The sources of power on TEG basis for digital technologies of agriculture

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Abstract. The paper presents scientific and technical solutions to improve the efficiency of decentralized power supply systems for consumers that implement digital technologies in agriculture. The author’s technology is described, which makes it possible to evaluate the effectiveness of TEG in an extended temperature range, as well as to study the modes of their operation with electric load. The results are given that determine the rational temperature range for hot junction 160 \( \ldots \) 200 \( ^\circ \)C, for cold -30 \( \ldots \) 50 \( ^\circ \)C. The dependence of the output power on the load current, described by a polynomial of the second degree, is obtained. The regularities of the influence of the load on TEG efficiency are determined. Based on the obtained experimental data, a power source circuit based on a heating device with TEG was developed.

1. Introduction
The phased implementation plan for the departmental project “Digital Agriculture” will require the creation of decentralized low-power power supply systems. This is due, first of all, to the fact that in Russia there are consumers isolated from centralized electricity supply and having weak transport links with industrialized areas. Basically, such consumers are located in remote areas of rural and indigenous populations [1].

The growing demand for electricity, on the one hand, is associated with the expansion of its scope, and on the other hand, the requirements for its environmental friendliness compel us to spend large resources on the search for new sources [2]. One way is to generate electricity using environmentally friendly technologies through the use of thermoelectric generators (TEG), since more than 90\% of the energy we use comes from thermal processes and more than 60\% of the energy produced is lost in the form of heat [3].

In this case, thermoelectric generation is one of the promising, and possibly the only affordable way to directly convert thermal energy into electrical energy, when for relatively small loads it is impossible or economically impractical to supply power lines [4].

A limitation on the way of mass application is the low coefficient of conversion of thermal energy into electrical energy (efficiency), ranging from 3 to 8\%, as well as the high price of TEG. It is known from the prior art [5] that estimating TEG power in an extended temperature range will make it possible to select a maximum point at a certain temperature at which the index of thermoelectric conversion efficiency of a semiconductor substance will be the highest. It is also known [6] that the efficiency of their work depends on the operating conditions of the load (consumers). Thus, it becomes possible to increase the efficiency of power supply systems by evaluating the effectiveness of TEG in an extended temperature range and debugging operating modes at the design stage.
The authors developed and patented a device (stand) [7] that allows one to evaluate TEG effectiveness in an extended temperature range, as well as to study the modes of their operation with electric load. The main differences from the known devices are constructive in nature and are realized through equipping the stand with appropriate sensors and measuring instruments with the technical ability to simulate TEG operating modes that arise during operation in real conditions. The purpose of this work is to study TEG in an extended temperature range and when the load changes, as well as to develop a technical device and recommendations for applying the results in practice.

2. Research methods
A detailed design, methodology and operating modes of the stand are described in [7]. To assemble TEG, a 3 W fan mounted on an aluminum radiator was used as a cooling device (Figure 1). A gas mixture from a cylinder was used as the primary source of thermal energy. To implement the scheme, low-temperature thermogenerator modules (TGM) of the TGM-199-1.4-1.15 type with a declared generated power of 10 W were used [8].

The TEG operating mode is determined both by the nature of the change in thermal energy at the TEG junctions, and by the change in its load [9]. The following operating modes were subject to research:

- with the temperature of the heater and the refrigerator regulated according to the specified control law to ensure the maximum amount of generated electric energy at the output of the TEG;
- with constant temperatures of the heater and refrigerator;
- with varying load resistance.

The experiment took place in three stages. First, the coordinated output current I, the output voltage U, the coordinated output power of the load P when controlling the temperature of the hot junction of T_TGM by means of a heat source in the range from 20 to 200 °C and the temperature of the cold junction of T_c TGM by means of a refrigerator in the range of 30 to 80 °C were determined. In this case, the temperature regime was determined at which the values of I, U, P will be maximum.

Then, at a given temperature regime at a constant temperature of the heater and the refrigerator, the dependence of the output power P_out on the load current I_load was determined, regulated in the range from 0 to 4 A.

Evaluation of the effectiveness of the TGM was carried out by the coefficient of performance, which is defined as the ratio [9]:

![Equipment for the experiment to determine the optimal operating modes of the TEG: 1 - block with TEG; 2 - removable panel with TEG; 3 - measuring unit; 4 - fan; 5 - thermocouples; 6 - clamping element; 7 - connector; 8 - thermogenerator module TGM-199-1.4-1.15; 9 - gas cylinder; 10 - scales; 11 - chronometer.](image)
\[ \eta = \eta_c \frac{m}{m + \frac{1}{zT_h}(m+1)^2 z \alpha \Delta T_m} \]

where \( \eta_c = \frac{T_h-T_c}{T_h} \) – efficiency of the ideal Carnot cycle;
\[ z = \frac{a^2}{xT_{int}} \] – quality factor of thermoelectric material;
\[ T_{av} = \frac{T_h+T_c}{2} \] – average junction temperature.

