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THERMOELECTRIC GENERATOR WITH A PORTABLE STOVE

The paper presents the results of the development and experimental research of a thermoelectric generator, which consists of a thermoelectric unit based on an army pot and a portable stove of widespread use. The obtained results confirm the possibility of using a thermoelectric generator to power mobile phone batteries and various gadgets. The achieved energy parameters significantly outperform the closest existing analogues. The expediency of constructive revision of the selected portable stove in terms of providing the possibility of using an open flame has been established. The economical calculations of the device have determined the average cost of the TEG 170. Bibl.7, Fig. 7, Tabl. 2.

Key words: thermoelectric generator, physical model, portable stove.

Introduction

Portable power sources are now in active demand in places where there is no centralized grid. Interest in such sources has grown in recent years due to the need to charge the electric batteries of modern laptops and gadgets. Ukrainian soldiers in Eastern Ukraine are particularly interested in such devices. Thermoelectric generators (TEGs) on solid fuel have serious advantages over generators whose operation is based on other physical principles: photovoltaic, wind. They are more reliable, easy to maintain, not afraid of shocks and vibrations, easily disguised in the field. With the help of such devices, one can not only get electricity, but also cook and heat food, heat in winter.

The purpose of this work was to create and study a highly efficient portable thermoelectric generator characterized by low weight and size parameters and economically accessible to a wide range of consumers.

A brief overview of portable TEGs with solid fuel heat sources with analysis of the achieved parameters and characteristics.

Scientists and engineers from many countries are actively working to create more efficient thermoelectric portable generators, which would be characterized by lower weight and size parameters, high enough efficiency and modern design.

The **Biolite Basecamp** [1] device can use fallen branches, dry wood chips, cones or other wood as fuel.

The power output to the USB port of this device is 5 W, the voltage is 5V. The weight of the device is 8.16 kg. The cooking surface area is 50.5 cm^2, the diameter of the device is 33 cm. The cost of the generator is 301 US dollars.

The disadvantage of this design is the significant weight and low efficiency of thermoelectric conversion. The ratio of electric power to the weight of the generator with the stove is 0.6.

The thermoelectric generator **FireBee Power Tower** [2] converts heat from any portable stove into electricity for charging smartphones, tablets and other electronic gadgets.

The device can be used with various heat sources, it can achieve an electrical power of 10 W at a voltage of 5V, but its disadvantage is that in addition to the heat of the stove, for its operation it needs a regular replacement of the heated water with cool water. This creates an inconvenience in the field and makes it much more difficult to use this device.

The thermoelectric generator [3] comprises thermoelectric generator modules, "hot" heat exchangers, "cold" heat exchangers. “Hot" heat exchangers are immersed in the reservoir of a hot geyser, and "cold" heat exchangers are buried in the "permafrost" or immersed in a cold reservoir. The thermoelectric generator works as follows. Hot "heat exchangers" are heated from the hot reservoir of the geyser and supply heat to the thermoelectric generator modules, while "cold" heat exchangers remove heat from the thermoelectric generator modules and are cooled in "permafrost" or in a cold reservoir. Due to the temperature difference created by "hot" and "cold" heat exchangers, thermoelectric modules generate electricity. Thus, for the operation of a thermoelectric generator, natural sources of heating and cooling are used. This design solution in the actual operation of the device requires the presence of natural sources of heat and cold. This fact makes impossible wide application of such a device.

The tourist generator PowerSpot Mini Thermixc [4] realizes a stable output power of 7 W and allows charging electronic devices in the appropriate time:
Mobile phone (1500 mAh) - 1 h 30 min
Smartphone (3000 mAh) - 3 h
iPhone 6 (1800 mAh) - 1 h 45 min
iPhone 7 (1969 mAh) - 2 h
iPhone 7 plus (2900 mAh) - 2 h 50 min
iPad / tablet (6500 mAh) - 6 h 30 min
GoPro HER04 (1160 mAh) - 1 h 10 min

The developers declare a service life of 50.000 hours at operating temperatures of 150 ºC – 400 ºC. For operation, the device consumes about 50 g of liquefied gas. This circumstance makes regular use of the generator in the field practically impossible.

The purpose of this work is to create and study a highly efficient portable thermoelectric generator, which would have low weight and size and would be economically available to a wide range of consumers.

Physical model of a TEG with a heat source

Fig. 1 shows a physical model of thermoelectric generator unit comprising a thermopile, heat spreaders for heat supply and removal from the thermopile, a device for intensive heat removal and a heat source – flat-parallel surface uniformly heated with flame.

