# Study of the Energy Efficiency of a Thermal Electrical Generator with a Hydraulic Heat Supply System

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Abstract: The article presents the results of a study of an alternative option for generating electricity as an approach to reducing dependence on traditional methods of generating electricity. We have proposed a variant of a thermal electric generator containing a thermoelectric converter with a hydraulic system for a forced supply of cold and hot heat carriers. The research aimed to determine the thermal generator's efficiency under different variants of external load and temperature differences on the thermal sides of the thermoelectric converter. The load was selected from a variable range: 0, 0.51, 1.8, 5.1, 15 Ω. The temperature range was from 10 to 45°C. Semiconductor sensor technology was used to monitor the temperature, electrical and thermal power parameters of a thermal power generator. The study of the generator operation without load revealed a linear change in the converter's thermoelectromotive force from 600 to 2600 mV. With an external load of 15 Ω, we managed to achieve the best performance in generating the output voltage, which varied linearly from 600 to 2500 mV. In the course of comparative studies, the highest generator power was recorded at an external resistance of 1.8 Ω, which varied from 0.05 to 0.43 W depending on the temperature difference. At this load value, the best energy conversion rates were also achieved, when the efficiency coefficient varied between 0.3 and 0.55%.

## 1 INTRODUCTION

Today, the rapid growth in electricity consumption is outstripping the pace of its generation [1]. This significantly exacerbates the problem of growing food shortages and increases the cost of consumption [2]. This need becomes even more acute without physical access to power lines in remote areas and territories [3].

A partial solution to these problems may be the use of alternative ways of generating electricity instead of traditional ways of generating it, in particular, the use of various renewable energy sources [4].

When choosing a certain alternative technology for generating electricity, questions are always raised about their efficiency, cost, technical possibilities of their application, availability of available energy sources for their conversion into an electrical equivalent, etc [5].

Thermal energy is the type of energy that is most used for various technical and technological processes. It is of particular importance in the field of electricity generation [6]. Most power-generating capacities operate on thermal energy, the production of which is associated with potential risks of environmental degradation [7]. In particular, excessive emissions of unused heat into the atmosphere.

In addition, vehicles, production facilities, household consumers, etc. are significant sources of residual heat emissions.

It is advisable to study the technology and technical means of using residual heat to generate electricity.

A well-known approach for the direct energy conversion of heat into electricity is the use of thermoelectric converters based on the Seebeck effect. Based on this conversion method, various installations have been developed to generate electricity using geothermal sources [8], vehicle exhaust gas energy [9], utilisation of heat from air conditioning units [10], human body energy [11], etc.

Thermoelectric generators are small, lightweight and reliable energy converters. They operate without noise and vibration due to the absence of any moving mechanical parts [12].

However, these generators are characterised by low conversion efficiency and high cost. This has limited their widespread use [13]. Thus, research on thermoelectric generators in recent years has focused on optimising their performance and reducing their costs.

## 2 MATERIALS AND METHODS

The study aims to determine the efficiency of a thermal electric generator with a hydraulic heat supply system under various external loads.

A schematic diagram of the experimental thermal electric generator is shown in Figure 1, and a photographic image is shown in Figure 2.

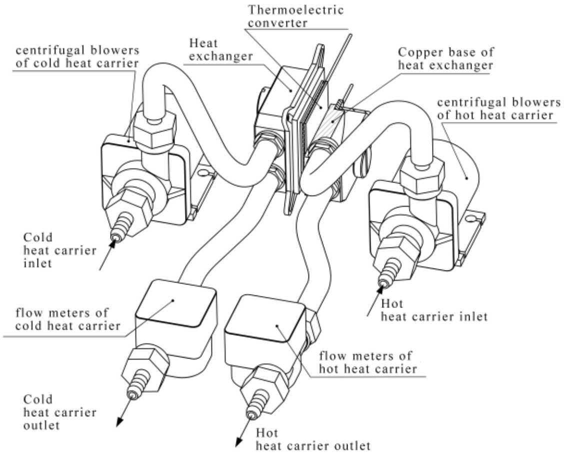

Figure 1: General scheme of a thermal electric generator.

The main component of a thermal electric generator is a thermoelectric converter based on the Seebeck effect. For a thermal electric generator to function, two heat sources with different temperature potentials are needed. Cold and hot liquid carriers are used as such sources.

Regenerative heat exchangers are used to ensure heat exchange between the heat carriers and the thermoelectric converter, which are mounted on different thermal sides of the converter.

The heat carriers in the heat exchangers are circulated by centrifugal blowers, the performance of which is controlled by a PWM controller.

