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Power supply installation for remote rural settlements with solar thermoelectric generator

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Abstract. An analysis of scientific studies has been carried out, which presents thermoelectric technologies based on solar energy that can satisfy not only the need for electricity generation, but also contribute to energy saving and environmental protection. The results of theoretical and experimental studies on the development of power supply systems based on thermoelectric generators in combination with photovoltaic panels, solar concentrators and heat pipes are also presented, allowing us to conclude that the creation of solar thermoelectric generators is relevant. The authors have developed a design and presented a description of the power supply installation operation with a solar thermoelectric generator and heat pipes transmitting thermal energy from a solar concentrator through a solid-state thermal storage to a thermoelectric generator. Expressions are given for calculating the main thermal characteristics of the elements of the proposed installation with a solar thermoelectric generator (solar concentrator and solid-state thermal storage), as well as the efficiency factor and output electric power of the thermoelectric generator.

1 Introduction

One of the effective solutions to the problem of increasing the efficiency of energy supply systems for remote rural settlements is the use of autonomous power installations based on renewable energy sources (RES), including using solar energy. The use of such power supply systems will eliminate the need to organize the transportation, storage and combustion of local fossil fuels, which will also have a positive impact on the environmental situation.

In modern conditions, RES can be used in small power installations that do not require significant capital investments. To date, the issue of power supply for remote settlements is solved mainly with the help of gasoline, diesel or gas generators, which negatively affects the environmental situation in the region.

In this regard, the practical implementation of small-scale power installations based on decentralized and combined power supply sources using local and RES, which are more efficient for a number of consumers, and in some cases without alternative, is of great importance.

For the production of electricity around the clock, solar concentrators have thermal storages in their scheme. The combination of these devices allows storing thermal energy for

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a long time period and using energy from an alternative source for energy supply to consumers.

A review of thermoelectric technologies based on solar energy is carried out together with an analysis of the shortcomings of existing systems [1]. Typical applications of thermoelectric cooling and thermoelectric power generation using solar energy are considered. Thermoelectric technologies based on solar energy can meet not only the needs for electricity generation, but also contribute to energy saving and environmental protection.

The results of theoretical and experimental studies of solar hybrid systems with thermoelectric generators (TG) are presented in [2, 3]. A solar hybrid system with photovoltaic panels, solar collectors (heaters) and a TG without the use of a solar concentrator (SC), as well as three systems with a different combination of SC and TG, were studied. The use of a thermosiphon cooling circuit designed to remove heat passing through the TG is justified. The performance of hybrid solar systems with a TG was also evaluated.

A TG design with the use of a loop heat pipe and a passive cooling device for heat dissipation due to natural convection is proposed. The developed design of the TG properly matches its output voltage with the storage battery and ensures the maximum generated power [4].

An experimental prototype of TG with SC and a discrete numerical model for evaluating the effectiveness of the proposed system are presented. The model takes into account the temperature dependence of the thermoelectric materials properties and predicts the best possible performance and design of the proposed system [5].

A hybrid solar installation for heating water with a TG based on bismuth telluride Bi_2Te_3 is proposed, using a double-shell evacuated glass tube, a finned heat pipe and a mini-composite parabolic concentrator [6, 7]. In order to optimize the design, a mathematical model of the proposed installation has been developed. The mathematical model takes into account the complex influence of the main parameters on the maximum output power and energy conversion efficiency of the proposed installation.

In the study, a functional scheme of the installation was developed, consisting of a multi-purpose thermoelectric system, which is powered directly from solar photovoltaic panels [8]. The heating mode is designed to heat rooms, while the cooling mode has been adapted to an adiabatic box that can cool food and beverages. A positive environmental effect from the practical implementation of such an installation was also noted.

Based on the review of previous scientific studies, a conclusion was made about the relevance of the development of a solar TG using a solid-state thermal storage (SSTS) and heat pipes. Such combined TG designs have not been considered before.

2 Materials and methods

Previously, the authors developed the design solar TG for power supply for remote settlements using solar energy, as an alternative to traditional diesel generator sets. The advantage of using thermoelectric modules in the proposed design in comparison with photovoltaic panels is justified. The main disadvantage of the proposed design is the presence of a liquid (oil) storage tank with a heat exchanger and a circulation pump. The presence of these elements leads to a complication of its operation and an increase in operating costs for servicing the oil storage tank and the circulation circuit of the TG due to the additional consumption of electricity by the circulation pump.

