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# THE HARNESSING OF THERMOELECTRIC GENERATORS UNDER ASPHALT

*This paper presents the schematic and operating principle of thermoelectric converter of thermal energy of soils. The physical and mathematical models of thermal generator using asphalt pavement as a concentrator of solar radiation thermal energy and those of soil thermal generator have been described. Computer models for such cases have been created. Analysis of simulation results has been made and a promising outlook for using thermoelectric generators under asphalt pavement as low-power supplies has been shown.*

**Key words:** thermoelectric generator, asphalt pavement, low-power supply.

## Introduction

*General characterization of the problem.* To achieve essential changes in energy saving is one of the key tasks of economic policy in the overwhelming majority of countries worldwide. Under the conditions of growing prices for energy resources, the use of state-of-the-art energy-efficient technologies yields tangible economic benefits and competitive advantages.

*Fig. 1. Appearance of Altec-8027.*

Power consumption level of many modern electronic devices (sensors, light-emitting diode lamps, etc) is from tens of milliwatts to several watts, leading to a search for efficient low-power supplies.

One of the variants of solving this problem is the use of thermoelectric power supplies utilizing the thermal energy of soil [1, 2].

Physical fundamentals for creation of such soil thermoelectric generators (STEG) have been created in the Institute of Thermoelectricity [3]. Based on the results of theoretical studies, samples of STEG have been developed and manufactured [3]. One of the variants of STEG is shown in Fig. 1.

Powers generated by soil thermoelectric generators become commensurate to power consumption of low-power electronic devices. With regard to a number of known advantages of STEG, their use as power supplies with service life up to 30 years becomes increasingly attractive [3, 4].

Ref. [5, 6] describe systems of energy harvesting and thermal into electric energy conversion that can be installed on the surface of road pavement and used for power supply to various sensors, road signs illumination, etc.

*The purpose of this work* is to study the possibilities of improving thermoelectric generators with a concentrator of solar radiation thermal energy in which capacity asphalt pavement is considered.

## Physical model of soil TEG

A physical model and operating principle of thermoelectric generator using the thermal energy of soil is shown in Fig. 2.

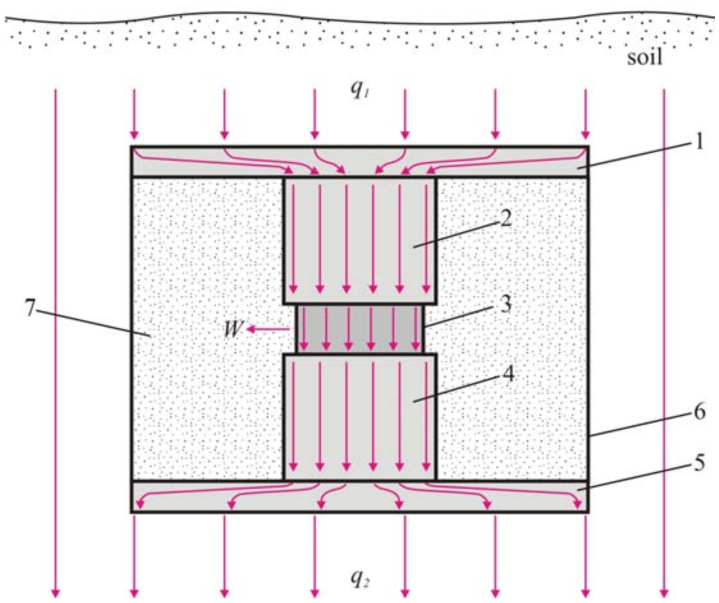


*Fig. 2. A physical model of thermal generator arranged in soil.*

Thermoelectric generator arranged in soil is composed of heat-absorbing collector 1, heat conductor 2, high-performance multi-element thermopile 3, heat conductor 4, heat sink 5, case 6 and thermal insulation 7. The operating principle of thermal generator is as follows: heat flux $q$ existing in soil comes to heat-absorbing collector 1, is fed by heat conductor 2 to the hot junctions of thermopile 3, removed by heat conductor 4 to heat sink 5 and scattered to lower layers of soil. To reduce thermal losses, case 6 of thermal generator is filled with heat-insulating material. Passing through the thermopile, heat creates temperature gradient thereupon which results in the generation of electric power $W$. It is noteworthy that throughout the day a direction of heat flow can change to the opposite. Therefore, structural components 1, 2 and 4, 5 of the generator are functionally interchangeable. This model is concerned with a quasi steady-state case whereby the dynamic processes in soil are considered to be slow. Under these conditions the heat capacity of power supply is ignored.