DS18b20 digital temperature sensors are used in the heat exchangers to determine the change in temperature of the heat carriers before and after heat exchange, which are mounted in the heat carrier pipeline at the inlet and outlet of the heat exchangers.

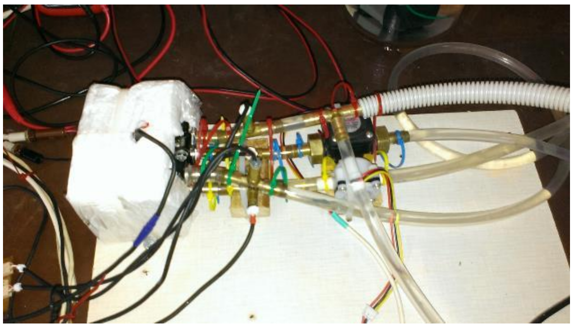

Figure 2: Photographic image of the experimental thermal electrical generator.

The volumetric flow rate of heat carriers is monitored by contact method using SEN-HZ21WA and YF-S401 volumetric flow meters with different measuring ranges.

The source of hot and cold heat carriers is calorimetric tanks.

One tank contains a thermistor heater to heat the hot carrier to the required temperature, which is controlled by an electronic thermostat. In the other tank, cold storage batteries are used to form a cold carrier with a temperature determined by the conditions of the experiment.

To monitor the temperature of the heat exchange surfaces of the thermoelectric converter, resistive temperature sensors were used, which were in direct contact with the surfaces.

A digital ammeter and a voltmeter were used to measure the electrical parameters of the thermoelectric generator.

A special microcontroller system based on the 8-bit RISK microcontroller Atmega328 is used to process signals from digital and analogue sensors.

This microcontroller system collects, stores and processes information from sensor technology and then sends it to a smart device via Bluetooth wireless communication.

The microcontroller system also displays the collected information on the LCD and stores it in the file space of the SD memory card.

The general view of the workplace for the experiments is shown in Figure 3.

To achieve this aim, a research programme was planned, which included two stages.

In the first stage, the thermal electric generator was tested without connecting an external load.

At this stage, the magnitude of the thermomotive force was measured at a step change in the temperature difference on the heat-exchanging sides of the thermoelectric converter. The temperature on its heat-absorbing side remained constant at 10°C throughout the experiment.

Figure 3: Workplace for the study of a thermal power generator.

The required temperature difference was created by changing the temperature on the heat-absorbing side by changing the temperature of the heat carrier in the regenerative heat exchanger, which is fixed on this side.

The increase in the temperature of the heat carrier was provided by Joule heat from a thermoelectric heater of the appropriate tank capacity.

The range of temperature difference was from 20 to 45°C.

The second stage involves conducting a series of experiments to build a characteristic of changes in the output electrical parameters of the thermal electrical generator and the level of energy efficiency as a function of the external load and the temperature difference on the heat exchange sides of the thermoelectric converter.

The methodology for the second stage of experimental research was to measure the output electrical parameters of the generator when the external load varies according to a variable series: 0.51 Ohm, 1.8 Ohm, 5.1 Ohm, and 15 Ohm.

The electrical values were measured for each external load value at different temperature differences on the heat exchange sides of the converter from 10 to 45°C.

The constant temperature on the heat-absorbing side of the thermoelectric converter was a prerequisite for the experiments.

The efficiency of a thermal electric generator is determined by comparing the output power received with the amount of heat removed on the heat-absorbing side of the converter.

The amount of heat consumed was determined by calculating the heat loss of the hot heat carrier in the heat recovery exchanger.

Heat losses were calculated based on the change in the temperature of the heat transfer medium at the inlet and outlet of the heat exchanger and its current flow rate.

## 3 RESULTS AND DISCUSSIONS

Figure 4 shows the change in the magnitude of the thermoelectromotive force from the temperature difference on the heat exchange sides of the thermoelectric converter in the absence of an external load.

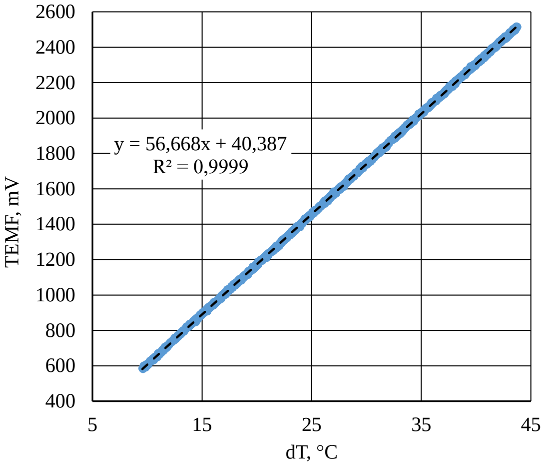

Figure 4: Dependence of the thermoelectromotive force of a thermoelectric converter on the temperature difference dT.

