DIDACTICAL STAND FOR THE STUDY OF THERMOELECTRIC GENERATORS

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REZUMAT. Această lucrare prezintă un stand didactic pentru studiul generatoarelor termoelectrice, dispozitive pentru conversia directă a căldurii în energie electrică. Deşi au eficienţă scăzută, sub 10%, utilizarea lor în generarea de energie este utilă datorită altor avantaje: complexitate redusă, lipsa părţilor în mişcare şi a întreţinerii. Lucrarea prezintă metodologia pentru studiul, testarea şi identificarea caracteristicilor energetice ale generatoarelor termoelectrice, precum şi proiectarea unui stand experimental pentru efectuarea acestor teste.

Cuvinte cheie: generatoare termoelectrice, testare.

ABSTRACT. This paper presents a stand for didactical study of the thermoelectric generators. Thermoelectric generators are devices that directly convert heat into electricity. Although their efficiency is low, below 10%, their use in power generation is beneficial due to other characteristics: reduced complexity, lack of moving parts and therefore the maintenance.The paper presents the methodology for studying, testing and power characteristics identification of the thermoelectric generators and the design of an experimental stand for performing the tests.

Keywords: thermoelectric generators, testing.

1. INTRODUCTION

Thermoelectric conversion is a technology that allows direct conversion of heat into electricity. Since a thermoelectric generator operates between two heat sources: a warm temperature T_1 and a cold temperature T_2, their effectiveness is limited by the second principle of thermodynamics (Carnot efficiency):

$$\eta_t = 1 - \frac{T_2}{T_1}. \quad (1)$$

However, thermoelectric generators operate at small temperature differences and have no moving parts and maintenance, that makes them very attractive for the production of electricity from heat sources with low thermal parameters as:

- recovery of waste heat from industrial processes (combustion gases from furnaces and boilers, water cooling of the compressors and electric furnaces etc.).
- heat recovery from exhaust pipes of vehicles.

Thermoelectric generators can be used to produce electricity by direct conversion of renewable energy as:

- solar energy;
- geothermal energy;
- cogeneration plants based on wood.

Also, due to their robustness, thermoelectric generators are suitable for special applications: airspace, military and telecommunications, cathodic protection of gas pipes, etc..

Manufacturing technology of thermoelectric generators has progressed greatly in recent years due to the high demand for thermoelectric refrigerators, knowing that powered with dc voltage, thermoelectric generators are reversible and can operate as heat pumps (refrigerator or air conditioning devices).

The paper presents the operating principle of thermoelectric generators and a test methodology to identify their main characteristic parameters. For this purpose, a stand for the study of thermoelectric generator characteristics is designed and built.

This stand can be used for educational purposes, to train students in energy conversion and renewable energy and for research purposes, in the case of doctoral students and researchers from industry.

It is known that a high power thermoelectric generator will contain hundreds or thousands of low-power thermoelectric modules (hundreds of watts). For design optimization it is recommended the experimental study of the behavior of a single module, or a small number of modules under thermal and electrical data, experimental results being extrapolated to high power thermoelectric generator design.

The technical characteristics of the thermoelectric module from this stand, initially were unknown. On the stand were performed experimental determinations, whose analysis allowed the identification of main thermal and electrical characteristics of the thermoelectric generator to be studied.

2. THERMOELECTRIC GENERATORS WORKING PRINCIPLE

Thermoelectric generators (TEG) are compact devices that convert heat power directly into electricity due to the Thomson, Peltier and Seebeck effects.

Seebeck effect (Figure 1) was discovered in 1821 by Thomas Seebeck.

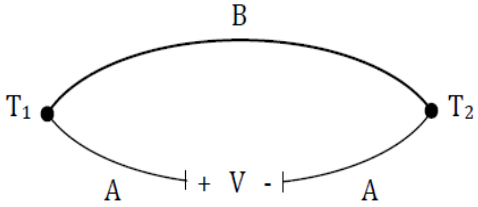

Fig. 1. The Seebeck effect principle [1].

Heating one junction of two wires made of different metals, one noted that a voltage is obtained in the circuit:

$$V_{AB} = (\alpha_A - \alpha_B) \cdot \Delta T \,, \tag{2}$$

where α_A and α_B are the two metals Seebeck coefficients and ΔT is the temperature difference between the two junctions [1]. The materials were classified as a generated voltage in relation to an ideal material, superconductor. In practice, lead is used as a reference scale.

The Peltier effect is discovered in 1834 by Jean Peltier and is actually a consequence of the Seebeck effect (Figure 2).

