Open Access Journal

Journal of Power Technologies 95 (Polish Energy Mix) (2015) 63–67

journal homepage:papers.itc.pw.edu.pl

Seebeck phenomenon, calculation method comparison[1]

Kamil Lubikowski*,a, Stanisław Radkowski[a], Krzysztof Szczurowski[a], Michał Wikary[a]

[a] *Warsaw University of Technology, Faculty of Automotive and Construction Machinery Engineering*
Narbutta Str. 84, 02-524 Warsaw, Poland

Abstract

This paper primarily investigates the Seebeck effect and modeling of thermoelectric phenomena observed during the work cycle of thermoelectric generators (TEG) in cogeneration systems. A simple mathematical model was applied for calculations, and subsequently the durability environment of the Ansys computer program for the purpose of modeling geometry and physical conditions, having assumed the starting conditions and material data. Tasks encountered in technical domains frequently require the modeling of complicated geometry of real objects, applying discontinuous or differentiable functions, which enable description of physical parameters and boundary conditions. This fact involves the introduction of a model divided into a finite number of parts with relatively uncomplicated shapes that will allow a solution to be obtained within their scope, subsequently combining them together in the finite element method (FEM). For empirical research use was made of the Laird Technologies generator: “56890-503 CP14, 71, 045” Laird PL26. In order to determine the load characteristics appropriate temperatures were applied to the cold and hot side of the thermoelectric generator. Subsequently, the system designed to regain energy from the heat was burdened with resistors. The final stage of the tests was installing the system in the exhaust section of the laboratory test stand at the Integrated Laboratory of the Mechatronics System of Vehicles and Construction Machinery, Warsaw University of Technology. The tests were carried out and the abovementioned characteristics designed. Laboratory classes for students were conducted at the test stand, illustrating the Seebeck effect.

Keywords: Cogeneration Energy, Thermoelectric Generator, Finite Element Method

1. Introduction

Growing attention has been directed lately to the use and development of cogeneration systems and renewable energy sources. In the automotive industry energy recovery systems, as well as bi-fuel combustion engine systems, hybrid systems, and others [1–6] are being developed in order to improve the energy transfer of the fuel-air mixture explosion to the wheels, decreasing at the same time consumption of conventional fuels.

The systems of energy recovery fall into the main scope of interest of this paper, especially systems based on the semi-conductor method, which was used in constructing Thermoelectric Generators (TEG) [8–10]. The finite element method (FEM) was applied to simulate thermoelectric phenomena. The finite element method is a tool used in the modeling of a wide spectrum of physical phenomena by means of solving differential equations (extraordinary solutions). Tasks encountered in technical domains frequently require the modeling of complicated geometry of real objects, applying discontinuous or only differen-

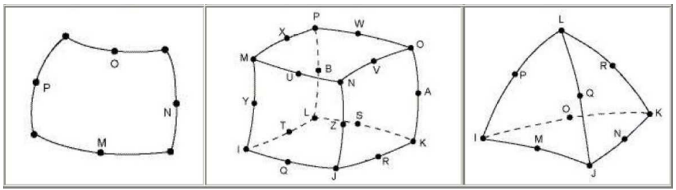


Figure 1: Finite Elements [7]

*Corresponding author
Email address: k.lubikowski@mechatronika.net.pl (Kamil Lubikowski*)

tiable functions, which enable description of physical parameters and boundary conditions. This fact involves the introduction of a model divided into a finite number of parts (dimensions, Fig. 1) with relatively uncomplicated shapes that will allow a solution to be obtained within their scope, subsequently combining them together in the finite element method.

The Peltier modules, in essence, act as a heat pump or electric generator [11, 12] (converting heat energy into electric energy). Depending on the direction of the current flow, the direction of the heat transport is determined; similarly, depending on the direction of the heat flow (temperature difference), electric energy is emitted.

The principle of operation for the thermoelectric cells is based on five physical phenomena: the Peltier effect, the Thomson effect, the Seebeck effect, the Joule effect, and heat (thermal) conduction.