The presented dependence demonstrates a clear linear dependence of the thermoelectromotive force on the temperature difference.

Thus, in the range of temperature changes from 10 to 45 °C, the thermoelectromotive force varies linearly with increasing value from 600 to 2500 mV.

Based on the regression analysis of the research data, the following equation was derived:

$$y = 56.668 \cdot dT + 40.387\,. \tag{1}$$

The degree of reliability of R2 of the given approximated equation to the nature of the change in the thermoelectromotive force is as close as possible to one.

This gives a good agreement between theoretical and experimental values of the thermoelectromotive force.

The main output electrical parameters that characterise the operation of any electric generator are the output voltage U, the electric current I and the power W.

The formation of all electrical parameters for a thermal electric generator is influenced by two determining factors: the temperature difference dT on the heat exchange surfaces of the thermoelectric converter and the external load $R_{external}$.

The first factor determines and shapes the width of the output voltage range, and the second factor sets the amount of current that will flow through the closed electrical circuit of a thermal power generator. Therefore, both factors are taken into account when studying electrical parameters.

Figure 5 shows the results of an experimental study of changes in the output electrical parameters of a thermal electric generator when the temperature difference varies within 10-45°C with a connected consumer of electrical energy with a resistance of 0.51 Ohm.

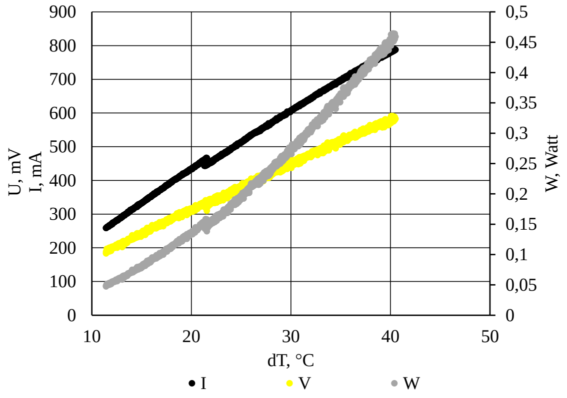

Figure 5: Changes in electrical parameters due to temperature difference dT at an external load resistance of 0.51 Ohm.

From the analysis of the pattern of changes in the output voltage and current in the electrical circuit, it is clear that these electrical parameters change in direct proportion to the value of the temperature difference dT. Their change obeys a linear law and can be described by the approximated equations of the straight line:

- for voltage:

$$U = 13.591 \cdot dT + 38.954\,; \tag{2}$$

- for current:

$$I = 18.071 \cdot dT + 62.807\,. \tag{3}$$

In the studied range of temperature differences on the heat exchange surfaces of the converter, the current in the circuit varies from 258 to 788 mA.

The voltage generated by the temperature difference and the level of external load on the generator is in the range of 185-586 mV.

The electrical power level of a thermal electric generator varies in a non-linear way and ranges from 0.05 to 0.46 W. The pattern of changes in the value of electric power can be described with a high degree of confidence by a regression equation:

$$W = 0.0002 \cdot dT^2 + 0.028 \cdot dT - 0.0118 \tag{4}$$

To conduct a comparative analysis of the electrical characteristics of a thermal electric generator at other values of external load resistance, it is necessary to reduce them to common coordinate systems.

Figure 6 shows the combined characteristics of the output voltage change.

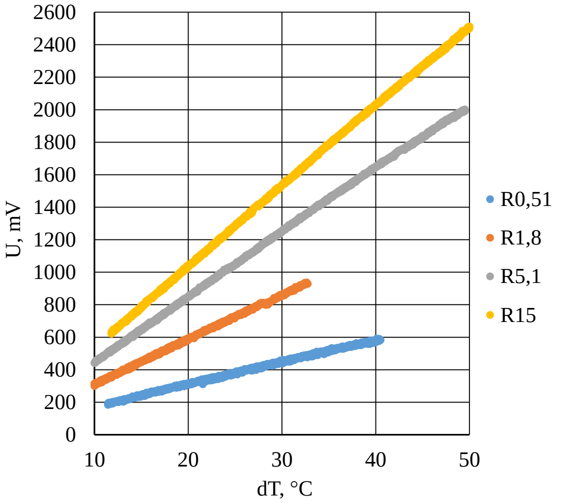

Figure 6: Comparative characteristics of electrical voltage under different external loads and temperature changes dT.