Previous works of the authors were also devoted to modeling the thermal state of the heat storage elements of the electric thermal storage (ETS) [9] and calculating the thermal characteristics of the ETS [10]. The results of experimental studies of the thermal state of heat storage elements in the heat charging and heat emission operation modes of ETS are presented [11].

Patent search on the websites of the Eurasian Patent Organization, as well as Rospatent and Google patents was used to analyze existing developments in this field of study. The analysis of the available calculated expressions was also performed to determine the main functional elements thermal characteristics of the proposed power supply installation (SC, heat pipes and SSTS), as well as the efficiency factor and output electric power of the TG.

3 Results and discussion

The design of the power supply installation with solar TG for remote rural settlements with SSTS and heat pipes (Pat. RU 2788266 C1) has been developed (Figure 1).

Solar TG for remote rural settlements contains a thermoelectric assembly 1, consisting of a thermoelectric module 2, an air cooler 3, a condenser zone 4 heat pipes of the SSTS discharge circuit, the SSTS 5 in thermal insulation 6, heat pipes 7 of the SSTS charging circuit, heat pipes 8 circuit for discharging the SSTS, an evaporator of the evaporation zone of heat pipes 11, installed at the focus of the reflector 10 of the SC 9, a control unit (CU) 12, a set of batteries 13 and an inverter (I) 14.

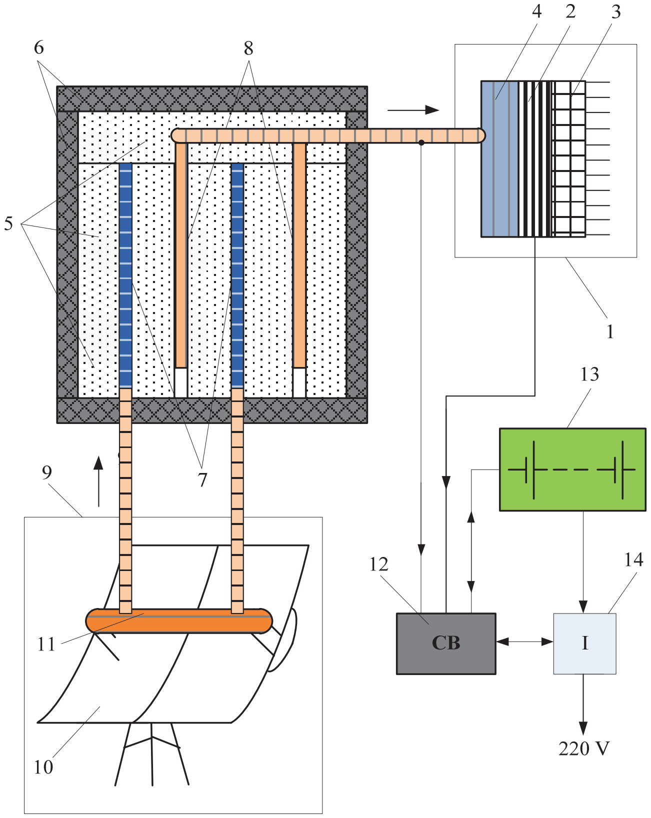

Fig. 1. Power supply installation for remote rural settlements with solar TG and SSTS.

The heat pipes forming the charging (heating) circuit and the discharge (heat energy return) circuit of the SSTS are located in the SSTS with thermal insulation. The use of heat pipes is expedient because they have a low internal thermal resistance, they do not require external energy for pumping an intermediate carrier, and there is no mechanical vibration, thermal stresses [12].

The evaporative zone of the heat pipes of the charging circuit, combined into a collector, is located in the focus of the SC.

Reflected sunlight heats the evaporative zone of the heat pipes (collector) of the charging circuit of the SSTS, while the heat of evaporation in the condensation zone of the heat pipes is transferred to the SSTS. The condenser zone of the heat pipes of the charging circuit is evenly distributed in the SSTS.

The evaporation zone of the heat pipes of the discharge circuit, also evenly distributed in the SSTS array, transfers thermal energy through the condenser zone of the heat pipes to the hot side of the thermoelectric module, located in the thermoelectric assembly between the condenser zone of the heat pipe and the air cooler of the cold side of the thermoelectric module.

To absorb thermal energy from the cold side of the thermoelectric module and maintain it in a cold state in relation to the hot side, an air cooler is used that is tightly attached to the cold side of the thermoelectric module.

