The Study and Modeling of a Thermoelectric Generator Module

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***Abstract* - This paper presents the study and modeling of a thermoelectric generator module, type TG 100. The identification of TEG's main parameters are presented. The method used is experimental and combined with a FEMM simulation. For the first time the main thermal parameters are measured and the results are compared with the simulation results and catalog data. After analyzing the measured data, results the importance of fitting the heating power with the cooling power in order to obtain the optimum point of operation. This parameter identification is very important for the design of an application.**

***Keywords*: thermoelectric generator**

I. 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):

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

However, thermoelectric generators operate at small temperature differences and have no moving parts and are maintenance free, 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, an experimental stand for the study of thermoelectric generator characteristics has been 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, the experimental results being extrapolated to high power thermoelectric generator design.

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.

II. THERMOELECTRIC GENERATOR 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 (Fig. 1) was discovered in 1821 by Thomas Seebeck.

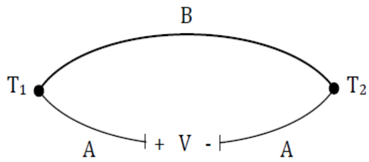

Fig. 1. The Seebeck effect principle [1].

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

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

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 (Fig. 2) [1].

If a current source is introduced in the Seebeck thermo-element circuit, in the two junctions a power is produced and

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consumed, so we have a heat transport from hot source to cold source [1].

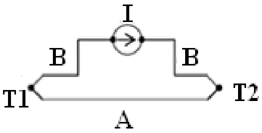

Fig. 2. The Peltier effect principle [2].

In such a way 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

$$q_A = \tau_A \cdot I \cdot \frac{dT}{dx} , \tag{4}$$

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 [K] is the absolute temperature and dα/dT is the change of Seebeck coefficient with the temperature [1].

A typical thermoelectric generator (Fig. 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 thermo-element requires a source of high temperature for the hot side and cooling for the cold side (environment, ventilation, water, etc.).

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.

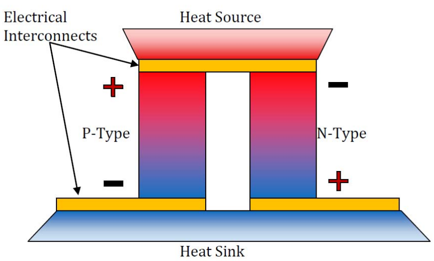

Fig. 3. The construction of a thermoelectric generator [1].

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 U is the generated voltage, 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 thermo-elements 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 thermo-element;
- electrical conductivity σ as high as possible to reduce the ohmic resistance and the Joule loss in the thermo-element.

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

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

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

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, there 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 thermo-elements are coupled in an ensemble by connecting them thermally in parallel and electrically in series.

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

Thermoelectric efficiency of such a generator can be expressed as follows

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

III. MEASUREMENTS WITH TG 100

TG 100, presented in Fig. 4, is the thermoelectric generator studied. Its dimensions are 10x10 cm, the maximum operating temperature is 200ºC.

The model built around it (Fig. 5) is formed by the electric resistance 2, that produces heat for the hot side of the generator, heat sink 3 and the cooler 4 have the role to decrease the temperature for the cold side of TG 100. An autotransformer is used to power the electric resistance with

100V. To measure the output voltage of the thermo-element is used the voltmeter 6.

For greater accuracy, hot and cold side temperatures were measured with Fluke 51 II contact thermometer.

Fig. 4. TG 100 Thermoelectric Generator [3].

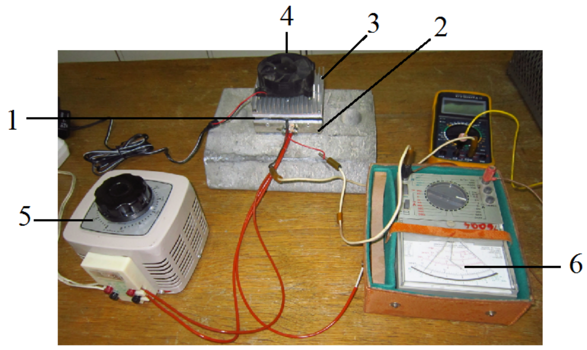

Fig. 5. Thermoelectric Generator Module: 1-TG 100, 2-heat source (electric resistance), 3-heat sink, 4-cooler, 5-autotransformer, 6-voltmeter.

Measurements results with and without the cooler are presented in Table I and Table II. Power produced by TG-100 is highly influenced by the temperature difference between the hot and cold side (Figs.6-8).

