Photovoltaic module with sunlight concentrators: numerical simulation of steady state thermal regime

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Abstract. Numerical simulation of a steady state thermal regime of photovoltaic modules with sunlight concentrators has been performed. Contribution of different heat transfer mechanisms in the total thermal balance was analysed. The applicability of the single cell model for calculating the photovoltaic module thermal regime was investigated using an assumption of identity of all similar photovoltaic “Concentrator-Converter” pairs in a module and for a matrix comprising 3x3 units.

1. Introduction
Photovoltaic (PV) modules with sunlight concentrators are promising sources for electricity due to the greater conversion efficiency compared to that of conventional flat-plane solar arrays [1]. With increasing the efficiency of PV converters operating at high irradiances, a cooling problem arises to prevent their overheating and corresponding reduction of generated electric power. Operation of modules in conditions of elevated ambient temperatures and at weak convectional heat removal will be accompanied by an even greater increase in the converter operation temperature with a corresponding drop of power generation [2]. Preservation of a high operation efficiency of PV modules in a wide range of ambient temperatures requires carrying out a detailed analysis of the heat transfer processes, what will allow to optimize the module design and, particularly, the cooling system.

2. Investigation aim
The PV modules of SMALFOC design developed in the Ioffe Institute [3] are a construction of 128 units of “Fresnel lens (FL) – solar cell (SC)” type (Fig.1a). Dimensions of each composite “silicone on glass” Fresnel lens are 60x60 mm² at the carrying glass thickness of 4 mm. The distance between a FL and a SC is determined by the lens focal distance and is 100 mm. The metallic 1 mm thick heat sink with SC is fixed under a protecting glass by an adhesive tape 0.1 mm thick. The metal outer surface is covered with a laminate 0.8 mm thick. The SC dimensions in plane are 3.0x3.4 mm² with thickness of 150 μm (Fig. 1b).
Numerical simulation of the whole complex of heat and mass transfer processes in a PV module is a rather time consuming task, first of all, due to the necessity to create a detailed mesh for each SC. However, allowing for the identity of all units and construction symmetry, consideration of the whole module is surplus one, and a detailed thermal analysis can be performed for a limited internal space of module [4]. In the present work, two geometric models are considered, which present a PV module part: a unit with a FL and a SC and a matrix comprising of 3x3 similar units. Vertical boundaries of the models are formed by planes passing through the peripheral boundaries of lenses. In the models, all constructive elements determining the peculiarities of heat transfer are reproduced. The main tasks of the given investigation were:

1. Analysis of the contribution of different heat transfer mechanisms to the total energy balance in a unit;
2. Analysis of the mutual thermal influence of adjacent SCs and a possibility for consequent analysis of thermal modes within an individual unit.

The calculation was carried out for typical PV module operation conditions: windless at an ambient temperature of \( T_0 = 25 \, ^\circC \), what ensures low convective heat transfer coefficients on the module surface. The module is oriented normally to the direct sunlight flux.

3. Mathematical model
In the mathematical model the following assumptions were done:

1. The SC internal multilayer structure is not considered and substituted for bulk germanium;
2. Heat-transfer in a FL is simulated in a form of thermal resistance approximation;
3. Sunlight absorption in glasses and in a SC is simulated as a volume heat source. In this case, in the region of concentrated radiation, accounted is only the total amount of energy, but the Gauss-like distribution of irradiance is not taken into consideration;
4. In a thin layer of air between the metallic heat sink and the protecting glass, heat transfer is carried out due to heat conduction and radiation, neglecting the convection nature.

In the mathematical model, three mechanisms of heat transfer between the structural elements of the photovoltaic module are taken into account:

1. Thermal conductivity in a lens concentrator, protective glass, SC, heat sink base, laminate;
2. Natural convection in the air gap between the lens and the protective glass;
3. Radiation heat transfer from opaque surfaces.