## Mathematical description of a physical model of soil TEG

Let us consider a cylinder-shaped soil thermal generator of height *H* and diameter *D*, with its heat-absorbing pad arranged at the depth *h* under the surface of soil [3].

In order to simplify a mathematical description of a physical model of soil thermal generator, we shall consider our model in a cylinder system of co-ordinates *r*, *z* where *z* axis is directed from the surface deep into soil.

To find the distribution of temperatures *T (r, z)* and thermal flow *q* in soil in the presence of STEG, one should first solve the thermal conductivity equation:

$$\frac{1}{\chi}\frac{\partial T(r,z)}{\partial t}=\frac{\partial^2 T(r,z)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z)}{\partial r}+\frac{\partial^2 T(r,z)}{\partial z^2} \quad (1)$$

With the boundary conditions

$$-k_0\frac{\partial T(r,z)}{\partial z}=q_0,\ z=0, \quad (2)$$

$$T(h,r<D/2)=T_и, \quad (3)$$

$$T(H+h,r<D/2)=T_l, \quad (4)$$

$$-k_0\int_s\frac{\partial T(r,z)}{\partial z}dS=\frac{1}{R_{\mathrm{STEG}}}(T_и-T_1),\ z=h, \quad (5)$$

$$-k_0\frac{\partial T(r,z)}{\partial r}=0,\ h<z<h+H,\ r=D/2, \quad (6)$$

where $q_0$ is the value of specific heat flux on the surface; $T_и$, $T_l$ are unknown temperatures of the receiving pad and lower end face of STEG to be determined; $R_{\mathrm{STEG}}$ is thermal resistance of STEG.

The physical meaning of the above boundary conditions is as follows: condition (2) assigns heat flux on the surface of soil; (3) and (4) express isothermality conditions of cylinder STEG end faces, (5) is a condition of thermal balance of STEG receiving pad, and (6) is a condition of adiabatic insulation of its lateral surface. The distribution of temperatures *T (r, z)* in soil in this case is a solution of exterior boundary-value problem for Eq. (1).

The electric power output of STEG in the general case can be written as:

$$W=f\left[T(r,z),k_0(r,z),\sum_{i=1}^{N}B_i,Z^*,L(r,z)\right], \quad (7)$$

where *T (r, z)* is temperature distribution in soil with STEG arranged in it; $k_0(r,z)$ is thermal conductivity coefficient of soil; $\sum_{i=1}^{N}B_i$ is an algebraic sum of *N* components of thermal balance in soil; $Z^*$ is thermoelectric figure of merit of thermopile in STEG; $L(r,z)$ is spatial coordinate of STEG arrangement in soil that characterizes its geometrical dimensions.

## Computer simulation of soil TEG

To study the work of soil thermoelectric generator under the steady state (the temperature on the surface of soil was 300 K, and at the depth of 55 cm – 285 K), a three-dimensional computer model of such generator was created. The computer model was built with the use of the Comsol Multiphysics software package [7] which permits simulation of thermophysical processes occurring in soil and TEG.

Calculation of temperature and heat flux density distributions in the thermoelectric generator and soil was done by finite-element method (Fig. 3) the essence of which is that object under study is split into a large number of finite elements, and in each of them the value of function is sought for that satisfies given differential equations of second order with the respective boundary conditions. The accuracy of solving the formulated problem depends on the level of splitting and is assured by the use of a large number of finite elements [7].

