_{lens2} flows from these elements; $Q_{HS\text{-}Lens}$ – thermal flow towards a lens panel from the heat sink resulted from a multiple diffusion reflection of the Q_{HS1} and Q_{lens2} flows from these elements; $Q_{SUN\text{-}HS}$ – thermal flow towards the heat-spreading plane as a result of sunlight passing through a lens and its absorption by the heat sink; Q_{power} – power flow removed from heat sink as a result of conversion of a part of concentrated sunlight into electricity.

The expressions for all thermal flows denoted in Fig. 2 have been obtained, and the thermal balance equations for the lens panel and the board allowing to determine their average integral temperature have been written. Also the expressions for the densities of thermal flow towards the lens panel and the board surfaces have been obtained to simulate the temperature field of the board with SCs.

The ultimate differences method was applied for the numerical solution of the thermal conductivity equation describing the three-dimensional stationary temperature field of the thermoconductive board. The developed mathematical model and software for PC have allowed to calculate the temperature field for the thermoconductive board as well as solar cells temperature, which are necessary for determining the output module parameters.

However, a number of assumptions accepted in developing the mentioned above simulation model result in some idealization of the considered heat exchange processes. To estimate the validity of the mathematical model for calculation of the board temperature field the experimental checking should be done.

3. EXPERIMENTAL SETUP

For simulation of the module thermal condition in space an experimental setup has been created (Fig. 3). In testing, first of all, the solar simulator should reproduce correctly the following solar irradiation parameters - spectrum (AM0), flux density (1367 W/m^2), angular divergence (32 min of arc) and uniformity of the flux in the test plane. The most suitable steady-state solar simulator meeting these requirements is a simulator Model-160 based on a high-pressure 5000 W xenon lamp. It reproduces spectrum close to AM0 in the wavelength range of 0.3-1.2 μm. The light flow density corresponding to the extraterrestrial solar constant is ensured by lamp current regulation. Nonuniformity of irradiance over the test area does not exceed 10%. The angular divergence confirmed at experimental checking is 32±1 min. of arc.

The thermal energy removal from the module under test can be correctly simulated by placing it in a vacuum chamber with a residual gas pressure of not higher than 10^{-3} Pa and with using the module fixing tools characterized by a very high thermal resistance. The thermal flows from external sources should be as low as possible. For this purpose in practice of thermo-vacuum tests the cryogenic screens are widely utilized. However, the unavoidable source thermal flow into vacuum chamber is a window through which the solar simulator irradiation is introduced to the test area with module. The influence of this flow can be lowered down by means of decreasing the window dimensions and placing the module as far from window as possible. The accuracy of module orientation normal to light beams should be not worth than 5-10 min. of arc. With allowance for this and also to meet the requirements to minimize the heat transfer from module the specially designed moving system with low thermal conductivity has been developed for the module assembly and alignment in a chamber.

For temperature measurements the chromel-capel thermocouples with wire diameter of 70 μm have been chosen, which minimize their effect on the thermal condition of an investigated object. Thermocouples calibration was carried out with allowing for the leads from vacuum chamber. Scheme and photo of the experimental setup are presented in Fig. 3 and Fig. 4.

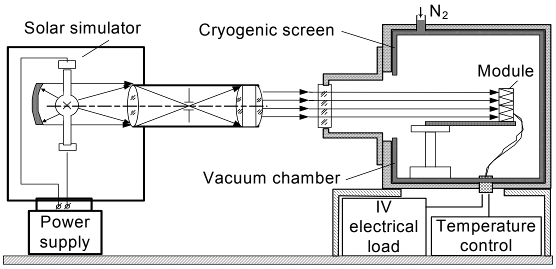

Figure 3: Scheme of the experimental bench for the solar module tests.

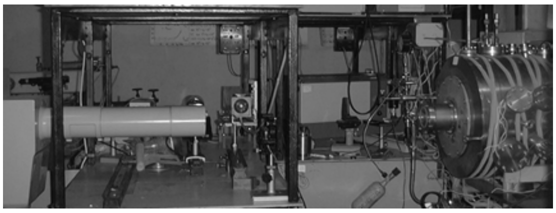

Figure 4: General view of the test bench for thermo-vacuum experiments.