Heat transfer in the air gap between a lens panel and protecting glass takes place due to natural convection and radiation. At considered conditions, the Rayleigh number determining the character of
air motion under action a temperature gradient is \( Ra = \frac{g \beta \Delta T l^3}{\nu a} \approx 10^6 \). Here \( g \) – acceleration due to gravity, \( \beta \) – coefficient of thermal expansion of air, \( \Delta T \approx 50 \, \text{K} \), \( l \) – height of the air gap, \( \nu \) – kinematic viscosity of air, \( a \) – thermal diffusivity of air. All physical properties were taken at \( T = 20 \, \text{°C} \). Small value of Rayleigh number tells on a laminar mode of convective motion and determines the choice of an air motion model.

On the external surface of the lens panel and laminate, the boundary condition consists of convective heat exchange with the environment and of radiation from the firmament \( T_0 = 0.0552 T_{ext}^{3/2} = 283 \, \text{K} \). The heat-transfer coefficients for mentioned construction units are determined by the empirical formula [5]:

\[
\alpha = \frac{ah}{\lambda} = 0.54 n(Gr \cdot Pr)^{0.25},
\]

where \( n = 1.3 \), \( Gr = \frac{g \beta \Delta T l^3}{\nu^2} \) – Grashof number, \( Pr = \frac{\nu}{\alpha} \) – Prandtl number, and the calculated heat transfer coefficients \( \alpha = 7 \, \text{W/m}^2 \cdot \text{K} \) for the lens block surface. \( n = 0.7 \) and \( \alpha = 4 \, \text{W/m}^2 \cdot \text{K} \) for the laminate surface.

On the vertical surfaces, a symmetry boundary condition is used. On the vertical walls of a real PV module a convective heat-transfer with the environment takes place, as in the case of the horizontal surfaces. This will result in some decrease in the SC temperature compared to the given calculation.

Lens panel heating due to absorption of sunlight energy is simulated by the volume heat source \( Q_{abs} = Q_s (1 - \rho) (1 - \tau) / h = 3900 \, \text{W/m}^3 \), where \( Q_s = 1000 \, \text{W/m}^2 \) – density of the incident sunlight, \( \rho = 0.077 \) – reflection coefficient, \( \tau = 0.983 \) – transmission coefficient, \( h = 4 \, \text{mm} \) – glass thickness. Heating of the protecting glass in the area of the focused sunlight is calculated in the similar way: \( Q_{abs}^g = S_l / S_g Q_s^r (1 - \rho) (1 - \tau) / h = 1.26 \cdot 10^6 \, \text{W/m}^3 \), where \( Q_s^r = Q_s (1 - \rho) \tau \) – density of the radiation flux passed through the lens panel, \( S_l / S_g \) – ratio of areas.

Absorption of the incident light by a SC is simulated by the volume heat source \( Q_v = Q_{se} - Q_s = 1.35 \cdot 10^9 \, \text{W/m}^3 \), where \( Q_{se} = Q_s (1 - \rho)^2 \tau^2 / h = 1.94 \cdot 10^9 \, \text{W/m}^3 \) – the incident sunlight, and \( Q_v = -Q_v K \eta_F \eta_F^0 \left( 1 - \beta_w (T - T_0) \right) / h = 5.87 \cdot 10^8 \, \text{W/m}^3 \) – portion of energy converted into electricity. Here \( K = 95% \) – coefficient of interception of the focused radiation by a SC, \( \eta_F = 85% \) – Fresnel lens efficiency, \( \eta_F^0 = 40% \) – SC efficiency at \( T_0 = 298 K \), \( \beta_w = -0.13% \) – SC efficiency temperature coefficient.

The simulation was performed in ANSYS FLUENT software. The computational mesh consists of hexahedral elements with gradual variation of the edge length. The total amount of elements is about 800 000 for the model of separate unit (Fig.2), and is about 7 000 000 for the matrix of 3x3 units. The mesh was generated with allowing for specific features of geometric models and of considered heat transfer processes. The most important calculation area – SC – contains 14 elements for each side and of 2 ones for thickness.

Simulation of radiation heat transfer between opaque construction elements is performed by means of the heat-exchange calculation method adopted for grey surfaces on the basis of angular coefficients [6]. The emissivity for all constructive elements is \( \varepsilon = 0.9 \).
4. Results
The performed preliminary calculations have shown that the air convection in the gap between the lens panel and the protecting glass is unsteady. For this reason, temperature distribution in a FL and in a lens panel changes with time. However, the minimum and maximum values remain constant and are determined by the global energy balance. In the steady state thermal mode, the peculiarities of the convection do not affect the temperature distribution in a protecting glass, in a SC and in a heat sink. The final calculation was carried out from the initial state till the moment of establishing constant average temperature in a SC.

