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Investigations of a Micropower Thermoelectric Generator Operating at a Low Temperature Difference

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Introduction

The thermoelectric generator can be used to directly convert heat energy into electric energy.

The phenomenon of the appearance of the electromotive force between two distinct metals in different temperatures was discovered by T. J. Seebeck in 1822. The theoretical basis of the thermoelectricity, however, was only created in the middle of the 20th century, when the semiconductors were begun to be utilized for this purpose [1].

Presently, the efficiency coefficient of the thermoelectric generators is relatively small, yet, this equipment does not have moving parts, is noiseless, environment-friendly, as well as reliable and do not require constant maintenance.

Renewable energy or surplus heat can be the primary heat energy sources of the thermoelectric generators.

Electrochemical battery have to be utilized, when conversing the solar energy directly into electric power (e.g. in photoelectric power plants) at night. However, for this purpose heat storage units with thermoelectric generators can be used as well. In this particular case, the heat storage units have priority over the electrochemical batteries due to their larger energy volume, the ability to operate for an unlimited number of cycles, and because they do not require the stabilization of the load mode and are environment-friendly.

Nowadays the wireless networks are widely spread in many applications (for radio transceivers, microcontrollers, transducers) [2]. Available energy resources are whether batteries, renewable or surrounding energy harvesting or both. In this case the electric power can be obtained from thermoelectric generators.

One of the first proposals to apply solar energy for the generation of thermoelectricity was described in source [3]. To achieve this, thermoelectric elements, the bottom side of which is being cooled by water, were fixed to the absorber plate of the collector. Systems, operating on this principle, are described in reference sources [4–6].

It should be noted that in most cases the thermoelectric Peltier elements for cooling are recommended to generate thermoelectricity.

During the investigations of thermoelectric systems [7] is was ascertained, that the increase of the flow rate of the hot heat transfer, when the values of this flow-rate are low, allows to increase the electric power in development and the efficiency coefficient. The flow rate of the cold heat transfer fluid was constant. The natural circulation of the heat transfer fluids is recommended.

Recently the electric power sources of low power and voltage, which are designed to supply the devices of microelectronics and sensors, have become the objects of interest. For this purpose voltage converters, the outlet voltage of which is 0.5 – 5 V [8, 9, 10], are recommended.

The aim of the investigations, described in this article, is to carry out the energy evaluation of the thermoelectric generator with natural heat transfer fluid circulation and low temperature difference.

This kind of thermoelectric supply source could be used to feed the electronic sensors and controllers, as well as other cases.

Analytical expressions

The current – voltage $U_t = f\left(I_t\right)$ characteristic of the thermoelectric element is a linear, described by an equation

$$U_t = \alpha \Delta T_j - I_t R_t . \tag{1}$$

In no-load the voltage of the thermoelectric element is dependent on the Seebeck coefficient α and the temperature difference between the element functions ΔT_j .

The developed power P_t of the thermoelectric element depends on the temperature difference ΔT_j and the load current I_t

$$P_t = \alpha \, \Delta T_j \, I_t - I_t^2 \, R_t . \tag{2}$$

When a certain temperature difference ΔT_j occurs, the curve $P_t = f(I_t)$ is in the shape of a parabola.

The thermoelectric element will develop the maximum power, when its load resistance is equal to the inner resistance R_t.

Hence, the voltage at the point of maximum power constitutes ½ of the no-load voltage. In this case the maximum power P_{tm}, developed by the thermoelectric element at a certain temperature difference ΔT_j, is

$$P_{tm} = \alpha^2 \, \Delta T^2 / (4R_t). \tag{3}$$

Such expression of the maximum power is presented in the reference sources [9, 11]. The maximum power is proportional to the square value of the temperature difference.

The efficiency coefficient of the thermoelectric element at the point of the maximum power η_{tm} [11].

$$\eta_{tm} = \left(\Delta T_j / T_{jh}\right)\left(4/\left(z_t T_{jh}\right) + 2 - \Delta T_j / \left(2T_{jh}\right)\right)^{-1}, \tag{4}$$

where z_t – figure of merit.

The first multiplier of the right side of this equation is the Carnot efficiency coefficient. The second multiplier is the efficiency coefficient of the thermoelectric process and it evaluates the losses due to the heat conduction and the Joule effect [11].