Object-oriented computer simulation was used to obtain temperature distributions (Fig.4) in soil thermoelectric generator under the steady state.

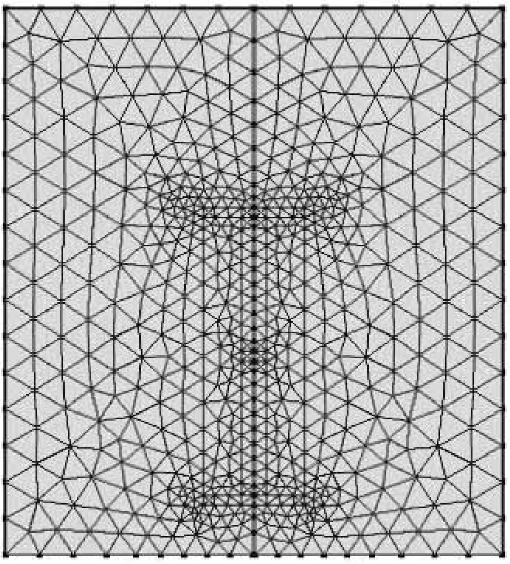

*Fig. 3. Finite-element method mesh.*

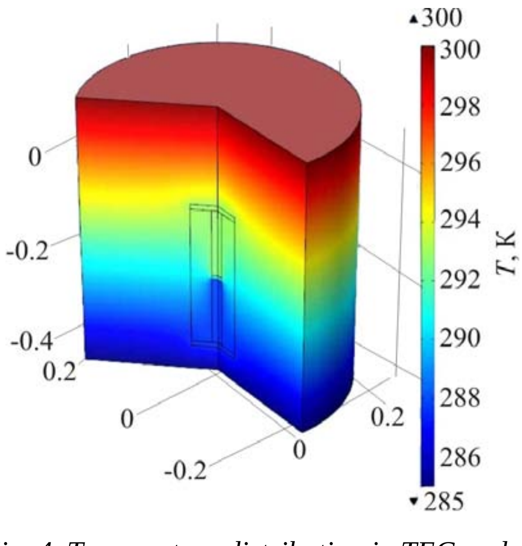


*Fig. 4. Temperature distribution in TEG and soil.*

## Physical model of TEG under asphalt pavement

One of the simplest variants to improve the operating efficiency of STEG seems to be its arrangement under asphalt that has much better coefficient of solar energy absorption.

A physical model of thermoelectric generator under asphalt pavement is represented in Fig. 5.

According to the physical model, an area of road pavement is a structure of five layers (asphalt pavement 1, concrete floor 2, a layer of broken stones 3, a layer of sand 8, soil 9) whose thermophysical characteristics (thermal conductivity $\kappa$, density ρ) and layer thicknesses are given in Table 1.

Soil thermoelectric generator is a cylinder bar which consists of heat-absorbing collector 4, thermal insulation 5, thermopile 6 and heat sink 7. The generator dimensions: Ø10×30 (cm).

The collector and heat sink of STEG are made of aluminum and consist of heat-absorbing (heat-dissipating, respectively) plates of size Ø10×1 (cm) and heat conductor of size Ø2.256×13.48 (cm). Mineral wool with thermal conductivity coefficient $\kappa_{insul}$= 0.032 $W \cdot m^{-1} \cdot K^{-1}$ is used as thermal insulation.