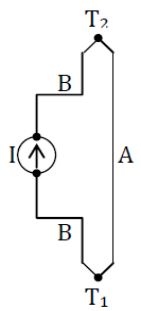

Fig. 2. The Peltier effect principle [1].

If a current source is introduced in the Seebeck thermoelement circuit, in the two junctions a power is produced and consumed, so we have a heat transport from hot source to cold source, a heat pump is made without motion parts:

$$Q_{AB} = (\Pi_A - \Pi_B) \cdot I \,, \tag{3}$$

where Π_A and Π_B are Peltier coefficients of the two metals; Q_{AB} is the pump power and I is the current flowing through the circuit [1].

The Thomson effect was discovered by William Thomson in 1854. It was first formulated the following relationship:

$$q_A = \tau_A \cdot I \cdot \left(\frac{dT}{dx}\right), \tag{4}$$

where q_A is the heat absorption rate per conductor unit length; τ_A is the Thomson coefficient for the conductor A and dT/dx is the temperature gradient per unit length of the conductor. The relationship is thermodynamically reversible and describes the behavior of a material [1].

Thomson has unified the three coefficients by the relation:

$$\tau = T \cdot \frac{d\alpha}{dT} \,, \tag{5}$$

$$\Pi = \alpha \cdot T \,, \tag{6}$$

where τ_{AB} is the Thomson coefficient; T is the absolute temperature (K) and $d\alpha/dT$ is the change of Seebeck coefficient with the temperature [1].

A typical thermoelectric generator (Figure 3) consists of two dielectric parts (usually ceramic) that serve as support for N and P type small semiconductors, electrically connected in series and thermally in parallel. Thus the thermoelement requires a source of high temperature for the hot side and cooling for the cold side (environment, ventilation, cold water etc.).

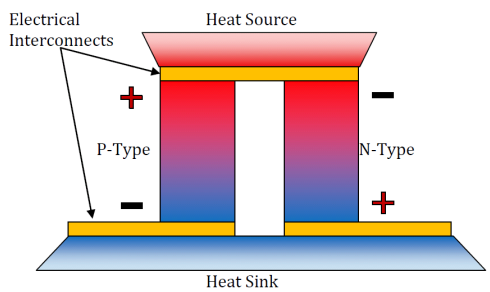

Fig. 3. The construction of a thermoelectric generator [2].

Components of N type and P type are made of different semiconductor materials (optimized for Seebeck effect), which have a different density of free electrons at the same temperature. As semiconductor materials are used: Bi_2Te_3, Sb_2Te_3 and Bi_2Se_3.

As the heat moves from the hot side to the cold side, charge carriers (electrons and holes) are carried with the heat. In this way a significant potential difference is generated (Seebeck voltage):

$$U = \alpha \cdot (T_h - T_c) \,, \tag{7}$$

where α is the Seebeck coefficient; T_h is the temperature of the hot source and T_c is the temperature of the cold source.

Materials used for the thermoelements must meet the following requirements:

- a high Seebeck coefficient α to produce a high voltage;
- thermal conductivity λ as low as possible, to reduce the heat flow that bypasses the thermoelement;
- electrical conductivity σ as high as possible to reduce the ohmic resistance and the Joule loss in the thermoelement.

These are contradictory requirements; metals have good electrical conductivity, but also good thermal conductivity.

To assess the quality of a thermoelectric generator is used the so-called figures of merit Z or Z_T:

$$Z = \frac{\alpha^2 \cdot \sigma}{\lambda}, \tag{8}$$

$$Z_T = \frac{\alpha^2 \cdot \sigma}{\lambda} \cdot T. \tag{9}$$

Table 1 shows the Seebeck coefficients and figures of merit for the main materials used in thermoelements construction, at room temperature.

Table 1

Seebeck coefficients and merit figures for materials thermoelement selection at room temperature [1].

Element/compound	α [10^{-6} V/K]	$\alpha^2\sigma/\lambda$ [$10^{-3}K^{-1}$]
$(Bi_{2-x}Sb_x)Te_3$	210	1-3
p-Bi_2Te_3	140	
p-Si	1300	0.0001
Sb	48	0.03
Ni-Cr (80/20)	25	0.04
Cr	22	0.03
Ni	-20	0.04
Cu-Ni	-35	0.09
Bi	-68	0.3
n-Bi_2Te_3	-110 la -250	1-3
$Bi_2(Se_xTe_{3-x})$	-250	

It can be seen that the p-type silicon has the highest Seebeck coefficient, but the smallest figure of merit because it has low electrical conductivity and high thermal conductivity, therefore is used rarely, only at high temperatures.