It should be noted that these transits were achieved only by making an assumption that the physical features of the thermoelectric element material (Seebeck coefficient, electrical resistivity, thermal conductivity) is not dependent on the temperature. Such assumption is justifiable, when the temperature interval of the element operation is relatively small [11].

The methodology and the experimental objects of the investigations

The Peltier elements PE-127-14-15S were used for the investigations. The dimensions of the element are 40×40×3.9 mm. 6 elements were used for the investigations: they were electrically connected in series of 3 and both circuits were connected in parallel. The total area of the thermoelectric elements was 0.0096 m^2. The thermoelectric elements were pressed between the aluminum heat exchangers with screws and springs. The surface of the heat exchangers (working length 12 cm, width – 8 cm) is planished and lubricated with heat conductive silicon pasta. The compression pressure is 30 kPa. The cold and hot heat transfer fluids flow through the heat exchangers. The upper hot heat exchanger is connected to the hot water tank of 80 l capacity with 2 m in length and 10 mm in diameter heat insulated pipes. Cold water from the water-supply system flows through the bottom cold heat exchange (Figure 1).

Laboratory and natural tests were carried out. During the laboratory investigations (when determining the current voltage characteristics of the generator) the hot water was being supplied from the water thermostat NBE.

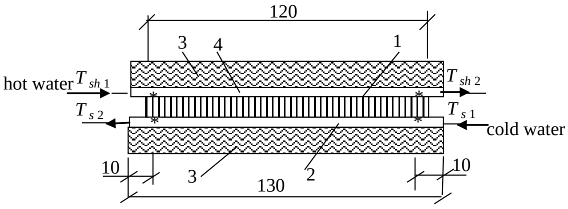

Fig. 1. Scheme of the experimental set-up and testing devices: 1 – thermoelectric element; 2 – cold heat exchanger; 3 – polystyrene plates; 4 – hot heat exchanger; ∗ – thermocouples

During the natural investigations the hot water tank was charged with solar collector.

The voltage and the current of the thermoelectric generator were measured with electronic devices. The temperature was measured with 0.2 mm width thermocouples of K type, which were connected to the microprocessor device Almemo 2290-8.

The amount of the electric energy Q_e, which was generated by the thermoelectric generator during a certain period of time, was determined by dividing this time Δt_i (by 15 min), and, thus, the average power P_i in this interval was determined as well

$$Q_e = \sum_i P_i \, \Delta t_i \,. \tag{5}$$

The efficiency coefficient η_g of the thermoelectric generator during a certain period of time

$$\eta_g = Q_e / \left(\Delta Q - Q_l\right), \tag{6}$$

where ΔQ – decreasing of accumulated amount of heat energy in the tank; ΔQ_l – heat energy losses of the water tank.

The efficiency coefficient of the Carnot cycle η_e is found according to the average surface temperatures of the hot T_{sh} and cold T_{sc} heat exchangers

$$\eta_e = \left(T_{sh} - T_{sc}\right) / T_{sh} \,. \tag{7}$$

The results of the investigation

After carrying out the laboratory experiments the comparative water tank heat losses were 2.15 W/K. The current – voltage characteristics of the thermoelectric generator are presented in the Fig. 2.

The expression, approximating the experimental date (if dimension U_g in V, I_g in A and T_s in ^{o}C)

$$U_g = 0.12 \, \Delta T_s - 4.12 \, I_g \,. \tag{8}$$

The correlation coefficient is 0.99 and standard square deviation – from 0.031 to 0.098.

In this case, the expression of the developed by thermoelectric power P_g in W generator is