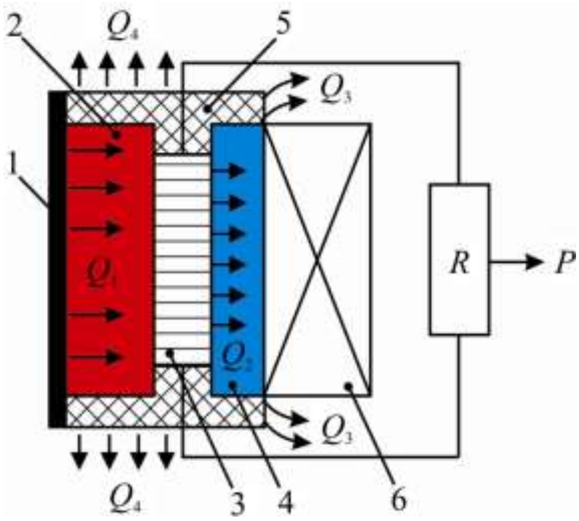


Fig. 1. Physical model of thermoelectric generator unit:
1 – heated surface; 2 – hot heat spreader;
3 – thermopile; 4 – cold heat spreader;
5 – housing; 6 – thermopile cooling block.

Since the generator is built into a heated surface, the processes of heat exchange between a real source of fuel combustion and this surface are not considered. The temperature of the heated surface is assumed to be equal to the temperature of the hot TEG heat exchanger.

Thus, heat supply from the heated surface to the hot side of the thermopile and heat removal from the thermopile cold junctions to the cold heat exchanger is carried out due to thermal conductivity and is described by the equations [5]:

$$Q_1 = \frac{\lambda_T S_T}{l_T}(T_T - T_\Gamma), \tag{1}$$

$$Q_2 = \frac{\lambda_m S_m}{l_m}(T_X - T_m), , \tag{2}$$

where λ_T, λ_m is thermal conductivity of material of the hot and cold heat conductors; T_T, T_m are temperatures of the hot and cold heat conductors; T_Γ, T_X is temperature of the hot and cold side of thermopile, respectively.

Thermal power Q3 is removed from the cold heat conductor by free convection into the water contained in the cooling block (pot capacity):

$$Q_3 = \alpha(T_m - T_0)S_m\,, \tag{3}$$

where $\alpha(v)$ is the coefficient of convective heat transfer between the cold heat conductor and water in the cooling block; T_0 is the temperature of the liquid in the cooling block.

The electric power generated by the thermopile is proportional to Q_1 and the efficiency of the thermopile η:

$$P = P_{TEБ} = Q_1\eta\,, \tag{4}$$

The main heat losses Q_4 occur on the thermopile through thermal insulation:

$$Q_4 = \frac{\lambda S_T}{L}(T_Б - T_0), \quad (5)$$

where λ is the thermal conductivity of the insulating material; S_T is the surface area of the hot heat conductor which is not occupied by the thermopile; L is the thickness of the insulating layer.

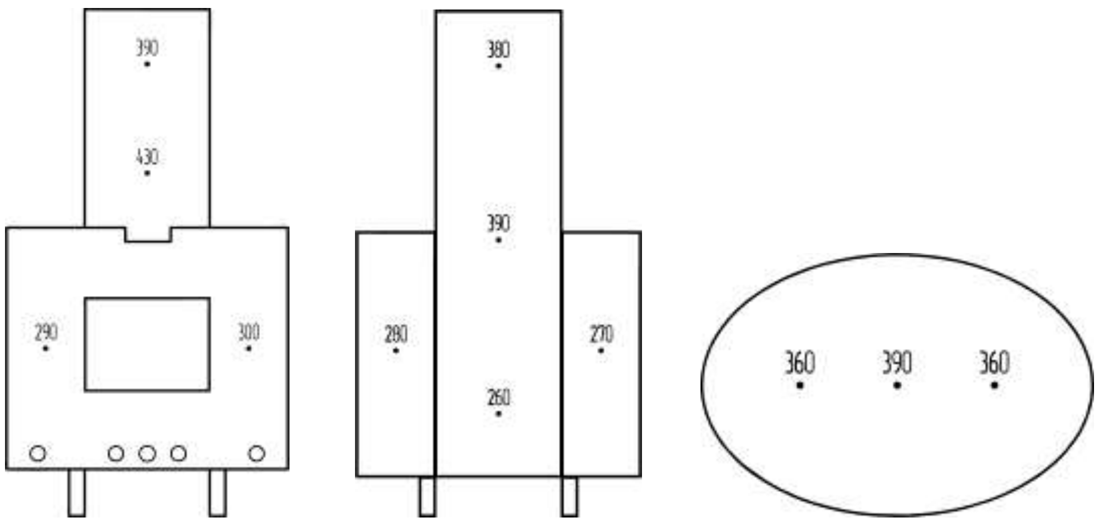
The heat balance equation for the selected model of the thermoelectric generator can be written as:

