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ULTIMATE POTENTIAL OF UNDERGROUND THERMOELECTRIC GENERATORS

Computer model was created for the determination of temperature distribution in soil with a dynamic effect on the Earth surface of solar radiation thermal power. Temperature distributions in sandy soil for different geographic coordinates were obtained. Specific electric power of underground thermoelectric generator using temperature difference in soil which can be obtained throughout the year and on a monthly basis in different geographic coordinates was determined.

Key words: temperature distribution in soil, underground thermoelectric generator, specific electric power.

Introduction

General characterization of the problem. Underground electric energy sources are attractive for autonomous power supply to low-power devices. First of all it concerns remote and hard-to-reach areas where maintenance of special equipment is complicated. Despite very low electric powers, such energy sources may become indispensable for power supply to special-purpose equipment, protective and guard systems, electronic devices of autonomous weather stations, etc. They offer the advantage of being hidden from unauthorized persons that may affect their performance capability or render them inoperable. They do not feel a significant impact of weather conditions, which makes underground energy sources more attractive as compared to photoelectric.

Underground thermoelectric generators [1 – 6] are promising low-power energy sources which use thermal processes occurring in soils and on their surface as a source of heat.

The main indicator of soil thermal state is its temperature which is determined by solar energy input and the thermal properties of soil itself. The key thermal processes, as noted in [2], take place in the near-surface soil layer.

Soil temperature is a dynamic value which changes at different depths of soil profile in different periods of time. It is characterized by daily and annual periodicity [7, 8]. With depth, the amplitude of temperature variation is reduced and the diurnal dynamics at the depth of 50 cm decays almost completely. Annual variation, just as diurnal, is related to the input and consumption of heat and is mainly governed by radiation factors. Most frequently, the annual variation of soil temperature is tracked by its mean monthly values.

In the northern hemisphere maximal mean monthly temperatures of soil surface are observed in July-August, when heat input is the greatest, and minimal – in January-February. The difference between maximal and minimal mean monthly temperature throughout the year is called the amplitude of annual variation and it depends most of all on geographic latitude. The annual temperature mode of soils has large vibration amplitude and is expressed to a greater depth than diurnal one.

In [9], the laws of thermal processes occurring in soils were analyzed for evaluating the efficiency of underground thermoelectric generators. The resulting temperature distributions in different types of soil at different geographic latitudes made it possible to determine maximum possible specific electric powers of underground thermoelectric generator.

The purpose of this paper is to obtain temperature distributions in sandy soil in different geographic coordinates (latitude, longitude) and to determine specific electric power of underground thermoelectric generator which can be obtained throughout the year and on a monthly basis.

Problem formulation and its solution

To obtain temperature distribution in soil, a physical model of soil area shown in Fig. 1 was considered.

The model considers thermal processes in soil with a dynamic effect on its surface of solar radiation thermal power $q_s(t)$ (W/m^2) within 24 hours. The properties of soil are characterized by the values of its heat capacity C_p, density ρ and thermal conductivity κ.

The model takes into account the diurnal variation of ambient temperature $T_{amb}(t)$, heat exchange between soil area with the environment due to heat transfer, convection and radiation. At certain depth l the temperature of soil T_0 is considered constant.

The sought-for values are temperature distribution in soil $T(t,z)$ and heat flux density $q(t)$ versus depth z and the time of day t.

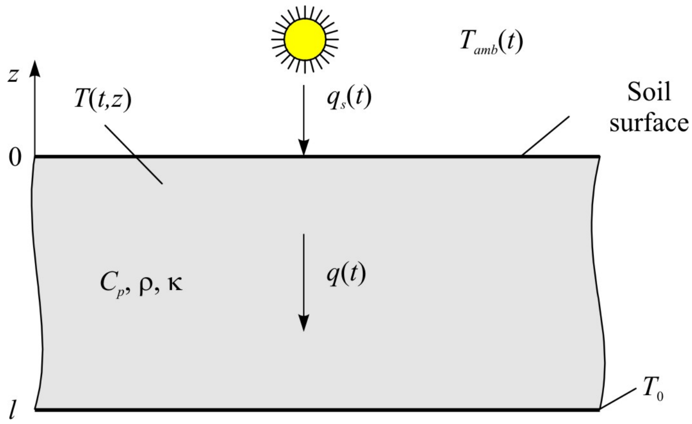

Fig. 1. Physical model of soil area.