$$P_g = 0.12 \, \Delta T_s \, I_g - 4.12 \, I_g^2 \tag{9}$$

and the maximum power P_{gm}, developed by the thermoelectric generator

$$P_{gm} = 0.000874\,\Delta T_s^2\,. \tag{10}$$

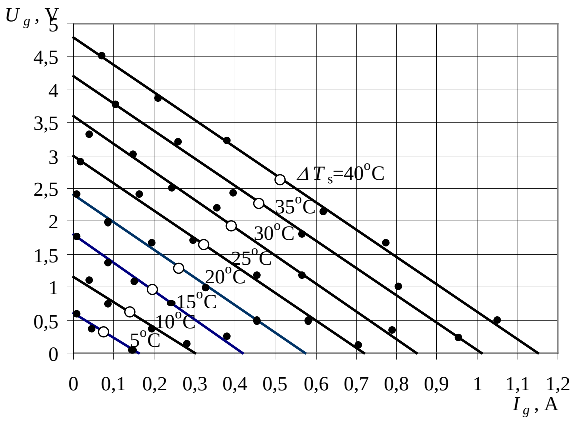

Fig. 2. The current – voltage characteristic $U_g = f(I_g)$ of the thermoelectric generator (• - experimental points; o – points of maximal power; $\Delta T_s = T_{sh} - T_{sc}$)

The form mathematical expression of energy parameters of the thermoelectric generator (8), (9) and (10) determined through experimentation, coincides with the theoretical expressions of the thermoelectric element parameters, indicates in (1), (2) and (3) equations.

When the temperature difference ΔT_s is the same between the surfaces of the thermoelectric generator heat exchangers and the load current is increasing, the voltage decreases in a linear manner. When the temperature difference is equal to 40°C the no-load voltage amounts to about 4.8 V. If the current is increased up to 0.4 A, the voltage decreases to 3.15 V.

When the temperature difference is reduced to 20°C, the no-load voltage decreases twofold. (to 2.4 V). When the load current is 0.4 A, the voltage decreases to 0.75 V.

The thermoelectric generator generates the maximum power when the load resistance is 4.12 Ω. When the temperature difference is 40 °C the thermoelectric generator generates electric power of roughly 1.4 W (the voltage is 2.4 V, the current - around 0.58 A).

When the temperature difference decreases to 20 °C, the thermoelectric generator generates power of about 0.35 W.

During the natural tests the water flow rate through the cold heat exchanger was changed from 4.0 to 16.4 l/h. The duration of one test was 8 hours. The results of one of the carried out tests are presented in Fig. 3.

The temperature changed from 50.3 to 41.7 °C at the beginning of the hot heat exchange surface (according to the direction of the current). The temperature was lower by 3.3-3.7 °C at the end of this surface according to the direction of the current. The average temperature of water tank during this test was from 55.5 to 45 °C. The temperature changed from 21.1 °C to 19.7 °C at the initial part of the cold heat exchanger according to the direction of the current. The temperature increased by 2.3-3.2 °C at the end part of the heat exchanger.

The surface temperature difference of the hot and cold heat exchangers was from 26.3 °C to 18.9 °C.

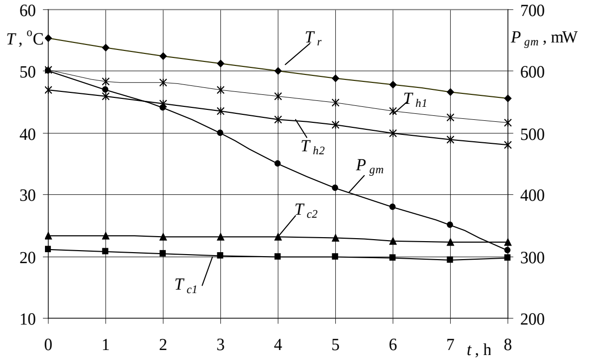

Fig. 3. The results of the natural tests of the thermoelectric modulus, when the cold water flow rate is 13.68 l /h. (T_r – temperature of tank; t – time)

The water temperature of the storage water tank had decreased by 9.8 °C in 8 hours and 3277 kJ of heat energy were lost. 2002 kJ or 62% of this energy consists of the tank heat losses. Therefore, 1275 kJ is needed to directly supply the thermoelectric generator with energy. In 8 hours the thermoelectric generator had generated 3.675 Wh of electric power. The voltage at the point of maximum power was 1.6-1.14 V (in case of no-load: 3.1-2.3 V).

The variations of the energy indicators of the thermoelectric generator, when the water flow rate is changed through the cold heat exchanger, are shown in Fig. 4.

