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SOLAR THERMOELECTRIC ENERGY CONVERTERS

Results of computer design of a solar thermoelectric generator with a solar energy concentrator whose walls serve for rejection of heat from the hot junctions of a thermoelectric energy converter have been presented. With the aid of object-oriented computer simulation the distributions of electric potential and temperature in a thermoelectric generator with regard to temperature dependences of the kinetic coefficients of materials, as well as contact resistances have been obtained. Design calculation of a thermoelectric converter has been made assuring optimal mode of solar into electric energy conversion which yielded the generator efficiency of 4.67 %. The cost of electric energy power generated by such a converter is 0.5 $/W, which makes it competitive in the market of solar energy converters.

Key words: solar energy, thermoelectric generator, computer simulation.

Introduction

General characterization of the problem. Creation of alternative renewable power sources is one of the most relevant issues today, since it contributes to solving the ecological problems of thermal contamination of the Earth leading to change of its climate.

The Sun is the largest source of renewable energy on the Earth. Its radiated power is $4\cdot10^{23}$ kW of energy, of which about 10^{14} kW of power falls on the Earth. In so doing, 1 m^2 of the area perpendicular to solar rays receives as little as about 1 kW of energy [1]. Such solar radiation density is insufficient to provide the necessary temperature differences in thermoelectric power converters. In this case it is reasonable to use special solar concentrators in the form of paraboloids, Fresnel reflectors or a combination of plane mirrors [1]. Thermoelectric converters are characterized by long service life and high reliability which makes promising their use in combination with solar concentrators [2, 3].

Analysis of the literature. The first solar thermoelectric generators (STEG) were made by the close of the XIX century. Among them, a generator developed by Russian astronomer V.K. Tserasky that activated the electric bell [1].

In the 1950s, due to the advent of novel material for thermocouples (*p-Zn-Sb*, *n-Bi-Sb*), interest in the possibility of direct solar radiation into electric energy conversion was rekindled [1, 4, 5]. Using a flat-plate collector in the form of a blackened copper plate as a concentrator of thermal energy yielded the generator efficiency about 1.05 % [4]. The generator with an optical concentrator that focused solar radiation on thermocouple hot junctions achieved the efficiency of 3.35 % [4]. Modern developments of solar thermoelectric generators [6-11] have been made both with and without optical concentrators of solar energy. Thus, paper [6] describes theoretical and experimental investigations of STEG with a plane concentrator of thermal energy. The authors assert that they have succeeded to achieve the generator efficiency of 4.6 %.

The purpose of this work is computer design of a solar thermoelectric generator with a solar energy concentrator whose walls simultaneously serve to reject heat from the hot junctions of thermoelectric energy converter, to achieve maximum efficiency and minimum cost of thermoelectric energy conversion which will make STEG competitive in the market of solar energy converters.

Physical, mathematical and computer models of STEG

The operating efficiency of a thermoelectric generator is determined as the efficiency of thermoelectric modules, as well as the efficiency of solar radiation into thermal energy conversion. Design optimization of STEG in this case consisted in maximum decrease of thermal losses and creation of temperature conditions for the realization of maximum efficiency of a thermoelectric converter [1].

Solar thermoelectric generator has three main components which are a solar radiation to thermal energy converter, a thermoelectric converter and a heat rejection device [1].

A paraboloid with a specular surface was used as a radiation concentrator. The receiving surface of the generator is a cut ball-shaped connecting conductor of the thermoelectric converter hot junctions (Fig. 1). The thermocouple cold junctions are in thermal contact with a paraboloid which is simultaneously the cold heat exchanger. For protection from atmospheric influence the paraboloid internal part is insulated with protective glass [12].

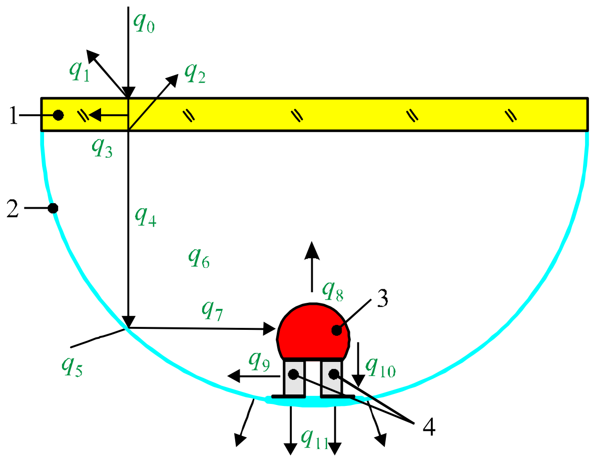

Fig. 1. Physical model of STEG. 1 – protective glass, 2 – solar parabolic concentrator, 3 – thermoelectric converter interconnects, 4 – thermoelectric energy converter.