2. Modeling of thermogenerators

2.1. Analytical Model

The TEG energy characteristics depend mostly on the Seebeck coefficient resulting from thermoelectric qualities [11–14]. The Seebeck coefficient is defined as a linear dependence and is basically conditioned by the material features of the applied semi-conductor, as a connector, for the building of the module. Mathematical relations are shown below [5, 11, 14]:

$$V = a \cdot \triangle T \quad (1)$$

where: V—potential difference observed at the terminals of the cell, V; α—Seebeck coefficient,
V/°C; ΔT—temperature difference.

$$\triangle T = T_h \cdot T_c \quad (2)$$

where: T_h—temperature of the hot side of the cell, °C, which is supplied thermal energy (heat) in the form of heat radiating from the heated exhaust; T_c—temperature of the cold cell, °C, which receives the heat flowing through the "plate", the cooling.

In Fig. 2 the voltage value is shown, depending on the temperature difference between the cold and hot sides of the thermoelectric generator. For the cold side, the temperature of 40 °C was adopted and remained constant (it was left unchanged during calculations). The temperature value of the hot side was originally assumed for the purpose of calculations at 50 Celsius, and it was increased till it reached 100°C. The maximum voltage value of the electric energy was obtained for the temperature difference of 60°C and it was 1.5 V.

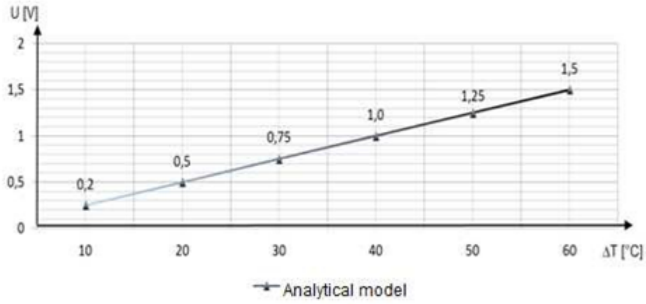


Figure 2: Results, voltage (theoretical method/analytical model)

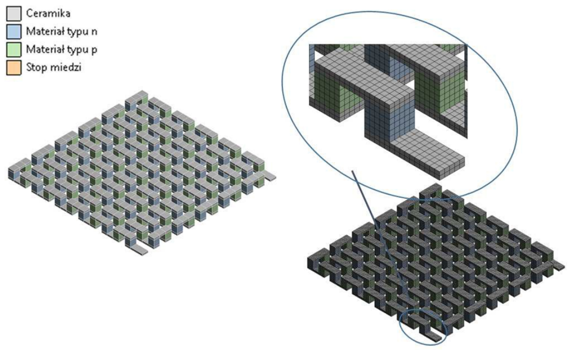


Figure 3: Engine performance according to [15]

2.2. Modeling with FEM

The computer software in durability environment, such as the Ansys program [7, 15–17], was used to simulate the operation of thermoelectric generators (TEG). First, the starting and boundary conditions were established in this program, then the geometric models shown in Fig. 3 were made. For the purpose of calculations the models of finite elements of the Peltier module were applied, as shown in Fig. 1. Because of its simple construction, the geometry does not require the introduction of simplifications, which could significantly affect the correct rendering of the thermogenerator's operation.

All round-ups were removed during the preparation of the computer model, in order to decrease the number of finite elements and enable shorter calculation times. The mesh in places that required such an operation was made dense.

The analysis was divided into 6 steps, with each of them being assigned a maximum 5 sub-steps in order to gradually apply thermal load. The temperature on the "cold" side, which in reality corresponds with the side being cooled, was set at 40°C and put at the bottom surface of copper connectors (Fig. 4). During performance of analyzes this temperature has a determined and constant value.

