Science and Technology City Hall
KRASNOYARSK, RUSSIA

VIII International Conference
AGRITECH-VIII 2023: Advanced Agritechnologies, Environmental Engineering and Sustainable Development

Power supply installation for remote rural settlements with solar thermoelectric generator

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KRASNOYARSK, RUSSIA

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 (SC) and solid-state thermal storage (SSTS)), as well as the efficiency factor and output electric power of the thermoelectric generator (TG).

Problem statement

The previous version of the TG design for power supply for remote settlements using solar energy has been proposed as an alternative to traditional diesel generator sets.

The advantage:

- using thermoelectric modules in the proposed design in comparison with photovoltaic panels is justified

The main disadvantage:

- The presence of a liquid (oil) storage tank with a heat exchanger and a circulation pump 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.

Objective

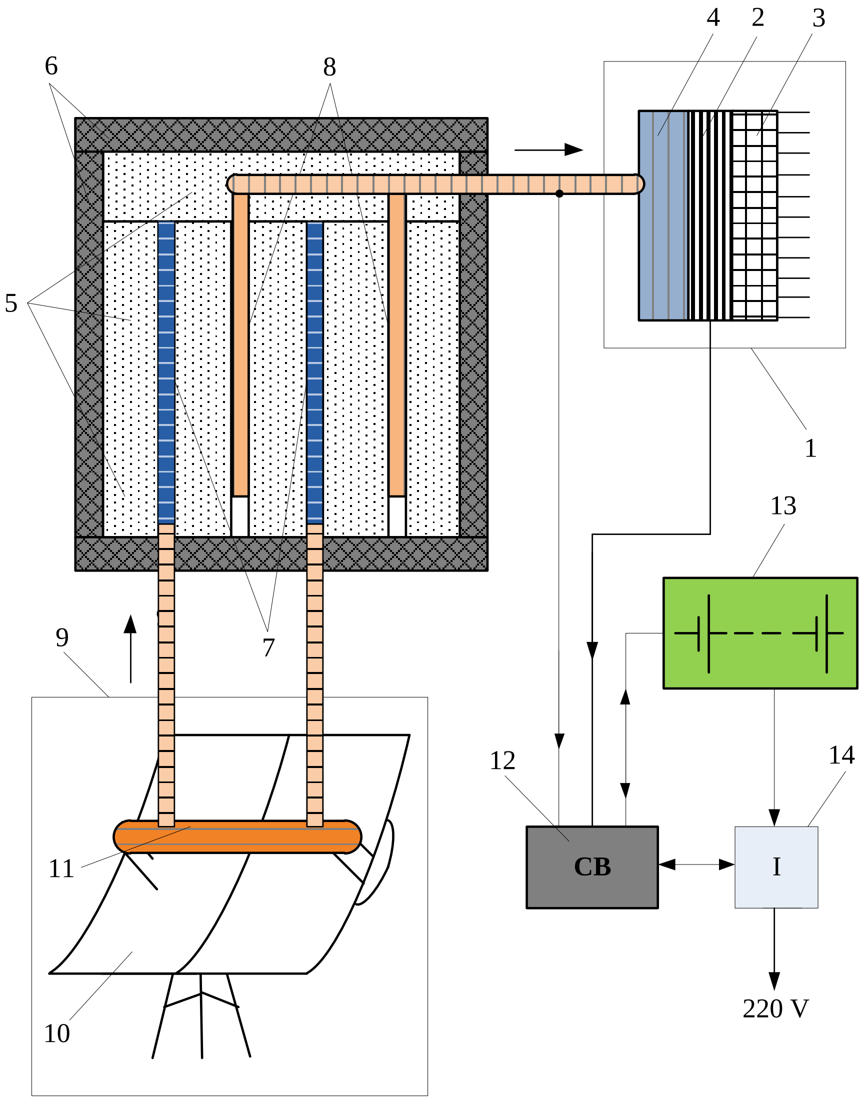
Development of the design of power supply installation with solar TG and SSTS to remote rural settlements and calculation of the main functional elements parameters of the proposed installation.

Solution methods

- 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 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.

Results

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



Results

- 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.
- 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.

Results

- 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:

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

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.

- The position coefficient of a stationary SC for direct solar radiation is determined by the expression:

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

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:

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

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).

Results

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

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

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

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

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

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 $W/(m^2 \cdot K)$); A_{hp} is the cross-sectional area of the heat pipe, m^2; $Q_{ev\_hp(ch,dis)}$ 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 value of heat losses from the surface of the SSTS casing to the surrounding space Q_{loss} is calculated for the average temperature of the casing surface $T_{cs} = (T_{cs,min} + T_{cs,max})/2$, by the expression:

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

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

Results

- We determine the amount of thermal storage in the SSTS according to the following expression:

$$Q_{st} = Q_{ins} + Q_{HSM} =$$
$$= c_{ins}\rho_{ins}V_{ins}\left(T_{ins,max} - T_{ins,min}\right) + c_{HSM}\rho_{HSM}V_{HSM}\left(T_{HSC,max} - T_{HSC,min}\right),$$

where Q_{ins} is the amount of thermal storage by the SSTS thermal insulation, kJ; Q_{HSM} is the amount of thermal storage by the SSTS heat storage core, kJ; c_{ins} is the heat capacity coefficient of thermal insulation, kJ/kg·K; ρ_{ins} is the volumetric density of thermal insulation, kg/m^3; c_{HSM} is the heat capacity coefficient of heat storage material (HSM), kJ/kg·K; ρ_{HSM} is the volumetric density of HSM, kg/m^3; V_{HSM} is the volume of HSM, m^3; V_{ins} is the volume of thermal insulation, m^3; $T_{ins,max}$, $T_{ins,min}$ are respectively the maximum and minimum temperature of the SSTS thermal insulation outer surface, °C; $T_{HSC,max}$, $T_{HSC,min}$ are respectively the recommended maximum and minimum temperature of the SSTS heat storage core (200 and 150 °C).

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

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

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

Results

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

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

where $\eta_{hs} \approx 0.7...0.8$ is the efficiency factor of the heat source (for solar installations); $\eta_{tm} \approx 0.05$ is the efficiency factor of thermoelectric modules; η_{sw} is the efficiency of the switching layers of thermoelectric modules, taking into account heat transfer losses by thermal conductivity and electrical losses; $\eta_{el\_in} \approx 0.95...0.97$ is the efficiency factor of the thermoelectric modules insulating layers, taking into account heat transfer losses by thermal conductivity; $k_{loss} \approx 0.95...0.97$ is a coefficient that takes into account heat losses in the structural elements and the TG casing.

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

$$W_{TG} = Q_{TG}\eta_{TG},$$

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 from the heat pipes condenser zone of the SSTS discharge circuit is determined by the expression:

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

Conclusion

1. 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).

2. 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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