The operating principle of STEG is as follows. Solar radiation passes through the glass protective surface 1, gets to the specular surface of parabolic concentrator 2, is reflected and focused on the interconnects 3, where it is converted into thermal energy. Part of the heat that passes through thermoelectric converter 4 is converted into electric energy. Heat from the cold thermocouple junctions is dissipated on parabolic concentrator 2 which also serves as the cold heat exchanger.

In Fig. 1 q_0 is the solar radiation flux that gets onto the protective glass, q_1 is the radiation reflected from the external glass surface, q_2 is radiation reflected from the internal glass surface, q_3 is radiation absorbed by the glass, q_4 is radiation that passed through the glass, q_5 is heat absorbed by the concentrator, q_6 is the heat lost on the concentrator internal side due to free convection and radiation, q_7 is the radiation focused on the interconnects of the hot junctions, q_8 is the heat losses on the receiving surface, q_9 is the heat losses due to convection and radiation on the lateral surface of thermocouple, q_{10} is the heat flowing through the thermocouple, q_{11} is the heat flux rejected from the concentrator surface due to free convection and radiation.

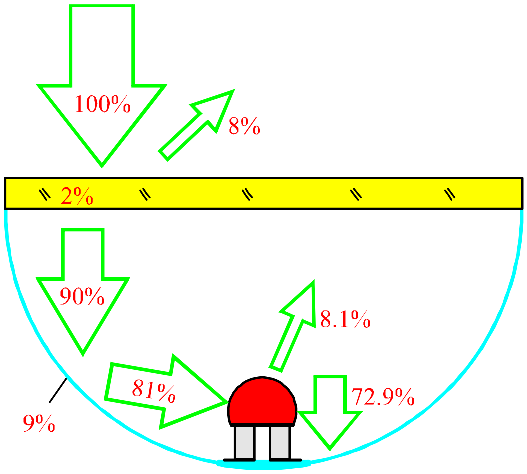

Fig. 2. Energy losses on the structural elements of STEG.

Theoretical calculations have shown that solar energy losses on STEG structural elements are as follows:

- 8 % of energy is reflected from the glass surface;
- 2 % is absorbed by the glass;
- 9 % is absorbed by the aluminum concentrator;
- 8.1 % is reflected from the thermocouple element receiving surface;
- 72.9 % of energy passes through the thermocouple legs.

For simplification of the problem the fluxes $q_1 - q_3$ were not taken into account. For the calculations we employed known transmission characteristics of the glass without account of absorbed heat q_3 spent for its heating up. It was also assumed that the volume restricting the protective glass and the mirror was filled with air.

To find temperature distribution in STEG, one should solve the thermal conductivity equation

$$q = \nabla(-\kappa \cdot \nabla T), \qquad (1)$$

where κ is the thermal conductivity, ∇T is the temperature gradient and q is the heat flux.

The boundary conditions:

– on the concentrator specular surface :

$$q = \varepsilon_1 \cdot q_4 - \alpha \cdot \Delta T_1 + \varepsilon_1 \cdot \left(G_1 - \sigma \cdot T_1^4\right), \qquad (2)$$

where ε_1 is the emissivity factor of the concentrator internal side, α is the heat exchange coefficient, ΔT_1 is the temperature difference between the concentrator internal side and the environment, σ is the Boltzmann constant, T_1 is the temperature of the concentrator internal side.

– on the receiving surface:

$$q = q_7 \cdot \left(2 \cdot \varepsilon_2 - 1\right) - \alpha \cdot \Delta T_2 + \varepsilon_2 \cdot \left(G_2 - \sigma \cdot T_2^4\right), \qquad (3)$$

where ΔT_2 is the temperature difference between the receiving surface and the environment, T_2 is the receiving surface temperature, ε_2 is the emissivity factor of the receiving surface.

– on the boundaries of thermal contact between the interconnects and thermocouple legs

$$q = \kappa \cdot \frac{\Delta T_4}{l}, \qquad (4)$$

where κ, l is the thermal conductivity and height of thermocouple legs, ΔT_4 is the temperature difference between the hot and cold thermocouple junctions.

– on the boundaries of lateral surfaces of thermocouple legs and the environment

$$q = \alpha \cdot \Delta T_3 + \varepsilon_3 \cdot \sigma \cdot \left(G_3 - \sigma \cdot T_3^4\right), \quad (5)$$

where ΔT_3 is the temperature difference between the lateral surface of thermocouple and the environment, T_3 is the temperature of thermocouple lateral surface, ε_3 is the emissivity factor of thermocouple lateral surface.