Comparison of the output voltage curves of the electric generator clearly shows that with an increase in the load level, a voltage drop is observed and its growth rate slows down as the temperature difference on the heat-exchanging sides of the thermoelectric converter increases.

Thus, when comparing the voltage levels at the maximum (0.51 Ohm) and minimum load (15 Ohm), the difference between them will be 460 mV at the minimum temperature difference with a gradual increase in this difference to 895 mV. At the same time, the voltage growth rate for the variant with a minimum load is 49 mV for each degree of temperature difference, as opposed to 13.6 mV/°C at maximum load.

For intermediate load values, the range of voltage deviation from the voltage at the minimum load within the same temperature difference is for 1.8 Ω - 264...748 mV; for 5.1 Ω - 116...274 mV.

The narrowing of the width of the voltage change ranges as the load decreases is reflected in the convergence of the voltage curves and the increase in their steepness. This helps to achieve a greater effect in generating electricity at the same temperature differences on the heat exchange surfaces of the thermoelectric converter.

Somewhat different conclusions can be drawn about the electrical characteristics of a thermal electric generator when comparing its output power under different load conditions (Figure 7).

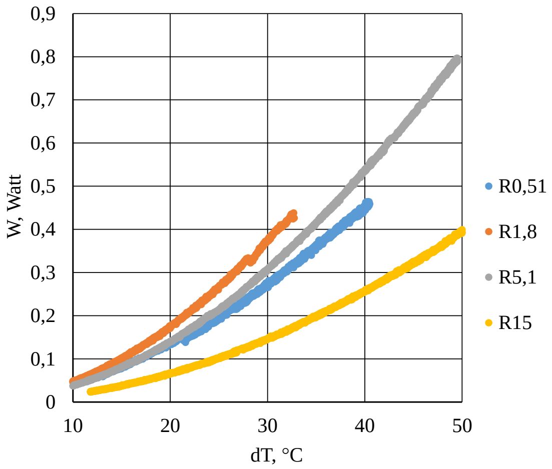

Figure 7: Comparative characteristics of electrical power at different external loads and temperature differences dT.

Thus, based on the comparison of the output power curves in Figure 7, it should be noted that the lowest power is provided by the generator when a consumer with an electrical resistance of 15 Ω is connected to it. The power level developed within the limits of dT change from 10 to 45°C is 0.023...0.256 W. This is almost two times less than the power provided by the generator when connected to a consumer with a resistance of 0.51 Ω over the entire range of dT. To supply this consumer, the generator, depending on dT, develops power in the range of 0.05...0.45 W.

In turn, for average load values, the generator power takes on higher values, in particular, for a load of 5.1 Ω at dT=20°C, the power is 0.14 W, for 1.8 Ω - 0.175 W.

A further increase in dT increases the power value, and already at dT=30°C for a 5.1-ohm load it reaches 0.31 W, and for 1.8 Ω - 0.38 W. This power level for the other load variants is only achievable at higher dT values: at 0.51 Ω, a power of 0.38 W is only achievable at dT=36°C, at 15 Ω - at dT=49°C.

Taking into account the relative position of the generator output power curves at different loads, it can be concluded that the highest power values and the highest growth rates can be achieved when using consumers with an average electrical resistance level between 1.8 and 5.1 Ω.

At the same time, the output power increases at a more significant rate as the electrical resistance of the consumer approaches the lower limit of the proposed range of electrical resistances.

Of particular interest is the level of thermal energy consumption in the production of electricity by a thermal electric generator and the degree of its efficient use.

Figure 8 shows the summary results of the level of heat energy consumption depending on the value of the electrical power output at different loads.

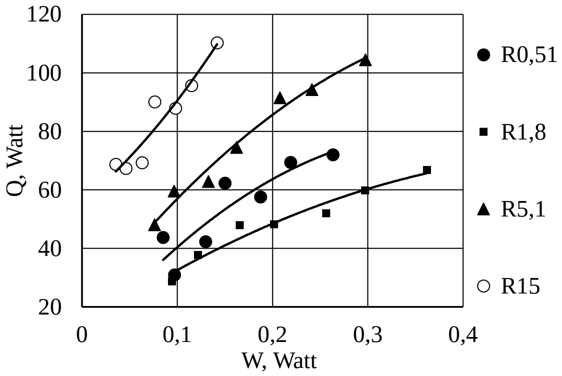

Figure 8: Comparative characteristics of heat consumption under different external loads and electrical power.

Figure 9 illustrates the character of the change in the coefficient of thermal energy use efficiency depending on the level of power generated by a thermal power generator when supplying different consumers.