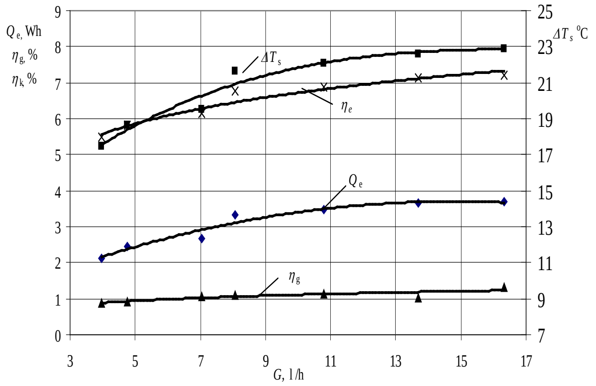

Fig. 4. The variations of the energy indicators of the thermoelectric modulus, when the water flow rate G is changed through the cold heat exchanger

However, after reaching the flow rate of 12-13 l/h, the amount of the generated energy increases only slightly and amounts to 3.67-3.68 Wh. When the cold water flow rate is 4-5 l/h, the average temperature difference decreases to 17.5- 18.6 °C in 8 hours. Thus, the amount of generated energy decreased to 2.14-2.44 Wh. On increasing the cold water flow rate, the temperature drop of the water, which flows through the hot heat exchanger, increases.

The temperature dropped by 2.7–3.8 °C due to the connection of the thermoelectric generator to the hot water tank of 80 l capacity.

Conclusions

In all cases the average temperature of the storage tank at the beginning of the process was 56.5±1 °C. It is clearly seen that, when increasing the cold water flow rate, the amount of energy generated by the thermoelectric generator in 8 hours increases, because the temperature difference between the surfaces of the heat exchangers increases as well.

The experimental investigations of the thermoelectric generator (the area of the thermoelectric elements being 0.0096 m^2) with natural heat transfer fluid circulation from the heat storage water tank, when the water from water-supply systems serves as the cold heat transfer fluid, were carried out.

The experiments revealed that, when the comparative cold water flow rate to area of the thermoelectric elements reaches 0.347 – 0.376 l/(s m^2), the amount of the energy generated in 8 hours increases marginally and amounts to 383 Wh/m^2.

The efficiency coefficient of such thermoelectric generator is around 1.1%. When the comparative flow rate of cold water is 0.116-0.145 l/(s m^2), the amount of the generated energy decreases by 34-42%.

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The aim of the investigations is to carry out the energy evaluation of a micropower thermoelectric generator with natural heat transfer fluid circulation and low temperature difference. For the purpose of the investigations thermoelectric elements with the total area of 0.0096 m^2 were used. The thermoelectric elements were installed between two flat-surfaced heat exchangers, through which both hot and cold heat transfer fluids flow. Temperature difference was 18.9 – 26.3 ^oC. The experiments showed that when the comparative cold water flow rate reaches 0.347-0.376 l/(s·m^2), the amount of the power generated in 8 hours increases only marginally and comprises around 383 Wh/m^2, while the coefficient of the generator efficiency amounts to around 1.1 %. Ill. 4, bibl. 11 (in English; abstracts in English and Lithuanian).

I. Šateikis, R. Ambrulevičius, S. Lynikienė. Mažos galios termoelektrinio generatoriaus, veikiančio esant mažam temperatūrų skirtumui, tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 10(106). – P. 113–116.

Tyrimų tikslas – atlikti labai mažos galios termoelektrinio generatoriaus, kuriame šilumnešis natūraliai cirkuliuoja ir kuris veikia esant mažam temperatūrų skirtumui, energinį vertinimą. Tyrimuose naudotas generatorius su 0,0096 m^2 ploto termoelektriniais elementais. Termoelektriniai elementai sumontuoti tarp šilumokaičių, kuriais teka karštas ir šaltas šilumnešis. Elementų paviršių temperatūrų skirtumas buvo 18,9–26,3 ^oC. Eksperimentai parodė, kad šaltojo šilumnešio lyginamajam debitui padidėjus iki 0,347–0,376 l/(s·m^2), generuojamas energijos kiekis didėja nedaug ir per 8 valandas sudaro apie 383 Wh/m^2, o generatoriaus efektyvumo koeficientas buvo apie 1,1 %. Il. 4, bibl. 11 (anglų kalba; santraukos anglų ir lietuvių k.).