During insufficient intensity of solar radiation or at night, the heating of the hot side of the thermoelectric module will be carried out due to the thermal energy stored in the SSTS.

The control unit (CU) performs the following functions: charge/discharge control of a set of batteries; control of TG operation depending on the amount of thermal energy stored in the SSTS and providing the consumer with electricity.

Thus, the proposed solar TG for remote settlements allows using SC, heat pipes, SSTS and thermoelectric modules to convert solar energy into electrical energy.

Below are expressions for calculating the main thermal characteristics of the elements proposed power supply installation (SC, heat pipes and SSTS), as well as the efficiency factor and TG output electric power.

Formulas (1) – (4) given below make it possible to determine the amount of generated energy and the power of the optical system of a stationary SC depending on the density of the incoming solar radiation flux.

The density of the incoming solar radiation flux on the inclined surface of the stationary SC I_{SC} for the calculation period is determined according to the expression [13, 14]:

$$I_{SC} = I_s k_s + I_d \left(\frac{1 + \cos\left(90^\circ - \varphi\right)}{2} \right) k_d, \tag{1}$$

where I_s is the flux density of direct solar radiation to a horizontal surface, W/m^2; k_s is the position coefficient of the stationary SC for direct solar radiation; I_d is the flux density of scattered solar radiation onto a horizontal surface, W/m^2; φ is the latitude of the area, °; k_d = 0.232…0.272 is the coefficient taking into account the degree of concentration of scattered solar radiation by the stationary SC [15].

The position coefficient of a stationary SC k_s for direct solar radiation is determined by the expression [13]:

$$k_s = \frac{\cos j_{ave}}{\sin h}, \tag{2}$$

where $\cos j_{ave}$ is the average value of the cosine of the angle of the Sun's ray incidence on the optical surface of the SC; sin h is the sine of the angle of the Sun's height above the horizon.

The power of the stationary SC optical system N_{SC} is determined by the expression [15]:

$$N_{SC} = I_{SC} F_{SC} \cos j_{cp} \eta_{opt} \eta_{rec}, \tag{3}$$

where F_{SC} is the area of the SC reflecting surface; $\eta_{opt} \approx 0.9$ is the optical efficiency factor; $\eta_{rec} \approx 0.9...0.95$ is the efficiency factor of the SC receiver (evaporator of the heat pipes evaporation zone of the SSTS charging circuit).

When the optical system of a stationary SC is operating in charging mode of the SSTS, its $N_{\mathrm{SC(SSTS)}}$ power, taking into account the heat loss in the SSTS, will be equal to:

$$N_{\mathrm{SC(SSTS)}} = \frac{N_{\mathrm{SC}}}{\eta_{\mathrm{SSTS}}}, \tag{4}$$

where $\eta_{\mathrm{SSTS}} \approx 0.92...0.95$ is the efficiency factor of the thermal storage system (SSTS).

Below is the expression (5) for determining the temperature difference along the heat pipes and describes the temperature regime of the heat pipes of the SSTS charging and discharging circuit.

The temperature difference ΔT along the heat pipes in the charge and discharge circuit of the SSTS can be determined by the expression [12]:

$$\Delta T = \frac{Q_{\mathrm{ev\_hp(ch,dis)}}}{A_{\mathrm{hp}} K_{\mathrm{hp}}}, \tag{5}$$

where K_{hp} is the heat transfer coefficient of the heat pipe (varies over a wide range depending on the geometrical characteristics of the heat pipe and heat exchange conditions on the surface of the evaporative and condenser zones 30000…150000 W/(m^2·K)[12]); A_{hp} is the cross-sectional area of the heat pipe, m^2; $Q_{\mathrm{ev\_hp(ch,dis)}}$ is the heat flux supplied to the evaporator of the heat pipes evaporation zone of the SSTS charging circuit or to the heat pipes evaporation zone of the SSTS discharge circuit, W.

The predicted surface temperature of the evaporator surface of the evaporation zone of the heat pipes of the SSTS charging circuit is 230...250 °C, and the surface temperature of the condensation zone of the heat pipes of the SSTS charging circuit will be 200...220 °C. Accordingly, the predicted temperature of the surface of the evaporation zone of the heat pipes of the SSTS discharge circuit will be ≈ 215...230 °C, and the surface temperature of the condensation zone of the heat pipes of the SSTS discharge circuit will be ≈ 190...200 °C, taking into account the SSTS efficiency factor η_{SSTS} from formula (4) and the coefficient k_{hp} from formula (12). The indicated temperature ranges of the evaporation and condensation zone of the heat pipes of the SSTS charging and discharging circuit are dictated by the need to provide a temperature of ≈ 200 °C on the hot side of the TG thermoelectric modules.