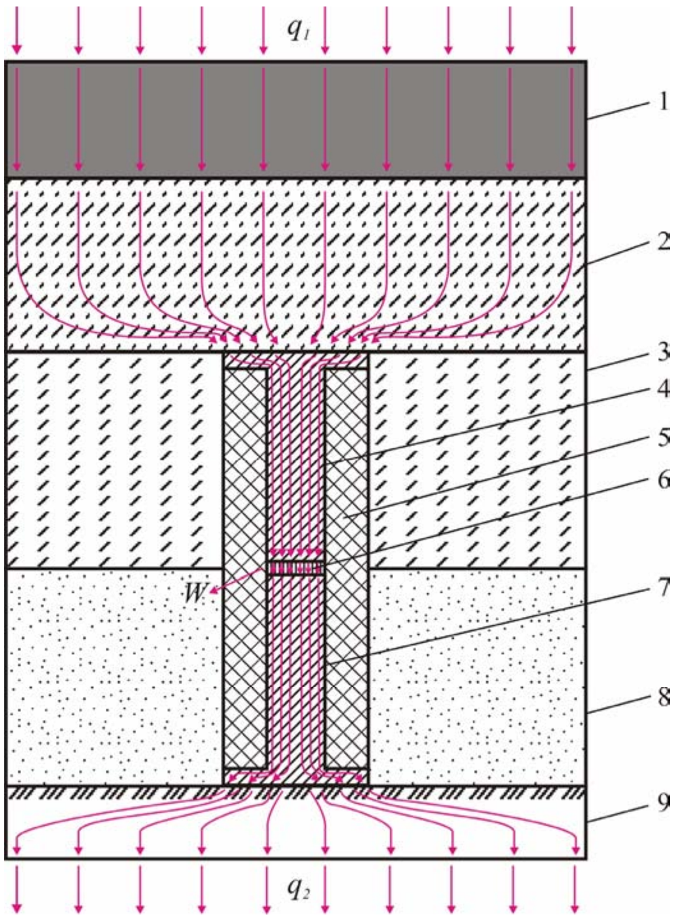


*Fig. 5.A physical model of STEG under asphalt:*

*1 – asphalt pavement, 2 – concrete floor, 3 – layer of broken stones, 4 – heat-absorbing collector, 5 – thermal insulation, 6 – thermopile, 7 – heat sink, 8 – layer of sand, 9 – soil.*

As is known, the EMF value of thermopile is mainly affected by temperature difference ΔT between its surfaces. Therefore, to achieve the objective of this paper, a bulk homogeneous sample of

$Bi_2Te_3$ semiconductor material of thermal conductivity $\kappa_t = 1.8\ W\cdot m^{-1}\cdot K^{-1}$ was considered as a thermopile. The thermoelectric converter is a cylinder bar of geometric dimensions Ø2.256×1.04 (cm).

*Table 1*

*Thermophysical properties of physical model components*

| | Thermal conductivity, $\kappa$ ($W\cdot m^{-1}\cdot K^{-1}$) | Density, $\rho$ ($kg\cdot m^{-3}$) | Density of layer, m |
|---|---|---|---|
| Asphalt pavement | 1,05 | 2100 | 0,08 |
| Concrete floor | 1,51 | 2400 | 0,12 |
| Broken stones | 0,064 | 200 | 0,15 |
| Sand | 0,35 | 1600 | 0,15 |
| Soil | 0,4 | 1800 | 0,05 |

In this physical model, asphalt pavement, concrete floor, broken stones, sand and soil will be considered to be homogeneous media and the fact that their thermal conductivity varies as a function of ambient conditions, namely humidity, temperature, material structure, etc. will be disregarded. Thermal processes are assumed to be slow, so a quasi-steady state is considered whereby TEG heat capacity is ignored.

## Mathematical description of a physical model of TEG under asphalt pavement

The amount of heat passing through asphalt pavement ($Q_1$) is the difference in the amount of heat coming to asphalt surface ($Q_0$) and the heat reflected from it. The reflection factor of asphalt pavement is 7 %, hence the expression for $Q_1$ will be as follows:

$$Q_1 = 0.93 \cdot Q_0 . \tag{8}$$

Heat flows passing through the asphalt $Q_2$, concrete $Q_3$ and aluminum heat conductor $Q_4$ are given by the expressions:

$$Q_2 = \kappa_{asf} \cdot \frac{S_{asf}}{L_{asf}} \cdot (T_2 - T_1)\,,\ Q_3 = \kappa_{bet} \cdot \frac{S_{bet}}{L_{bet}} \cdot (T_3 - T_2)\,,\ Q_4 = \kappa_{Al} \cdot \frac{S_{Al}}{L_{Al}} \cdot (T_4 - T_3)\,, \tag{9}$$