Temperature distribution in soil stratum is described by the nonstationary Fourier's law:

$$\rho C_p \frac{dT}{dt} + \nabla\left(-\kappa \nabla T\right) = 0 . \quad (1)$$

Convective heat exchange on the soil surface is described by equation

$$-\vec{n}\vec{q} = q_0 , \quad (2)$$

where $\vec{n}$ is normal to soil surface, $\vec{q}$ is heat flux through soil surface, q_0 is heat flux from soil surface due to convection:

$$q_0 = h\left(T_{amb} - T\right), \quad (3)$$

where h is coefficient of convection.

Radiation from the soil surface is described by the Stephan-Boltzmann law

$$q_r = \sigma\varepsilon\left(T_{amb}^4 - T^4\right), \tag{4}$$

where σ is the Stephan-Boltzmann constant, ε is surface emissivity factor.

The boundary conditions for Eq. (1) – (4) are:

– at $z = 0$ thermal flux on the soil surface $q = (1 - k_s)q_s(t)$, where k_s is soil albedo, $q_s(t)$ is solar radiation thermal power [10];

– at $z = l$, $T = T_0$.

Computer model for solving Eq. (1) – (4) was created in Comsol Multiphysics environment [10]. Calculation of temperature distribution in soil was done by the finite element method the essence of which is that the object under study is broken up into a large number of elements, and in each of them the value of function is sought for which satisfies given second-order differential equations with the respective boundary conditions. The accuracy of solving the formulated problem depends on the level of breaking up and is assured by using a large number of finite elements.

The formulated problem was solved with the use of heat transfer with surface-to-surface radiation computer module, which is intended for simulation of heat transfer processes due to thermal conductivity, convection and radiation. The position of the Sun and its power were assigned in the external radiation source module with indication of geographic coordinates of object under study, the date and time of investigation.

Ambient temperature $T_{amb}(t)$ was assigned as the function of time according to averaged data of climatological observations within 2015 [11] for geographical points of various latitudes. Table 1 lists the cities with corresponding geographic coordinates that were selected for investigation.

In the model, the temperature of soil at the depth of 2 m is considered to be constant and equal to + 7 °C [8]. Calculations were performed for one day of each month in the year (the 15 th).

Table 1

Geographical coordinates of points under investigation and cities for which the data of climatological observations were taken

Point №	Latitude, degree		Longitude, degree		Time zone, UTC	City	Country
	North	South	West	East			
1	2	3	4	5	6	7	8
1.	60		150		-9	Seward	USA
2.	60		120		-7	Edmonton	Canada
3.	30		90		-6	New Orleans	USA
4.	0		60		-3	Boa Vista	Brazil
5.		30	60		-3	Reconquista	Arhentina
6.	30			0	+0	Adrar	Algeria
7.	60			30	+3	Saint-Petersburg	Russian Federation
8.	30			30	+2	Cairo	Egypt
9.		0		30	+3	Kampala	Uganda

Table 1 continued

1	2	3	4	5	6	7	8
10.		30		30	+2	Durban	SAR
11.	60			60	+5	Perm	Russian Federation
12.	30			60	+3	Zahedan	Iran
13.	60			90	+7	Krasnoyarsk	Russian Federation
14.	30			90	+8	Thimphu	Bhutan
15.	60			120	+9	Yakutsk	Russian Federation
16.	30			120	+8	Hangzhou	China
17.	0			120	+8	Makassar	Indonesia
18.		30		120	+8	Kalgoorlie	Australia
19.	60			150	+11	Magadan	Russian Federation
20.		30		150	+10	Dubbo	Australia

In the paper, the analysis was performed for sandy soil whose thermophysical characteristics are given in Table 2.

Table 2

Thermophysical characteristics of sandy soil

Thermal conductivity, W/(m·K)	Heat capacity, J/(kg·K)	Density, kg/m^3	Reflection factor (albedo), %	Radiation factor, %
0.52	770	1200	30 – 35	0.9

Analysis of the results and their discussion

Computer simulation was used to obtain temperature distributions in sandy soil with a dynamic effect on its surface of solar radiation thermal power at different depths from the surface to the depth of 2 m every 10 cm in different geographic coordinates.