Because semiconductors are not working at very high temperatures, are obtained about 5% efficiency. Currently, there are started researches for the use of other materials that will improve the performance of thermoelectric generators.

To increase the power unit, several thermoelements are coupled in an ensemble by connecting them thermaly in parallel and electric in series (Figure 4).

Thermoelectric generators are widely used in the following fields: military, medical, industrial, automotive, scientific laboratories, the opto-electric, telecommunications, microelectronics. They are also used to supply cathodic protection of gas pipes and spacecraft instruments.

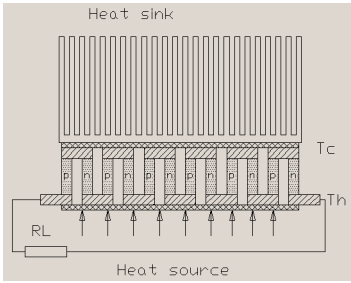

Fig. 4. Thermoelectric module.

Thermoelectric efficiency of such a generator can be expressed as follows:

$$\eta = \frac{\text{Generated Power}}{\text{Transfered Heat}}. \tag{10}$$

3. THERMOELECTRIC GENERATOR STAND STRUCTURE

Figure 5 presents the thermoelectric generator to be studied.

Fig. 5. Thermo-electric generator TOG 127.

Figure 6 presents the thermoelectric module designed and built around this thermoelectric generator.

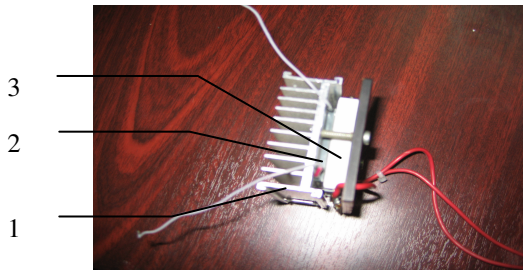

Fig. 6. The thermoelectric module: 1 – heat sink (radiator); 2 – thermoelectric generator; 3 – heat source (resistors).

Figure 7 presents the stand for studying the thermoelectric generators. The thermoelectric module 2 is heated with 4 ceramic resistors of 0.56Ω, 10W, connected in series to a 5V power source 4. At the output of thermoelectric assembly is used a load resistance 1. Measurement devices are used too, for voltage and current at the output of the generator.

It is also used a thermal imager 3 of type FLUKE Ti20 [4] for the measuring of the temperatures of the hot and cold side of the thermoelectric module.

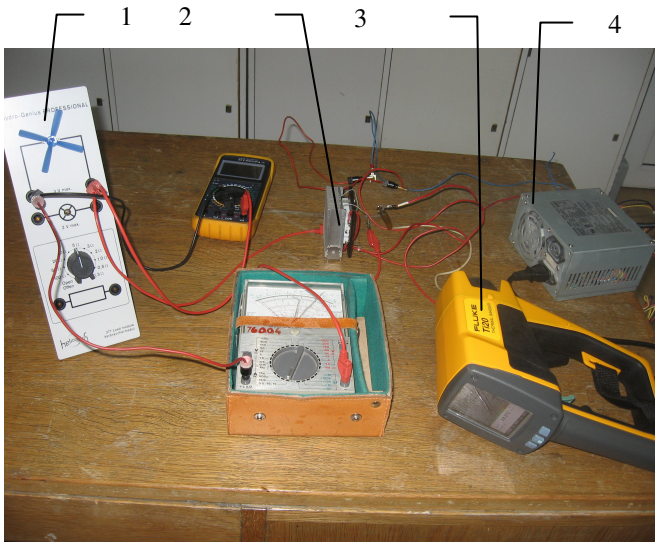

Fig. 7. Thermoelectric generator stand: 1 – Load (a calibrated resistor); 2 – Thermoelectric module; 3 – The thermal imager FLUKE Ti20; 4 - The power source.

In Table 2 are presented the measured parameters of the thermoelectric module: the output voltage and output current for the module, the hot side temperature T_1 and cold side temperature T_2 and also different values considered for the load resistance. Were also calculated the power produced by the generator and the temperature difference between the two parts of it.

Table 2

Mesured and calculated parameters for the thermoelectric generator

Crt. no.	R_S [Ω]	U [V]	I [mA]	P [mW]	T_2 [°C]	T_1 [°C]	ΔT [°C]
1	20	0.3	15	4.5	43	105	62
2	10	0.45	35	16	47	110	63
3	5	0.326	60	19.6	50	115	65
4	3	0.268	70	18.76	53	120	67
5	2	0.206	85	17.51	56	124	68
6	1	0.114	108	12.31	57	125	68
7	20	0.523	20	10.46	60	129	69
8	10	0.464	33	15.31	62	131	69
9	5	0.338	60	20.28	62	132	70
10	3	0.276	72	19.87	63	134	71
11	2	0.211	88	18.56	64	135	71
12	1	0.116	110	12.87	64	135	71

After analyzing the measurements presented in Table 2 it can be seen that the maximum power produced by the generator is 20.3 mW and it is obtained for a load resistance of 5 Ω, cold side temperature in this case is T_2=62°C and the warm side temperature is T_1=132°C, temperature difference is 70°C.