– on the concentrator external surface

$$q = \alpha \cdot \Delta T_5 + \varepsilon_4 \cdot \sigma \cdot \left(T_5^4 - T_0^4\right) \quad (6)$$

where Δ_{T5} is the temperature difference between the concentrator external side and the environment, ε_4 is the concentrator emissivity factor, T_5 is the concentrator temperature, T_0 is the ambient temperature, G is the incoming radiation heat flux for each separate boundary

$$G = G_m + F_{amb}\sigma T_{amb}^4, \quad (7)$$

where G_m is the radiation value from other boundaries of structural elements, F_{amb} is the field of vision factor equal to field of vision part which is not subject to other surfaces, T_{amb} is the temperature at a distant point in the directions included to F_{amb}.

Finding a solution for Eq. (1) with the boundary conditions (2 – 6) is a complicated problem whose analytical solutions are too awkward and not subject to analysis [13].

This problem was solved with the use of Comsol Multiphysics computer program of object-oriented simulation [14]. Computer model of solar thermoelectric generator created with its help permitted calculation of its physical fields, determination of major energy characteristics and optimization of STEG design.

Computer model of STEG (Fig. 1) consists of an aluminum parabolic concentrator (mirror) 2, a blackened copper receiving pad 3 shaped as a cut ball, and a thermocouple 4. The thermocouple cold junctions are in thermal contact to the parabolic concentrator which forms the cold heat exchanger.

Computer simulation was performed with the following initial conditions: solar radiation density is 1000 W/m^2, ambient temperature is 300 K. Rejection of heat from the cold heat exchanger was done by free convection and radiation to the environment. In conformity with the real physical and optical properties [15, 16] of solar thermoelectric generator structural elements, the following values of absorption and reflection factors were taken, namely: transmission factor of the glass is 0.9, reflection factor of the aluminium mirror is 0.9, emissivity factor of the receiving pad ε_2 and the external side of the parabolic concentrator ε_4 is 0.9, emissivity factor of the lateral surface of thermocouple legs ε_3 and the concentrator internal surface ε_1 is 0.1. Standard Bi_2Te_3 based thermoelectric material was used (Fig. 3) [17, 18]. Design optimization of STEG was made with respect to the parabolic concentrator diameter D, the concentrator thickness d and the thermocouple thermal resistance. The initial value of D was selected as 20 mm, as long as exactly with this diameter the focus remained under the protective glass. The concentrator diameter D was increased so that the paraboloid focus remained unvaried. The initial value of the concentrator thickness d = 0.2 mm.

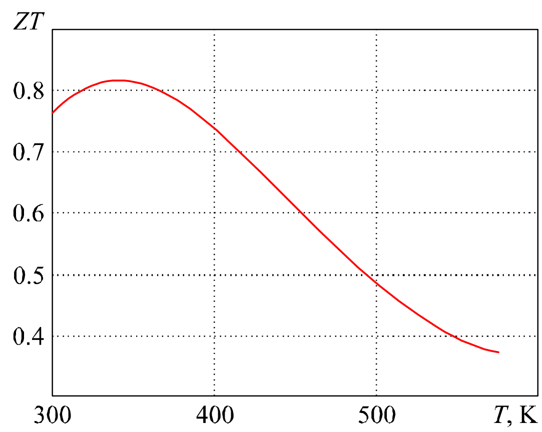

Fig. 3. ZT of Bi_2Te_3 based thermoelectric material.

For each design variant the cross-section area (thermal resistance) of thermocouple legs was optimized so as to assure the hot temperature 300 °C, as long as exactly at this temperature the maximum efficiency for selected thermoelectric material is achieved.

Optimization results

Computer simulation has resulted in the values of temperature on the cold thermocouple junctions of STEG (Fig. 4), the temperature distributions on the cold heat exchanger (Fig. 5), as well as the values of EMF and electric power. The efficiency values of the solar thermoelectric generator have been calculated for different paraboloid diameters and thicknesses (Fig. 6). It has been established that STEG efficiency reaches 4.65 %. Also, the effect of contact electric resistances has been studied that results in reduction of STEG energy characteristics by 8 %.