As was stated in [9], the temperature on the soil surface has the greatest amplitude of vibration. With the depth increase, these vibrations decay and at the depth of 50 cm they are practically absent. So, subsequent calculations were performed just for the temperature difference created between the soil surface and its value at the depth of 50 cm.

Specific thermal flux passing through the soil surface to the depth of 50 cm can be determined by means of expression:

$$q = \kappa \frac{(T_2 - T_1)}{L}, \tag{5}$$

where κ, L are thermal conductivity and sandy soil layer thickness, respectively; T_1, T_2, are temperatures of the soil surface and at the depth of 50 cm, respectively.

To calculate the efficiency of underground thermoelectric generator, one can use the expression

$$\eta = \frac{1}{4}\frac{(T_2 - T_1)}{T_2} Z \frac{(T_2 + T_1)}{2}, \qquad (6)$$

where Z is the figure of merit of thermoelectric material which for calculations was $3 \cdot 10^{-3}$ K^{-1}. According to [12], the divergence between the efficiency in formula (6) and the exact values usually does not exceed 10 %.

Thus, from the formula

$$W = \eta q, \qquad (7)$$

one can determine specific electric power W that can be obtained from underground thermoelectric generator.

Integration by the formula

$$A = \int_0^{\tau} \eta q(t) dt, \qquad (8)$$

of the electric power (7) yields the value of total specific energy that can be obtained from underground generator within the day ($\tau = 24$ h). The calculations were based on the mean monthly values of ambient temperature, so the specific energy during the month was determined as the product of produced diurnal energy on the number of days in respective month. Fig. 2 gives the results of calculation of specific electric energy that can be produced by underground thermoelectric generator throughout the year in sandy soil for different latitudes.

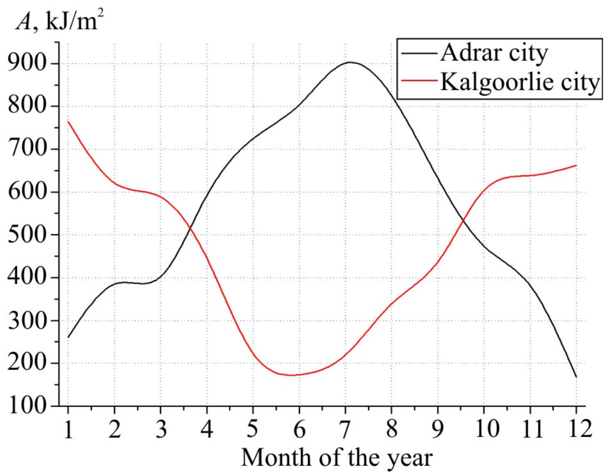

Fig. 2. Annual variation of specific electric energy of underground thermoelectric generator at the North (Adrar city) and South (Kalgoorlie city) latitudes.

Fig. 2 clearly shows annual amplitude variations and seasonality at different latitudes.

Fig. 3 gives mean monthly values of specific electric energy that can be obtained from underground thermoelectric generator along equatorial zone at different geographic longitudes (*a*) and along the latitude for 30^0 and 120^0 of East longitude (*b*), where sign «-» corresponds to West longitude and South latitude.

Analyzing Fig. 3 *a* it may be noted that the mean value of specific electric energy is 538 kJ/m^2 in which case the deviation along equatorial zone does not exceed 4 %. Fig. 3 *b* shows a clear latitude dependence of specific electric energy, which is attributable to the value of thermal radiation obtained throughout the year as a result of the position of the Sun. The slight deviation of the values from the longitude can be explained by climatic conditions of certain region.