where $S_{asf}$, $S_{bet}$, $S_{Al}$, $L_{asf}$, $L_{bet}$, $L_{Al}$, $\kappa_{asf}$, $\kappa_{bet}$, $\kappa_{Al}$ are the areas of heat-absorbing pads, layer thickness and thermal conductivity of asphalt, concrete and aluminum heat conductor, respectively; $T_1$, $T_2$, $T_3$, $T_4$ are the temperatures of heat-absorbing asphalt pad, “asphalt-concrete” contact, “concrete-heat-absorbing pad of aluminum heat conductor” contact, “heat-absorbing pad of aluminum heat conductor-thermoelectric converter” contact, respectively.

Heat flows on the hot $Q_{hteb}$ and cold $Q_{cteb}$ side of thermoelectric converter for the case of homogeneous isotropic material:

$$Q_{hteb} = \alpha_{teb} \cdot T_4 \cdot I - \frac{1}{2} \cdot I^2 \cdot \sigma_{teb} \cdot \frac{L_{teb}}{S_{teb}} - \kappa_{teb} \cdot \frac{S_{teb}}{L_{teb}} \cdot (T_4 - T_5)\,, \quad (10)$$

$$Q_{cteb} = \alpha_{teb} \cdot T_5 \cdot I + \frac{1}{2} \cdot I^2 \cdot \sigma_{teb} \cdot \frac{L_{teb}}{S_{teb}} - \kappa_{teb} \cdot \frac{S_{teb}}{L_{teb}} \cdot (T_4 - T_5)\,, \quad (11)$$

where $\alpha_{teb}$, $\sigma_{teb}$, $\kappa_{teb}$ are the Seebeck coefficients, electric conductivity and thermal conductivity of thermoelectric converter, respectively; $I$ is current generated by converter; $S_{teb}$, $L_{teb}$ are the area and height of thermoelectric converter, respectively; $T_4$, $T_5$ are "hot" and "cold" side temperatures of thermoelectric converter, respectively.

Knowing the hot and cold side temperatures of thermoelectric converter, it is possible to obtain the values of heat flows on these sides. And, with the knowledge of the flows, we can calculate converter power ($W$) by the following relationship:

$$W = Q_{hteb} - Q_{cteb}\,. \quad (12)$$

## Computer simulation of TEG under asphalt pavement

To investigate the work of thermoelectric generator under asphalt pavement in the steady state (the temperature on the surface of soil was 300 K, and at the depth of 55 cm – 285 K), a three-dimensional computer model was created using the Comsol Multiphysics software package.

Computer simulation allowed obtaining temperature distributions (Fig. 6) in thermoelectric generator under asphalt pavement in the steady state.

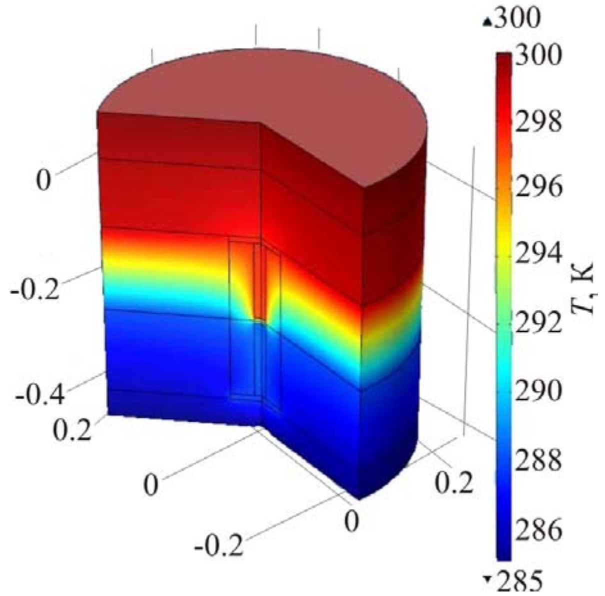


*Fig. 6. Temperature distribution in TEG under asphalt pavement.*

## Discussion of simulation results

Figs.7 and 8 show isotherm lines obtained by computer simulation for thermoelectric generator in soil and under asphalt pavement.