On the "hot" side, which corresponds with the heated

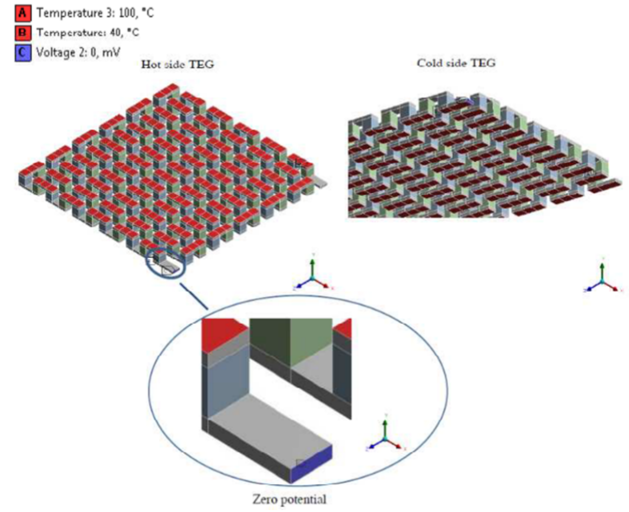
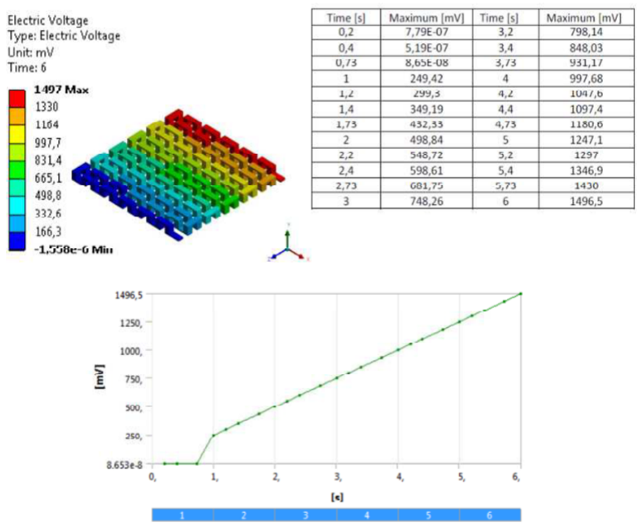


Figure 4: The boundary conditions

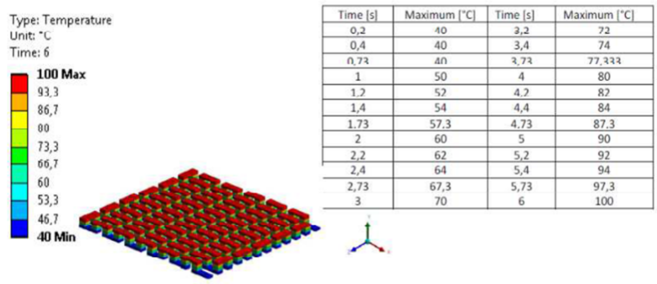


Time [s]	Maximum [mV]	Time [s]	Maximum [mV]
0,2	7,79E-07	3,2	798,14
0,4	5,19E-07	3,4	848,03
0,73	8,65E-08	3,73	931,17
1	249,42	4	997,68
1,2	299,3	4,2	1047,6
1,4	349,19	4,4	1097,4
1,73	432,33	4,73	1180,6
2	498,84	5	1247,1
2,2	548,72	5,2	1297
2,4	598,61	5,4	1346,9
2,73	681,75	5,73	1430
3	748,26	6	1496,5

Figure 5: Results, schedule voltage

side, the temperature was increased during the simulation. In the first step the value of 50°C was determined and it was increased by 10°C with every subsequent step until it reached 100°C. In order to direct the current flow of the electric energy generated when receiving the temperature difference, zero potential was placed at one of the ends.

The analysis results of the presented model are shown in Fig. 4. The Figure illustrates the voltage flow in the computer model, and its growth together with the increasing temperature difference. Maximum values were obtained in the last time step, i.e., for the temperature difference of 60°C. The greatest value registered is 1.497 V. The values of electric energy voltage (mV), which were obtained during subsequent steps, are shown in the table at the top right-hand corner of Fig. 5. The central bottom



Time [s]	Maximum [°C]	Time [s]	Maximum [°C]
0,2	40	3,2	72
0,4	40	3,4	74
0,73	40	3,73	77,333
1	50	4	80
1,2	52	4,2	82
1,4	54	4,4	84
1.73	57.3	4.73	87.3
2	60	5	90
2,2	62	5,2	92
2,4	64	5,4	94
2,73	67,3	5,73	97,3
3	70	6	100

Figure 6: Results, temperature

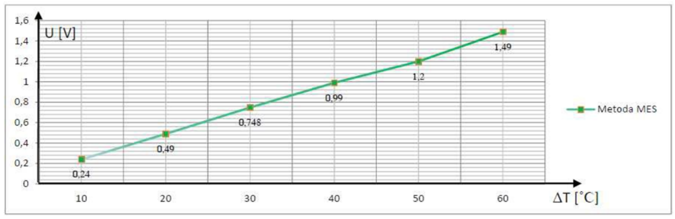


Figure 7: Results, voltage (Finite Elements Method)

part shows the characteristics of temperature growth in time. The abscissa axis denotes the time step of the simulation, whereas the ordinate axis shows the voltage values expressed in millivolt units. The next figure, Fig. 6, illustrates the temperature flow on the model of geometric TEG. The way of denoting data is similar to the previous figure (voltage flow). The FEM results of the values of electric energy voltage during temperature change on the hot side are shown in Fig. 7 in the form of linear characteristics.