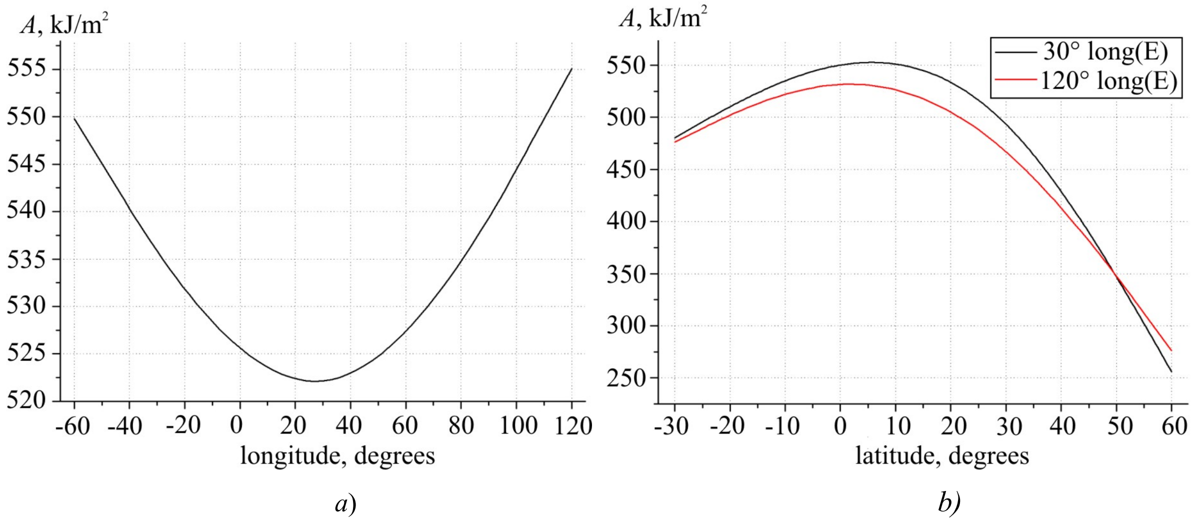

Fig. 3. Mean monthly values of specific electric energy that can be obtained from underground thermoelectric generator along equatorial zone at different geographic longitudes (a) and along latitude for 30^0 and 120^0 East longitude (b).

Fig. 4 shows the distribution of specific electric energy that can be obtained from underground thermoelectric generator throughout the year in different geographic coordinates.

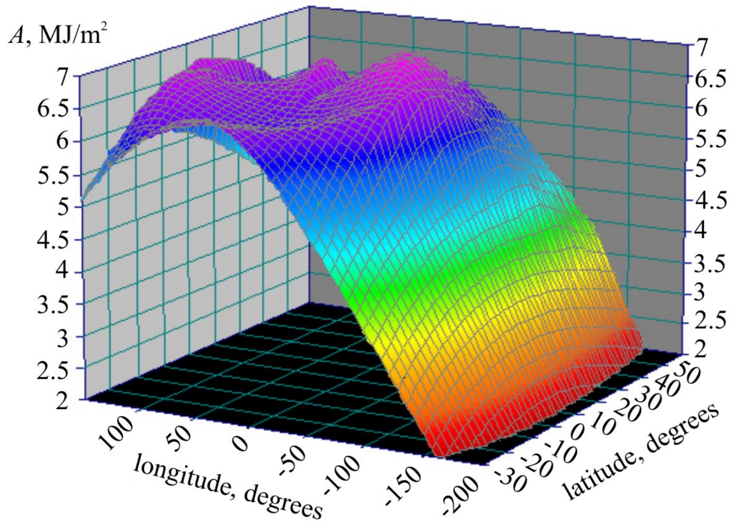

Fig. 4. Specific electric energy that can be obtained from underground thermoelectric generator throughout the year in different geographic coordinates.

On the basis of Fig. 4 one can determine the approximate values of electric energy that can be obtained from underground thermoelectric generators in any region which allows evaluating the efficiency and expedience of their use.

Conclusions

1. Maximum possible values of specific electric energy that can be obtained throughout the year and on a monthly basis from underground thermoelectric generators in different geographic coordinates were calculated which makes it possible to evaluate the efficiency of their use.
2. It was established that the mean value of specific electric energy throughout the year along equatorial zone is 538 kJ/m^2 and the deviation at different latitudes does not exceed 4 %.

3. It was determined that the mean value of specific electric energy along latitude is 400 kJ/m^2 and the deviation at different longitudes does not exceed 6 %.

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