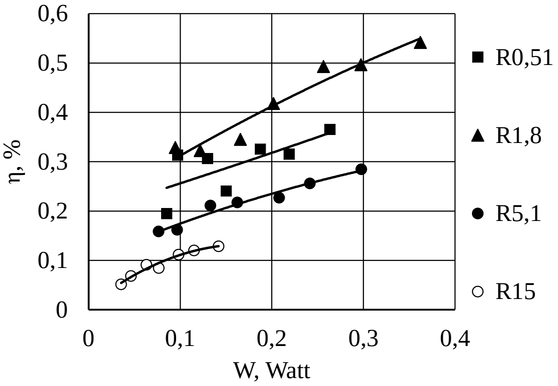

Figure 9: Comparative characteristics of the coefficient of thermal energy efficiency depending on the power level.

According to the dependencies in Figure 8, it can be seen that as the electric power increases for all variants of external loads, there is a steady increase in heat consumption. Within the framework of the experiments, the range of heat consumption is from 30 to 112 W.

The most significant level of thermal energy consumption is observed when powering a consumer with an electrical resistance of 15 Ohm, while to ensure a power level within 0.05...0.15 W, it is necessary to consume thermal energy in the amount of 67...112 W. These limits of heat consumption are the highest when ensuring identical levels of electricity use by different consumers over the entire range of output power produced by the generator.

The least amount of heat is used by a thermal electric generator when supplying a consumer with an electrical resistance of 1.8 Ω. For example, to meet the electricity needs of a given type of consumer in the range of 0.1 to 0.37 W, it is necessary to use 30 to 67 W of heat.

When consumers with an electrical resistance other than 1.8 Ω are connected to the generator, both upward and downward, the level of heat consumption increases. At the same time, a decrease in external resistance increases the amount of electricity consumption to a lesser extent.

Thus, when comparing the levels of heat consumption for resistances of 1.8 Ω and 0.51 Ω with the same generator power, the amount of heat used for a consumer with a lower resistance is 10-30 W more. This difference gradually increases as the need to generate more and more electricity increases.

As for a consumer with an electrical resistance of 5.1 Ω, the amount of thermal energy required to generate electricity in the range of 0.07 to 0.3 W increases by an average of 25...40 W compared to a consumer with the lowest level of heat consumption.

The efficiency of converting heat energy into electricity can be determined by the efficiency factor, which can be calculated as the ratio of the amount of electricity produced to the amount of heat energy consumed.

Let's consider how this coefficient changes for a thermal electric generator with different values of output power and external electrical resistance.

According to the graphical representation in Figure 9, it should be noted that the thermoelectric conversion of thermal energy into its electrical equivalent is rather low. Based on the data presented, the efficiency ratio ranges from 0.05 to 0.55%.

Despite the rather low level of the efficiency coefficient, the pattern of its change and the range of fluctuations for different variants of external load and generated power have different features.

The lowest values of the efficiency coefficient in the entire power range are achieved by a thermal electric generator with a connected consumer with a resistance of 15 Ω. In this variant of the generator's operation, with a power variation from 0.03 to 0.14 W, the efficiency factor is constantly growing, increasing by two and a half times from 0.05 to 0.13%. The character of its change is close to parabolic.

The best thermal energy efficiency is achieved by an electric generator when powered by an external consumer with a resistance of 1.8 Ω. When the power level is changed from 0.1 to 0.37 W, the thermal electric generator has a linearly increasing efficiency factor that is in the range of 0.3...0.55 %.

This high efficiency of heat energy use is fully consistent with the lowest heat consumption and the best power generation properties compared to other generator operating options. This was noted earlier.

For all other consumers, the efficiency factor has the same tendency to change as the amount of heat consumed by the power generator.

In particular, with an external resistance of 0.51 Ω, the efficiency factor takes values from 0.19 to 0.37%, which is 10-20% less when compared to a resistance of 1.8 Ω. Increasing the external resistance to 5.1 Ω reduces the efficiency coefficient and forms its change range from 0.16 to 0.285%.

# 3 CONCLUSIONS

A comprehensive analysis of energy costs and efficiency of their use showed a rather low level of thermoelectric conversion of thermal energy into electricity for this version of the electric generator. Its efficiency factor does not exceed 1%.

The practical use of this type of generator is possible only if there is free or residual thermal energy that is not generated specifically for the operation of this generator. Or in cases where there are no other ways to generate electricity.

A significant power generation capacity using thermoelectric converters is possible only with a radical increase in their number and the creation of favourable conditions for intensifying the processes of heat emission and heat absorption.

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