$$\begin{cases} Q_1 = P + Q_2 + Q_4, \\ Q_2 = Q_3 + Q_4 \end{cases} \quad (6)$$

The solution of the system of equations (6) makes it possible to determine the main energy and design parameters of the thermoelectric generator unit in particular and a complex unit with a portable heater in general.

Optimization of TEG design

Optimization of the generator unit was preceded by an experiment to determine the temperatures of the elements of the selected portable stove [6]. Fig. 2 presents the results of such measurements.



a) *b)* *c)*

Fig.2. Results of measuring the temperatures of the heater walls (°C)
a) – front view, b) – rear view, c) – top view.

Optimization computer calculations, which took into account the experimental temperature measurements, made it possible to determine the design parameters of the thermoelectric generator unit which was designed to be placed on the cooking surface of a portable stove.

From the computer analysis it followed that thermoelectric generator unit based on a military pot should contain two thermoelectric generator modules in its bottom facing the heat source. The

Altec-1061 module is installed as the optimal thermoelectric module for certain temperature and thermal conditions.

Calculation of energy characteristics of the TEG with a stove

The approximate calculated mass of firewood at one loading in the stove m = 60g = 0.06 кg. When burning one load of firewood, the released energy E is:

$$E = G\cdot m = 750 \text{ (kJ)} \qquad (7)$$

where G=12.56 mJ/kg is calorific value of firewood.

Thermal power Q absorbed by thermoelectric modules:

$$\eta = \frac{P}{Q} \rightarrow Q = \frac{P}{\eta} = 110 \text{ (W)} \qquad (8)$$

where $P = 5$ W is calculated electric power generated by modules, $\eta = 0.045$ is the efficiency of modules at the hot and cold side temperatures T_h = 300°C and T_c = 100°C, respectively.

Operating time t at one loading while minimizing heat losses:

$$Q = \frac{E}{t} \rightarrow t = \frac{E}{Q} = 2 \text{ (h)} \qquad (9)$$

Thermal power $Q_н$ consumed to heat water in the generator pot:

$$Q_н = Q - P = 105 \text{ (W)} \qquad (10)$$

Time t of heating water in the generator pot:

$$Q_н = \frac{c\cdot m\cdot(T_1 - T_0)}{t} \rightarrow t = \frac{c\cdot m\cdot(T_1 - T_0)}{Q_н} = 1 \text{ (h)} \qquad (11)$$

where c=4.22 $kJ/kg\cdot K$ is heat capacity of water;

m=1l is the volume of water in the pot;

T_1=100 °C is the final water heating temperature;

T_2=20 °C is the initial temperature of water in the pot.

In the absence of heat loss, the operating time of the thermoelectric generator at one loading of fuel can be approximately 2 hours.

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Description of TEG design

The design of a thermoelectric unit for work with a portable stove is shown schematically in Fig. 3.

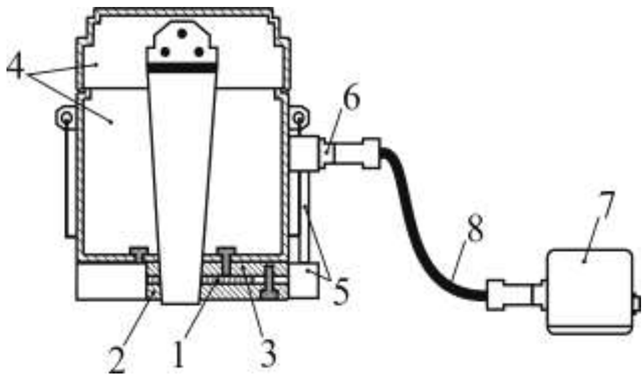

Fig.3. Schematic of thermoelectric generator unit.1 – thermopile; 2 – heat-conducting plate;3 – heat sink plate; 4 – army pot with a lid;5 – protective housing; 6 – electric output; 7 – electronic voltage stabilization unit; 8 – electric connecting cable.