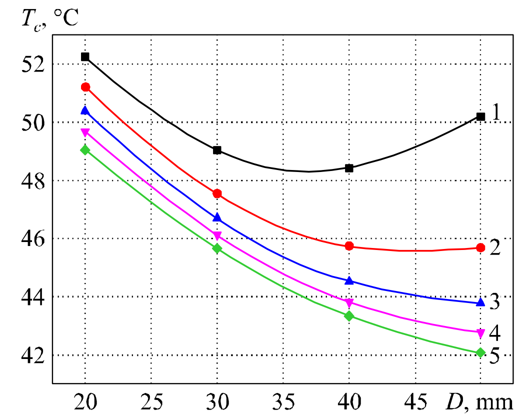

Fig. 4. Plot of thermocouple cold temperature T_c versus the concentrator diameter for its different thicknesses d.
1 – d = 0.2 mm; 2 – d = 0.4 mm;
3 – d = 0.6 mm; 4 – d = 0.8 mm; 5 – d = 1 mm.

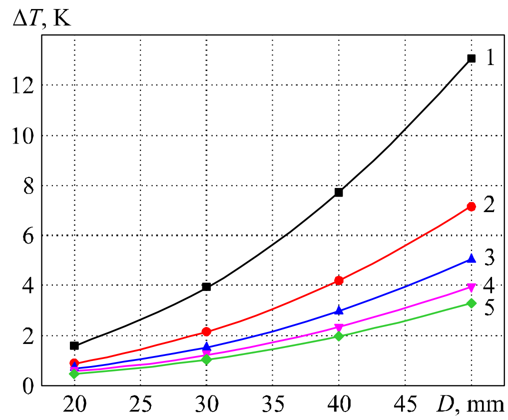

Fig. 5. Plot of ΔT between the centre and edge of the aluminum concentrator versus its diameter for different concentrator thicknesses d.
1 – d = 0.2 mm; 2 – d = 0.4 mm; 3 – d = 0.6 mm;
4 – d = 0.8 mm; 5 – d = 1 mm.

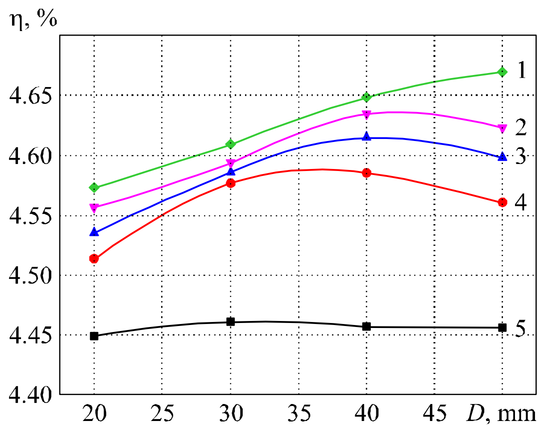

Fig. 6. Plot of STEG efficiency versus the concentrator diameter for its different thicknesses d.
1 – d = 1 mm; 2 – d = 0.8 mm; 3 – d = 0.6 mm;
4 – d = 0.4 mm;5 – d = 0.2 mm.

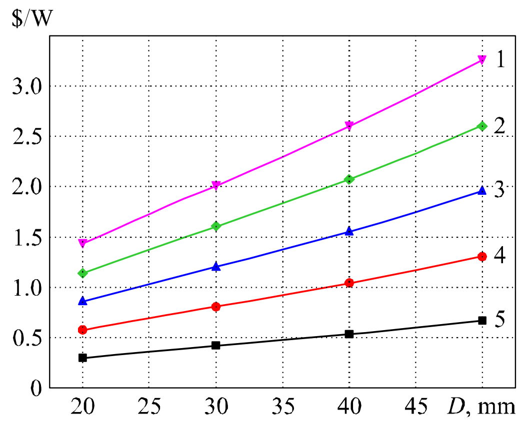

Fig. 7. Plot of the cost of 1 W generated by STEG versus the concentrator diameter for its different thicknesses d. 1 – d = 1 mm; 2 – d = 0.8 mm;
3 – d = 0.6 mm; 4 – d = 0.4 mm; 5 – d = 0.2 mm.

The generator economic parameters have been estimated. Fig. 7 shows the plots of 1 W of electric power generated by STEG versus its geometric dimensions. As can be seen from the plot, for the concentrator thickness 0.2 mm and diameters D from 20 to 35 mm, its cost is about 0.5 $/W. Such parameters make STEG competitive in the market of solar energy converters.

It should be noted that further increase in STEG efficiency is possible due to the use of thermoelectric materials with higher *ZT* value, mirrors with better reflection and protective glass with better transmission, as well as selective coatings for reduction of radiation losses.

Conclusions

1. Object-oriented computer simulation has been used for design optimization of a solar thermoelectric generator which allowed increasing the generator efficiency to the value of 4.67 %.
2. It has been established that account of contact resistances in computer model allows improving the accuracy of calculations of the energy characteristics of a solar TEG by 8 %.
3. The possibility of creating STEG has been established. The cost of 1 W of its generated electric energy power can be about 0.5 $, making it competitive in the market of solar energy converters.

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