Dependences (6) – (10) are also presented for determining the thermal characteristics of the SSTS [10].

The value of heat losses from the surface of the SSTS casing to the environment Q_{loss} is calculated for the average temperature of the surface casing $T_{\mathrm{cs}} = (T_{\mathrm{sh,min}} + T_{\mathrm{sh,max}})/2$, by the expression:

$$Q_{\mathrm{loss}} = k_{\mathrm{rad}} \alpha_{\mathrm{c\_ave}} F_{\mathrm{SSTS}} (T_{\mathrm{cs}} - T_{\mathrm{a}}), \tag{6}$$

where $\alpha_{\mathrm{c\_ave}}$ is the average convection heat transfer coefficient of the SSTS casing outer surface to the ambient air, W/m^2·K; T_{a} is the ambient air temperature, °C; F_{SSTS} is the area of the SSTS casing outer surface, m^2; $k_{\mathrm{rad}} = 1.05…1.08$ is coefficient that takes into account heat loss by radiation from the surface of the SSTS casing.

The required thickness of the thermal insulation layer δ_{ins} SSTS, at which its heat loss will correspond to Q_{loss}, can be determined from the equation:

$$\delta_{\mathrm{ins}} = \frac{\lambda_{\mathrm{ins}} F_{\mathrm{ave}} (T_{\mathrm{ins,int}} - T_{\mathrm{cs,max}})}{Q_{\mathrm{loss}}}, \tag{7}$$

where λ_{ins} is the thermal conductivity coefficient of the thermal insulation material, W/m·K; $T_{\mathrm{ins,int}}$ is the temperature of thermal insulation inner layer at the end of the charging mode, °C; F_{ave} is the average value of the area of the SSTS casing outer surface and the surface area of the thermal storage core thermal insulation of the SSTS, m^2.

$$F_{\mathrm{ave}} = \frac{F_{\mathrm{ins}} + F_{\mathrm{SSTS}}}{2}, \tag{8}$$

where F_{ins} is the surface area of thermal insulation, m^2.

We determine the amount of thermal storage in the SSTS Q_{st} according to the following expression:

$$\begin{aligned} Q_{\text{st}} &= Q_{\text{ins}} + Q_{\text{HSM}} = \\ &= c_{\text{ins}}\rho_{\text{ins}}V_{\text{ins}}\left(T_{\text{ins,max}} - T_{\text{ins,min}}\right) + c_{\text{HSM}}\rho_{\text{HSM}}V_{\text{HSM}}\left(T_{\text{HSC,max}} - T_{\text{HSC,min}}\right), \end{aligned} \tag{9}$$

where Qins is the amount of thermal storage by the SSTS thermal insulation, kJ; QHSM is the amount of thermal storage by the SSTS heat storage core, kJ; cins is the heat capacity coefficient of thermal insulation, kJ/kg·K; ρins is the volumetric density of thermal insulation, kg/m3; cHSM is the heat capacity coefficient of heat storage material (HSM), kJ/kg·K; ρHSM is the volumetric density of HSM, kg/m3; VHSM is the volume of HSM, m3; Vins is the volume of thermal insulation, m3; Tins,max, Tins,min are respectively the maximum and minimum temperature of the SSTS thermal insulation outer surface, °C; THSC,max, THSC,min are respectively the recommended maximum and minimum temperature of the SSTS heat storage core (200 and 150 °C).

It is supposed to use chamotte or magnesite as a HSM in the SSTS. Using the equations given in [16], the heat capacity coefficient of chamotte and magnesite and their specific heat storage capacity qHSM were determined for the temperature range 200...150 °C of the SSTS heat storage core. The results are presented in Table. 1.

Table 1. Specific heat storage capacity and coefficient of heat capacity of HSMs.