To protect the electrical terminals of the thermopile from direct flame and external mechanical loads, the generator contains a protective housing **5**, which ends with an electrical output **6**. Using an electric cable **8,** the thermoelectric generator is connected to the electronic output voltage stabilization unit **7**. The appearance of the unit is shown in Fig. 4.

Fig. 4. Appearance of the thermoelectric unit

The Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine has developed, researched and standardized a thermoelectric unit for universal use with various heat sources and fuels. Table 1 shows the main parameters of the Altec - 8046 unit [7].

<u>*Table 1*</u>

Basic parameters of the Altec-8046 thermoelectric unit

1	Electric power, W	5
2	Electric voltage output, V	5.10
3	Pot volume, l	1.3
4	Overall dimensions, mm	170 × 170 × 100
5	Mass, kg	1

Methods of experimental research

The purpose of research conducted at the Institute of Thermoelectricity was to determine the energy characteristics of a thermoelectric army pot on a portable stove. The maximum electric power of the generator was measured in the range of water temperatures T_w = (20-100) °C every 10°C from the moment of ignition of the stove. The schematic of the experiment is shown in Fig. 5.

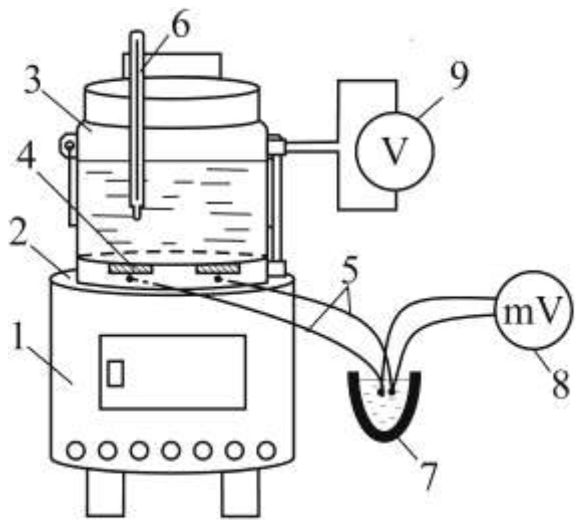

Fig.5 Schematic of the experiment to study the energy characteristics of thermoelectric army pot.
1 – tourist stove; 2 – cooking surface; 3 – thermoelectric generator;
4 – thermoelectric generator modules; 5 – thermocouples;
6 – thermometer; 7 – vessel with melting ice;8 – millivoltmeter; 9 – voltmeter.

When studying the energy characteristics of the generator, at all stages of the experiment, the fuel consumption was recorded to determine the obtained thermal power and the efficiency of thermoelectric conversion.

Research results

The time dependences of the energy characteristics of the Altec-8046 thermoelectric unit with a portable stove are presented in Fig. 6.

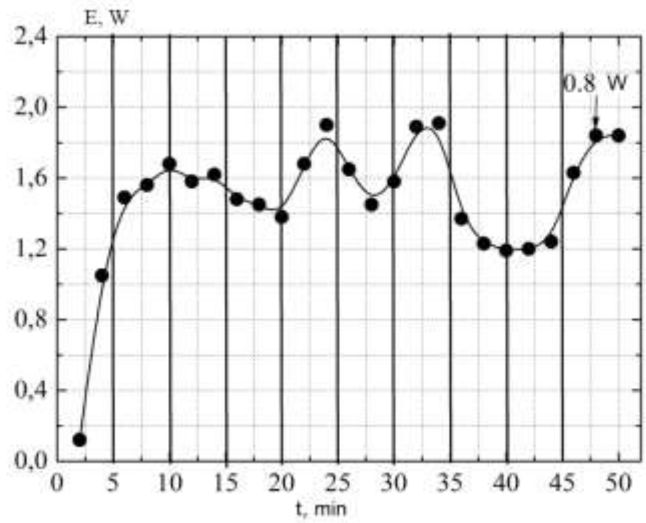

Fig. 6. Dependence of electromotive force E of thermoelectric modules on time t. Vertical black lines indicate the moments of throwing fuel into the stove.

In these studies, firewood was used as fuel. Firewood consumption g = 840 g / hour. Thermal design power of the stove Q = 2.9 kW. For comparison, a study of a thermoelectric generator unit was carried out on an open flame from dry alcohol. Fig. 7 shows the obtained dependence of the electromotive force and the value of power on time.