Thus, the efficiency of the TGM is a complex function of the temperatures of the hot and cold junctions \( T_h \) и \( T_c \), the average temperature of the junctions \( T_{av} \), the quality factor of thermoelectric materials \( Z \) and the relative load resistance \( m \).

The optimal load value \( m_{opt} \) is found from the expression [9]:
\[ m_{opt} = \sqrt{1 + zT_{av}} \]

Efficiency was determined by load regulation \( R_{load} \) from 0 to 20 Ohm.

3. Results

Figure 2 shows the characteristics of the TGM obtained by controlling the temperature of the heater and refrigerator.

Figure 2c clearly shows that the rational mode of operation, in which the coordinated output power of the load is maximum \( P = 10 \) W, is the mode at \( T_h=200 \) °C and \( T_c=30 \) °C. The recommended temperature ranges for hot junction \( \Delta T_h=160...200 \) °C, for cold - \( \Delta T_c=30...50 \) °C. In this interval, the output voltage will vary in the range of 7 ... 10 V, and the matched output current will be 1.5 ... 2.2 A.

Figure 3a shows the dependence of the output power on the load current. The dependence is described by a polynomial of the second degree:
As it can be seen from the graph, the output power increases reaching a maximum value of 10 W at a load current of 2 A. Further, with an increase in the load current, the output power decreases. The dependence of the TGM efficiency upon a change in load (figure 3b) shows that the increase in operating efficiency occurs linearly to a resistance value of $R = 2$ Ohms. Maximum efficiency $\eta = 4.75\%$. Further, the value of the efficiency decreases and reaches $2\%$ with a resistance of $R = 20$ Ohms.

$$y = -2.74x^2 + 9.89x - 0.11.$$  

For power supply to decentralized consumers of low power, the authors developed a TEG-based system [10] using the example of a harvesting and receiving point for collecting wild plants. The system contains an electric power source based on a heating device with TGM-199-1.4-1.15 in the amount of 18 pcs, an inverter and a battery. Consumers are represented by digital equipment for working with data connected to a socket group with bipolar sockets and a lighting system.

Taking into account the obtained experimental data, it is necessary to improve this system by introducing into TEG a control unit with temperature sensors for hot and cold junctions, and elements for controlling the flow of coolant into the heating device.

Figure 4 shows a diagram of a power source based on a heating device with TEG.

**Figure 3.** Graphs of electrical characteristics of TGM.

**Figure 4.** Scheme of an electric power source based on a heating device with TEG: 1 - gas cylinder; 2 - pressure gauge; 3 - gear; 4 - a flexible hose; 5 - burner; 6 - piezoelectric element; 7 - a radiator; 8 - fan; 9 - heat receiver; 10 - TGM; 11 - wires; 12 - spring washers; 13 - meter-controller; 14 - temperature sensor of the refrigerator; 15 - heater temperature sensor; 16 - consumer (digital device).
The source of electricity works as follows. Reducer 3 opens the gas, which comes from a cylinder 1 with a manometer 2 through a flexible hose 4 and is ignited using a piezoelectric element 6. From the burner 5, the flame acts on the heat receiver 9 and one side of the thermogenerator module 10 is heated, and the other is cooled by a radiator 7 with fan 8. At the same time at the ends of the wires 11 there is a potential difference (thermoelectric power) coming to the consumer 16 through an inverter (not shown). The measuring instrument-regulator 13, with a reducer 6, controls the value of the flame and the rotation speed of the fan 8 until the temperature sensor of the heater 15 and the temperature sensor of the refrigerator 14 fix the temperature values \( T_h = 200 \, ^\circ C \) and \( T_c = 30 \, ^\circ C \), optimal for TGM 10, respectively, at which there will be a maximum value of the output voltage.

4. Conclusion

Thus, it becomes obvious that for the introduction of digital technologies in agriculture, decentralized low-power power supply systems built on the basis of TEG are best suited. For a wider practical application of TEG on fossil fuels, it is necessary to increase the efficiency of power supply systems by evaluating TGM effectiveness in an extended temperature range and debugging operating modes at the design stage. An increase in the efficiency of such systems can be achieved by rational use of the heat of the combusted fuel by adjusting the temperatures of the cold and hot junctions in the optimal range.

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