Table 1. Heat fluxes through surfaces of a PV module unit cell.

| Heat flux direction                  | Heat amount, W | Radiant flux portion |
|-------------------------------------|----------------|----------------------|
| Heat flux towards the bottom surface|                |                      |
| SC → Heat sink                      | 2.06           | 0%                   |
| Heat sink → Laminate                | 1.43           | 0%                   |
| Laminate → Environment              | 1.43           | 0%                   |
| Heat flux towards the top surface   |                |                      |
| Heat sink → Air                     | 0.52           | 3%                   |
| Air → Protecting glass              | 0.52           | 3%                   |
| Protecting glass → Air gap          | 0.64           | 67%                  |
| Air gap → Lens block                | 0.64           | 67%                  |
| Lens block → Environment            | 0.70           | 0%                   |

Table 1 presents heat fluxes through surfaces in the individual unit model determining the global heat balance and also the energy portion transferred by radiation. Through the rest surfaces, the heat fluxes are negligibly small. The main source of heating is a SC. Then, the largest part of heat goes to the environment through the heat sink, and the smallest one – through the lens panel. In the given PV module design, the main thermal resistance limiting heat transfer to the environment is the laminate layer, a thin air layer between the heat sink and the protecting glass and also the air gap between the glasses.

Fig. 3 shows the temperature field in the vertical section of a PV module in the vicinity of a SC. The protecting glass element in the area of the focused sunlight has the largest temperature of 72°C. This is caused by a low glass thermal conductivity (6), by presence of an air gap (4) with a large thermal resistance $l/\lambda$, where $l$ – gap length, $\lambda$ – thermal conductivity, and also by small heat transfer due to natural convection and radiation from its top surface. It should be noted that the peculiarities of the protective glass (6) heating determine the structure and intensity of the convective flow in the air gap (7).
Fig. 3. Temperature field in the module vertical section in the vicinity of a SC. (1) – laminate, (2) – metallic heat sink, (3) – SC, (4) – thin air layer, (5) – element of the protecting glass in the region of focused sunlight, (6) – protecting glass, (7) – air gap.

Fig. 4 shows temperature distribution on the SC surface. It should be pointed out that, in the given calculation, the heat release in a SC is uniformly distributed over the volume. Allowing for the real Gaussian profile of irradiance will result in even greater temperature field heterogeneity. In the single-unit model, the average (over the cell volume) SC temperature was 72 °C, and in the 3x3 model, the mean temperature for all the SCs was 73 °C.

Fig. 4. Temperature distribution on the SC surface.

Despite the nonstationary nature of convective flow and due to a substantial thermal resistance between the air gap and heat dissipating base (see the heat fluxes in Table. 1), the temperature distribution over the heat sink is not changed in time. Fig. 5 shows the temperature field in the heat sink for the two models. It is evident that the field structure is similar, although there is a slight difference at the mount site of the individual SC.
Fig. 5. Temperature distribution in the metallic heat sink: a) single cell model, b) 3x3 units model.

The heating of the Fresnel lens occurs due to internal heat source in the lens panel and radiation coming from the protective glass in the form of convective flow. The first two factors determine the average temperature, and its distribution depends on the structure of the convective flow and reflects the temperature field in the protective glass (6) (see Figure 3). The temperature drop across the surface of the Fresnel lens significantly influences the quality of focusing due to the temperature dependence of the refractive index of silicone [7]. In both models, the maximum difference does not exceed 3 °C.

5. Conclusion
The temperature field in the internal volume of the module, bounded by a lens panel and a back plane protective glass, is calculated using the approximation for a single unit of the photovoltaic module and for the 3x3 units set accounting typical operating conditions. The main heat transfer mechanisms and construction elements limiting efficient transfer of the excess heat towards the environment have been determined. It has been shown that the unit cell model allows reproducing the heat and mass transfer in a PV module with a sufficient accuracy.

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