In this Table it can be seen two series of measurements performed every two minutes. The hot side temperatures are increasing in the second series of measurements, but the increase of generated power is insignificant because the temperature diferences between hot side and cold side of thermoelectric generator have remained almost the same.

In figure 8 is presented the image, taken by thermovision camera FLUKE Ti20, for the thermoelectric assembly at the beginning of the experiment (the measurement Nr. 1), when the temperatures are not to high and the power produced is low. The generated power is only 4.5 mW, especially because of the discrepancy between the load resistance (20Ω) and the inner resistance of the thermoelectric generator (3.39Ω).

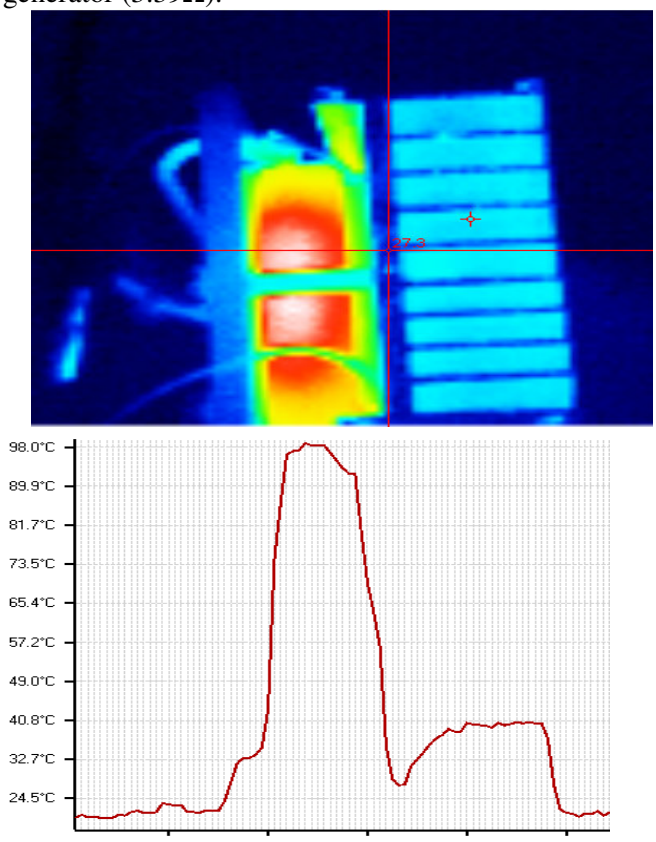

Fig. 8. Infrared images and temperature profile for the thermoelectric module assembly at the beginning of the experiment: R_S=20Ω, T_2=43°C, T_1=105°C, P=4.5mW.

In figure 9 is presented the image at the end of experiment (the measurement Nr. 12), when the temperatures are the highest from the cycle.