Since solar simulator test area is limited be the size (100 mm dia.), the reduced test model of a full-scale module was designed and fabricated for thermo-vacuum experiments (Fig. 5). The design of a full-scale module was described in [2-4]. The basic elements of the module fragment construction are: 75 x 25 mm^2 lens panel with three linear lenses of 25 mm width each, a heat-spreading plane with linear photoreceivers and four ebonite fixing elements to arrange lens panel and heat sink at a distance of 30 mm.

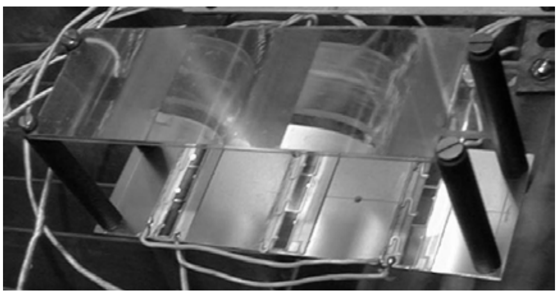

Figure 5: The module part for thermo-vacuum tests

Each linear photoreceiver consists of three dual-junction cells connected in parallel on a flexible printed circuit card. Photoreceivers were mounted on a 0.3 mm thick aluminum heat-spreading plane with the use of thermoconductive adhesive. To improve the heat abstraction from heat sink the latter one was covered by enamel with high heat-dissipating properties. The ebonite fixing elements were covered by aluminum foil to avoid its influence on the heat dissipation.

4. EXPERIMENTAL SEQUENCE

The experiments were carried out in the following order:

- the moving system with a module fragment placed on it is installed in a vacuum chamber, and electric circuits are connected to a vacuum plug. A module is aligned in the position of normal irradiation incidence on the lens panel;
- the vacuum chamber is evacuated and the cryogenic screen is filled with liquid nitrogen for its cooling;
- the steady-state thermal mode of the module fragment is controlled by the readings of a thermopiles signal. A visual control of the lens focal line position is performed through an inspection window of the chamber with a filter weakening irradiation;
- after reaching the equilibrium thermal state of the module fragment in the open circuit mode, its temperature is measured;
- measurements for obtaining a current-voltage characteristics of the module fragment are carried out, and the maximum power point is determined;
- the electrical load mode is transferred into the state of the maximum power, and after the steady-state mode is achieved the module fragment temperature is measured again.

Thus, during tests the problem of measurements of the module fragment temperature at different electrical load modes has been solved, and experimental results, which could be compared to mathematical calculation data have been obtained.

5. RESULTS

Fig. 6 presents the results of calculations of the heat-spreading plane temperature field of the module fragment operating in the maximum power mode. Dots mark the places of the thermocouple locations, which allow to compare more clearly the calculation and experimental results. Table 1 is summarizes the temperature values in the designated points obtained by calculations and experimentally for the open circuit voltage and maximum power modes.

Allowing for the measurement technique and calculation errors one can consider a fit of the calculated and experimental results achieved as quite satisfactory one.

Thus, the aims set for experiments have been achieved, and the obtained results allowed to confirm the validity of the improved mathematical model and of the procedure for calculation of the module heat-spreading plane temperature field.

6. CONCLUSION

The good fitting of the calculated and experimental results of the temperature fields for the heat-spreading plane with solar cells and the analysis of theoretical and instrumental errors of the used method for temperature determination have shown that the developed theoretical and experimental procedures and means allow to predict with a good accuracy the solar cell temperature condition of concentrator PV modules in space.

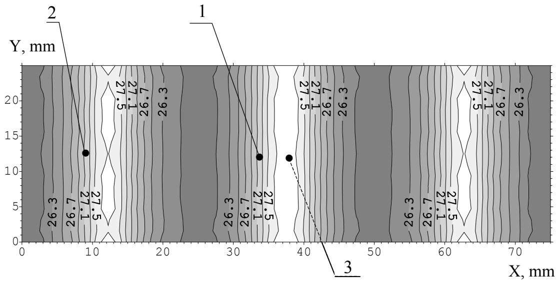

Figure 6: Temperature field of the top side of theheat-sink in the maximum power mode: 1, 2, 3 - thermocouples.

Table 1

Temperature values (^oC) obtained by calculations and experimentally for the open circuit voltage and maximum power modes.

Thermocouples	Module operational mode			
	Open circuit voltage		Maximum power	
	Calculation	Experiment	Calculation	Experiment
1	37.6	36.0	27.3	27.5
2	37.2	35.5	26.9	27.5
3	35.6	34.0	25.3	24.0

7. ACKNOWLEDGEMENTS

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