Parameter / Material	Magnesite	Chamotte
c_{HSM} (150 °C), kJ/(kg·K)	1.09	0.92
q_{TC} (150 °C), kJ/kg	164	138
c_{HSM} (200 °C), kJ/(kg·K)	1.11	0.93
q_{TC} (200 °C), kJ/kg	222	186

The amount of thermal storage Q_{st} by the SSTS allows determining the time of its warming up τ_{warm} to the temperature $T_{\text{HSC,max}}$:

$$\tau_{\text{warm}} = \frac{Q_{\text{st}}}{3600(\Sigma Q_{\text{con\_hp}} - Q_{\text{loss,max}})}, \tag{10}$$

where $Q_{\text{loss,max}}$ is the heat loss at the maximum temperature $T_{\text{cs,max}}$ of the SSTS casing surface (see formula (6)), W; $\Sigma Q_{\text{con\_hp}} = N_{\text{SC(SSTS)}}k_{\text{hp}}$ is total heat flux removed from the heat pipes condenser zone of the SSTS charging circuit, W; $k_{\text{hp}} \approx 0.9\ldots0.95$ is the coefficient taking into account losses during the transfer of thermal energy through heat pipes.

Below are formulas (11) – (13) for calculating the efficiency factor and TG output electric power.

The full efficiency factor of the TG η_{TG} can be determined by the expression:

$$\eta_{\text{TG}} = \eta_{\text{hs}}\eta_{\text{tm}}\eta_{\text{sw}}\eta_{\text{el\_in}}k_{\text{loss}}, \tag{11}$$

where $\eta_{\text{hs}} \approx 0.7\ldots0.8$ is the efficiency factor of the heat source (for solar installations) [17]; $\eta_{\text{tm}} \approx 0.05$ is the efficiency factor of thermoelectric modules [18]; η_{sw} is the efficiency of the switching layers of thermoelectric modules, taking into account heat transfer losses by thermal conductivity and electrical losses; $\eta_{\text{el\_in}} \approx 0.95\ldots0.97$ is the efficiency factor of the thermoelectric modules insulating layers, taking into account heat transfer losses by thermal conductivity; $k_{\text{loss}} \approx 0.95\ldots0.97$ is a coefficient that takes into account heat losses in the structural elements and the TG casing.

The main materials of switching in thermoelements are metals with high thermal conductivity, therefore temperature losses are insignificant and do not exceed 1...5 °C. The electrical losses in the switching are also small, because its resistance in each particular circuit of the thermoelectric element is taken to be two orders of magnitude less than the resistance of semiconductors. If the circuit and switching material are chosen correctly, heat and electrical losses in the switching of thermoelements of the TG can be neglected. Electrical losses in the insulation of thermoelements can be assumed to be practically absent [17].

Based on the above, the output electrical power of the TG W_{TG} can be determined from the expression:

$$W_{\text{TG}} = Q_{\text{TG}} \eta_{\text{TG}}, \tag{12}$$

where Q_{TG} is the heat flux supplied to the TG thermoelectric modules from the heat pipes condenser zone of the SSTS discharge circuit, W.

The heat flux supplied to the TG thermoelectric modules Q_{TG} from the heat pipes condenser zone of the SSTS discharge circuit is determined by the expression:

$$Q_{\text{TG}} = \frac{Q_{\text{st}} \eta_{\text{SSTS}} k_{\text{hp}}}{3600} \tag{13}$$

A thermoelectric generator module TGM-199-1.4-2.0 has been selected to provide an output electrical power of TG ≈ 500 W in the amount of 70 pcs. with the maximum temperature of the hot side T_{h} = 200... 220 °C (from the SSTS) and the temperature of the cold side T_{c} = 30 °C in accordance with the recommendations given in [18]. Main features: dimensions are 40·40·4.4 mm; electrical resistance under operating conditions (at 200 °C); R_{ac} is 3.7 Om; current at load I_{load} is 1.41 A; voltage at load U_{load} is 5.2 V; power generated P (at T_{h} = 200 °C and T_{c} = 30 °C) is 7.3 W; efficiency factor is 5.1%.

4 Conclusion

The design of a solar TG installation for remote rural settlements in combination with the SSTS and heat pipes that transmit thermal energy from a stationary SC is proposed. The proposed installation scheme simplifies its design (the absence of an oil storage tank and a circulation pump), which implies an improvement in operational characteristics and an increase in the reliability of the system compared to the previously considered scheme of a solar TG. The novelty of the developed design lies in the use of the SSTS in combination with heat pipes and SC (Pat. RU 2788266 C1).

Expressions are presented for calculating the main functional elements of the proposed installation with solar TG (SC and SSTS), which allow determining their main thermal characteristics, as well as the efficiency factor and TG output electric power.

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