TABLE I
MEASURED AND CALCULATED PARAMETERS FOR THE THERMOELECTRIC GENERATOR WITHOUT THE COOLING FAN.

Time [s]	**Th[ºC]**	**Tc[ºC]**	**Uout [V]**	**Δθ [ºC]**	**α = U/ Δθ (10^{-6} V/K)**
0	23,2	22,3	0.2	0,9	0,22
3’	29	25,5	0.7	3,5	0,20
6’	37	32	0.9	5	0,18
9’	45	39	1.1	6	0,18
12’	54	47	1.25	7	0,18
15’	60	53	1.35	7	0,19
18’	66	59	1.4	7	0,20
21’	72	65	1.45	7	0,21
24’	82	74	1.52	8	0,19
27’	88	80	1.56	8	0,20
30’	92	83	1.7/1.6	9	0,19
33’	95	86	1.8	9	0,20
36’	100	91	1.8	9	0,20
39’	105	95	1.85	10	0,19
42’	109	99	1.9	10	0,19
45’	113	103	1.9	10	0,19
48’	116	104	1.9	12	0,16
51’	119	107	1.92	12	0,16
54’	120	108	1.95	12	0,16

TABLE II
MEASURED AND CALCULATED PARAMETERS FOR THE THERMOELECTRIC GENERATOR WITH THE COOLING FAN.

Time [s]	**Th[ºC]**	**Tc[ºC]**	**Uout [V]**	**Δθ [ºC]**	**α = U/ Δθ (10^{-6} V/K)**
57’	116	86	4,5	30	0,15
60’	108	73	4,7	35	0,13
63’	98,5	67	4,3	31,5	0,14
66’	92	64	4	28	0,14
69’	87	60	3,9	27	0,14
72’	84	58	3,7	26	0,14
75’	82	57	3,55	25	0,14
78’	81	56	3,5	25	0,14
81’	79	54	3,4	25	0,14
84’	77	52,5	3,3	24,5	0,13
87’	77	52,5	3,3	24,5	0,13
90’	76,5	52,5	3,25	24	0,14
93’	76	52	3,23	24	0,13
96’	75,5	51,5	3,2	24	0,13
99’	75,5	51,7	3,2	23,8	0,13

From figure 6 can be observed that the dependence U(Δθ) looks like a straight line with the slope proportional to the equivalent Seebeck coefficient. From the figures 7 and 8 can be seen that with natural cooling, in time, the temperature difference and respectively the voltage has stabilized to small values, than has been introduced forced cooling with a computer fan, and the temperature difference and respectively the voltage has increased. But in short time these values began to decrease and have been stabilized to values greater than in case of natural cooling system.

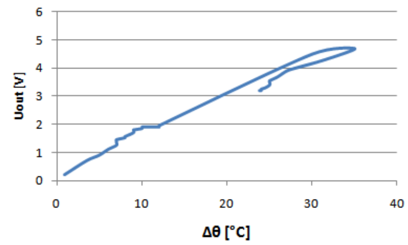

Fig. 6 The dependence U(Δθ).

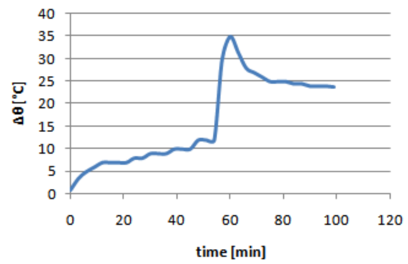

Fig. 7 The dependence Δθ(t).

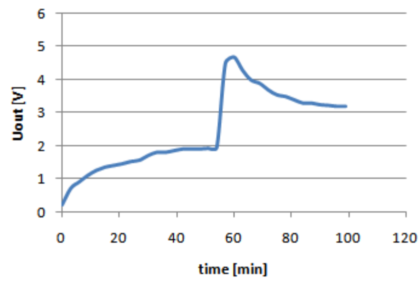

Fig. 8 The dependence U(t).

This thermoelectric generator with natural cooling will be thermally analyzed by Finite Element Method (FEM).

IV. TG 100 Module Analysis with Finite Element Method

For modeling the assembly described above was used heat flux module of FEMM program (Finite Element Method Magnetics, version 4.2) [4]. Field discretization was made with 11189 nodes and 22046 elements, as shown in Fig. 9.