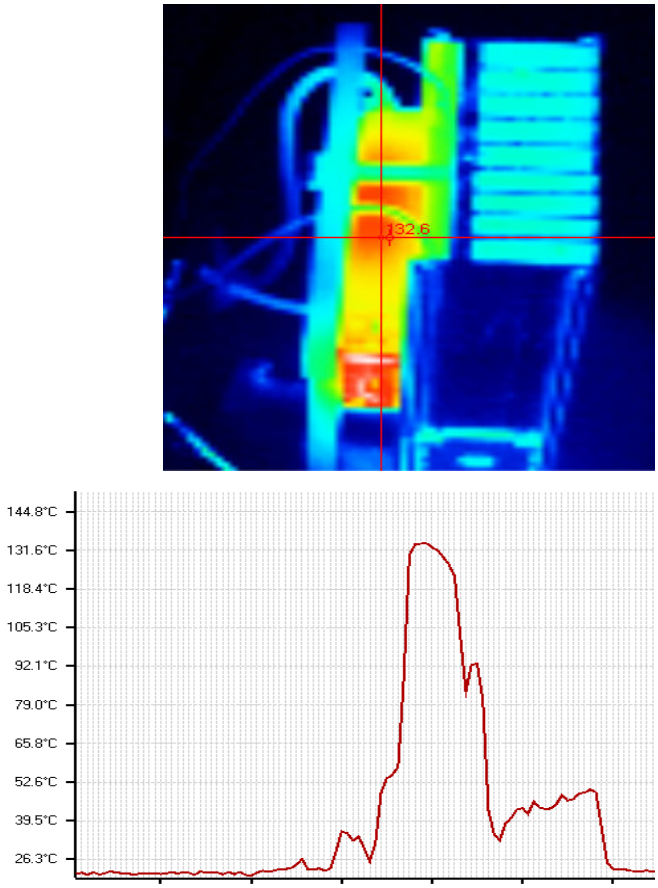

Fig. 9. Infrared images and temperature profile for the thermoelectric module assembly at the end of the experiment: R_S=1Ω, T_2=64°C, T_1=135°C, P=12.87mW.

In this case, the generated power is very low (12.87mW), also because of the discrepancy between the load resistance (1Ω) and the inner resistance of the thermoelectric generator (3.39Ω). In this picture the temperature of radiator is not correct because the profile line passes between two fins.

From the Table 2 can be seen that the maximum generated power of P=20.28mW corresponds to the measurement Nr. 9, to a voltage of 0.6V and to the load resistance of 5Ω. These values can be considerred as rated power, rated voltage and rated load resitance. This rated load resistance is very closed to inner resistance of thermoelectric generator, as is stated in the electric circuit theory.

This measurement, made in rated conditions, can be used for calculation of the Seebeck coefficient:

$$\alpha = \frac{U}{(T_1 - T_2)} = \frac{0.338V}{70°C} = 0.0048\ V/°C. \quad (11)$$

The thermoelectric module image and the temperature profile, coresponding to this optimal point of operation is presented in figure 10.

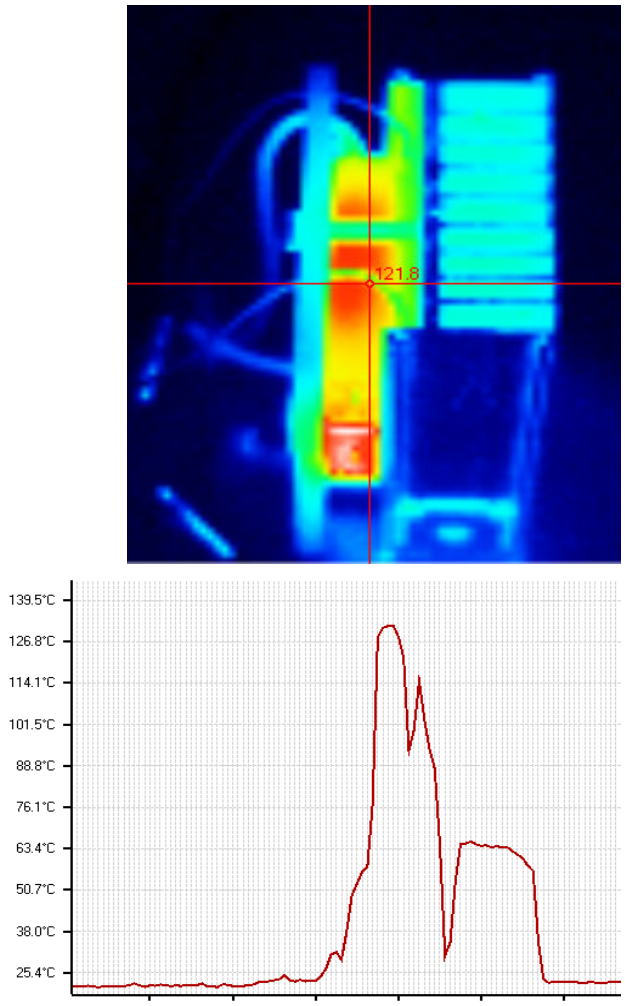

Fig. 10. Infrared images and temperature profile for the thermoelectric module assembly at the maximum power generated (the rated power): R_S=5Ω, T_2=62°C, T_1=132°C, P=20.28mW.

From these measurements is difficult to calculate the efficiency of this thermoelectric generator because of the difficulties in evaluation of the heat transferred between the hot side and cold side and the total heat losses by convection and radiation. In order to estimate the energy efficiency of a thermoelectric generator, the measurementss must be accompanied by a Finite Element Method thermal analysis [5,6].

4. CONCLUSIONS

This paper presents a testing methodology for the identification of the main electrical and thermal parameters for an thermoelectric generator. It is also presented a designed thermoelectric module and a stand for performing the tests. For a small thermoelectric generator, the proposed tests are performed and analysed.

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