From the analysis of Figs.7 and 8 it is evident that asphalt pavement brings about the increased concentration of isothermal lines passing through thermoelectric converter. In this way a greater temperature difference is obtained, which yields higher thermopower of generator. Thus, the value of temperature difference on the converter of thermal generator under asphalt pavement was $\Delta T$=7.73 K (with a general difference of 15 K), and on thermoelectric generator in soil under identical conditions - $\Delta T$=4.43 K. As is known, the value of generated electric power of thermoelectric converter is directly proportional to its thermopower value which is given by the relationship

$$E = \alpha \cdot \Delta T, \tag{13}$$

$\alpha$ is the Seebeck coefficient, $\Delta T$ is temperature difference between the upper and lower surfaces of thermal converter.

Thus, the electric power of thermoelectric generator under asphalt pavement was 1.55 mW which is almost twice greater than the electric power of soil generator (≈0.8 mW) under similar conditions.

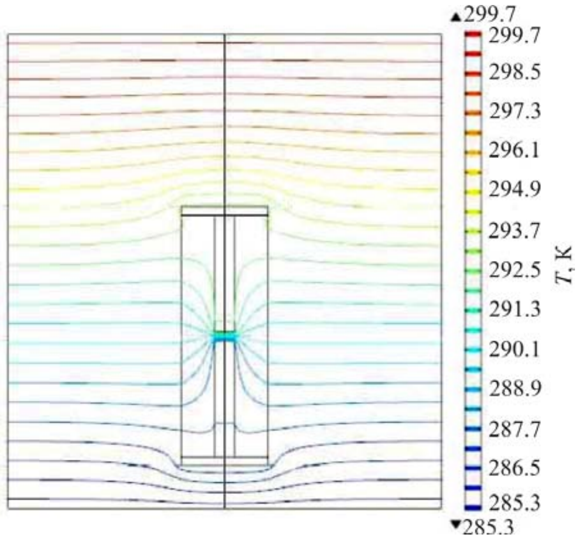


*Fig. 7. Isotherm lines for thermoelectric generator in soil.*

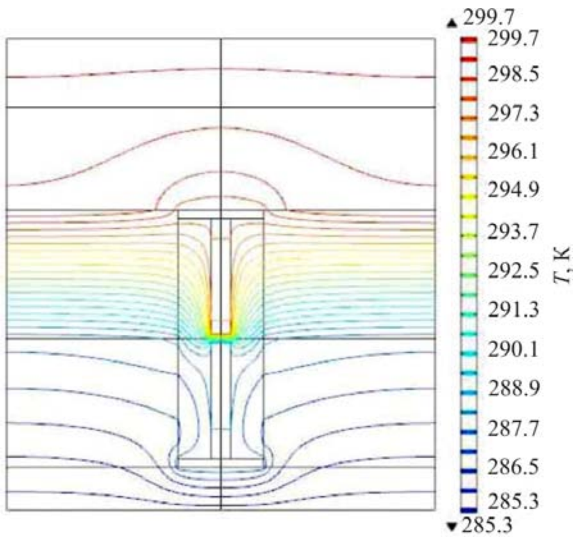


*Fig. 8. Isotherm lines for thermoelectric generator under asphalt pavement.*

Thus, due to the use of heat-concentrating materials, such as asphalt on the surface of heat-absorbing pad of STEG, its power can be increased considerably, which is important for low-power electronic equipment supply. Placing such generators opens up the prospects for their use in road asphalt pavement with a view to supply various sensors, light-emitting diode lamps for roadway lighting, road signs illumination, etc.

## Conclusions

1. A physical model and computer simulation of thermoelectric generator in the steady state using temperature difference in soil have been developed for the case of placing the generator under asphalt pavement.
2. Based on a specific example of generator Altec-8027 it has been confirmed that the presence of asphalt pavement improves the energy parameters of generator, the voltage and power approximately 1.7 fold.

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