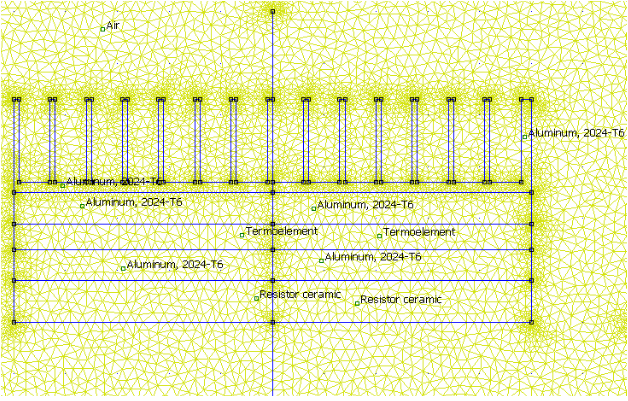

Fig. 9. FEMM discretization of thermoelectric generator module.

In the simulation program were reproduced the normal measurements conditions.

For FEMM testing was used TG 100 heated by the resistor at a power lower that its maximum power (450 W). The resistor has been powered from an autotransformer with reduced voltage

$$P = \frac{U^2}{R}, \quad U = \sqrt{P \cdot R} = \sqrt{100 \cdot 117} = 108\ V, \qquad (11)$$

where R = 117 Ω is the value of the electric resistance that has the heating role.

In modeling results (Fig. 10.) it can be seen that the heat comes from the resistance, where are the highest temperatures. The lowest temperatures are in the radiator zone which has the cooling role of the thermo-element.

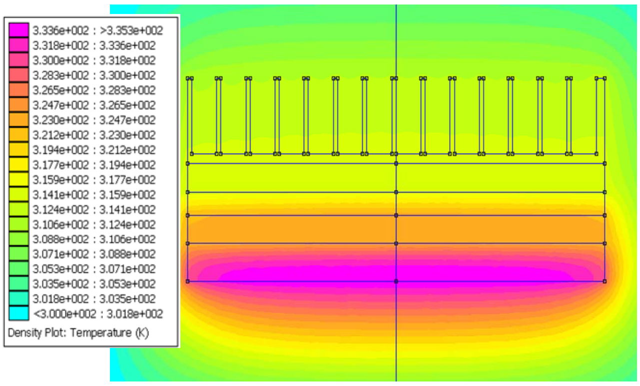

Fig. 10. Thermal diagram of the thermoelectric module (heat flux) and temperature table.

From FEMM analysis of heat flux the following data were extracted:

- Total heat flux made by the resistance Φ_t = 111 W;
- Heat flux through the thermoelectric generator is 81 W;
- Temperature difference between the hot and the cold side of the generator is Δθ = 9 ºC, approximately equal with the measured temperature in Table II (without cooler).

Thermal resistance from FEMM simulation is

$$Rth = \frac{\Delta\theta}{\Phi} = \frac{9K}{81\ W} = 0.11\ K/W \qquad (12)$$

and it is very close to the measured one.

In Fig. 11 it can be seen that the resistance has the highest temperature, between 370 K and 350 K (97-77 ºC), it heats the thermo-element at approximately 77ºC and a temperature drop takes place along it and through the heat sink until 57 ºC (330 K).

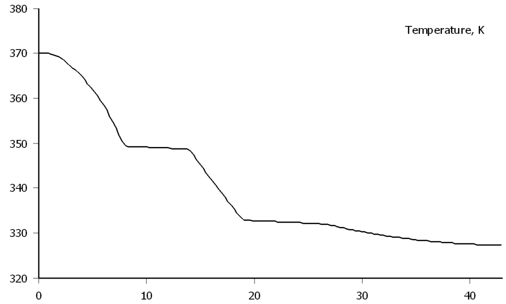

Fig. 11. Vertical temperature distribution in the given FEMM model of the thermoelectric module (bottom-up, as defined by the central line).

V. Conclusions

An experimental stand for the study of thermoelectric generator characteristics, that can be used for educational purposes, has been designed and built.

This paper also presents the FEMM modeling and experimental testing of a TG 100 thermoelectric generator, performed at reduced parameters (only 81 W through TG 100 and reduced temperatures). Data obtained are similar.

TG 100 generated voltage is low (3 V), but from the tests made it can be seen the importance of fitting the heating power with the cooling power in order to obtain the optimum point of operation. To use TG 100 in a large domain (3-24 V) and to supply a constant voltage (e.g. 12 V d.c.) it is recommended a DC-DC converter.

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