The comparison of the obtained results showed the expediency of refining the portable stove, which would allow operation of the thermoelectric unit with an open flame. This design solution can improve the efficiency of TEG by a factor of ~ 1.6.

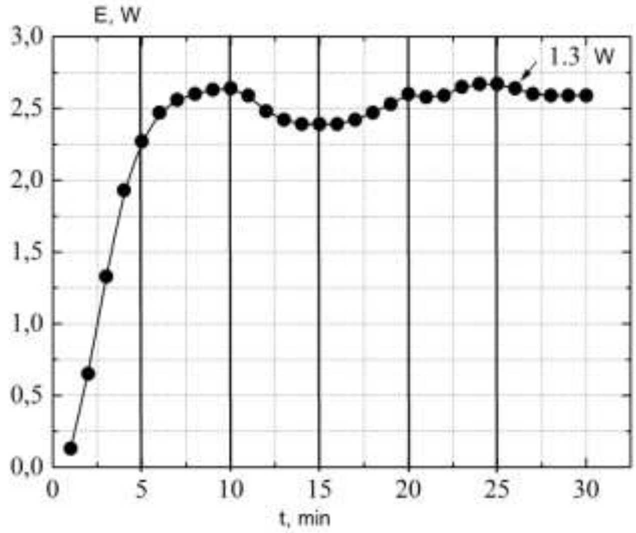

Fig. 7. Dependence of electromotive force on time in the variant of open flame

The consumption of dry alcohol g = 420 g / h. In this case, the thermal power of the stove was Q = 3.6 kW. The volume of water poured into the pot is 1 liter. The achieved efficiency values were about 1% for a TEG with a portable stove. The ratio of the output power to the weight of the device with a wood-fired stove is ~ 0.8, with an open flame - 1.3. These values are higher than those of the closest analogues.

Economic calculations of the cost of the developed device were carried out. Table 2 presents the cost of a single product of a thermoelectric generator with an army pot "Altec-8046" versus the batch size.

Table 2

The cost of thermoelectric generator versus the batch size

Batch size, pcs.	1	10	100	1000
Cost, $	190	178	163	150

Conclusions

1. A thermoelectric generator based on the Altec-8046 thermoelectric unit with a portable stove has been developed.
2. Studies carried out on various fuels have shown the possibility of using the developed device for power supply of modern means of communications and various gadgets.

3. The achieved values of the output electric power with respect to the weight of the device significantly outweigh the closest known analogues.
4. The expediency of constructive revision of the selected portable stove in terms of providing the possibility of using an open flame has been established.
5. The energy efficiency of a TEG with a portable stove after its improvement can increase by a factor of 1.6.
6. The economic calculations of the device have determined the average cost of the TEG as $170.

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ТЕРМОЕЛЕКТРИЧНИЙ ГЕНЕРАТОР З ПОРТАТИВНОЮ ПІЧКОЮ

У роботі наводяться результати розробки та експериментального дослідження термоелектричного генератора, що складається з термоелектричного блоку на базі армійського казанка та портативної пічки широкого використання. Отримані результати підтверджують можливість використання термоелектричного генератора для живлення акумуляторів мобільних телефонів та різноманітних гаджетів. Досягнуті енергетичні параметри суттєво переважають найближчі існуючі аналоги. Встановлено доцільність конструктивного допрацювання вибраної портативної пічки в частині забезпечення

можливості використання відкритого полум'я .Економічні розрахунки пристрою визначили середню вартість ТЕГ на рівні 170 доларів США. Бібл. 7, рис. 7, табл. 2.
Ключові слова: *термоелектричний генератор, фізична модель, портативна пічка.*

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ТЕРМОЭЛЕКТРИЧЕСКИЙ ГЕНЕРАТОР С ПОРТАТИВНОЙ ПЕЧЬЮ

В работе приводятся результаты разработки и экспериментального исследования термоэлектрического генератора, состоящего из термоэлектрического блока на базе армейского котелка и портативной печи широкого применения. Полученные результаты подтверждают возможность использования термоэлектрического генератора для питания аккумуляторов мобильных телефонов и различных гаджетов. Достигнутые энергетические параметры существенно превышают таковые, присущие ближайшим существующим аналогам. Установлена целесообразность конструктивной доработки выбранной портативной печи в части обеспечения возможности использования открытого пламени. Экономические расчеты устройства определили среднюю стоимость ТЭГ на уровне 170 долларов США. Библ. 7, рис. 7, табл. 2.
Ключевые слова: термоэлектрический генератор, физическая модель, портативная печь.

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