3. Laboratory tests, verification models

For empirical research, use was made of the Laird Technologies [18] generator: "56890-503 CP14, 71, 045" Laird PL26, Fig. 8.

The idea of testing generators, analogically to the mathematical calculations and FEM simulations, consists in

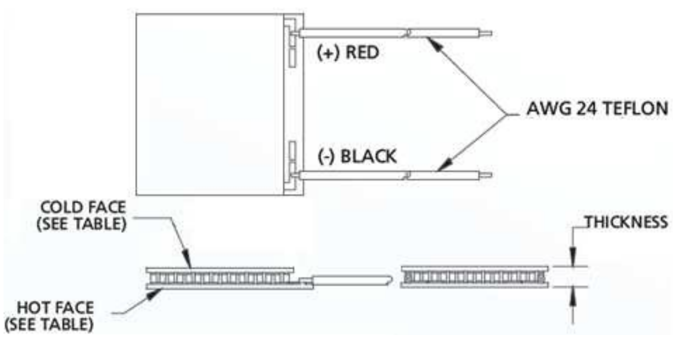


Figure 8: An example of Thermoelectric module [9]

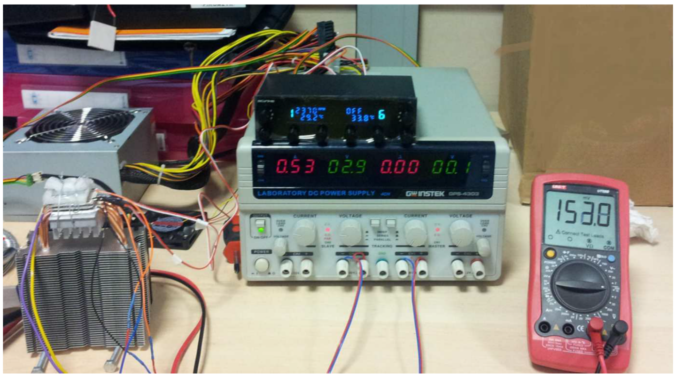


Figure 9: Test Bed [5]

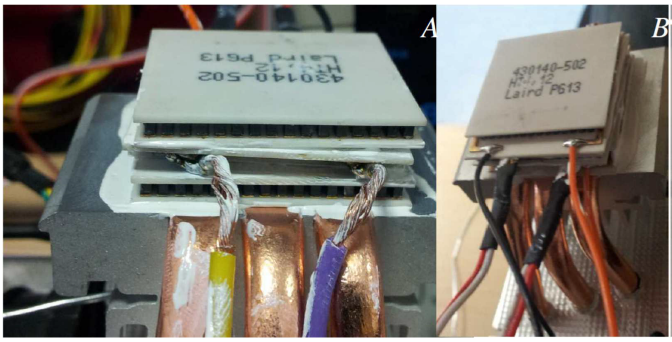


Figure 10: Setting the position of the Peltier cells. (A) view of the terminals of the test cell, (B) view cell with thermocouples to determine the serving temperatures

using the Seebeck effect, i.e., in delivering heat energy to the hot side of a thermoelectric generator (TEG), with simultaneous absorbing of heat energy from the cold side, in order to carry out observation of electric energy.

In order to deliver heat energy the Peltier generator was employed, the hot side of which heated the tested generator's hot side (in the later phase a modified part of the exhaust system was used at the laboratory work stand). For heat absorption the Peltier cell was also used, connecting with thermoconducting paste the cold side of the tested generator and of the cooling generator.

Three Peltier generators were used in the first phase. The middle generator with clamps visible on the radiator's left side (green and purple, Fig. 10A) was tested, so it functioned as an electric energy source. The other generators operated in accordance with their intended use (Fig. 10B). They were powered with electric energy from adjusted laboratory supplier GWINSTEK GPS-4303 [5]. This is a four-channel supplier with adjusted voltage values 0...30 V and values of current 0...3 A. Two channels were used for tests, connecting two generators, one with cooling properties, the other with heating properties. The system is pictured in Fig. 9.

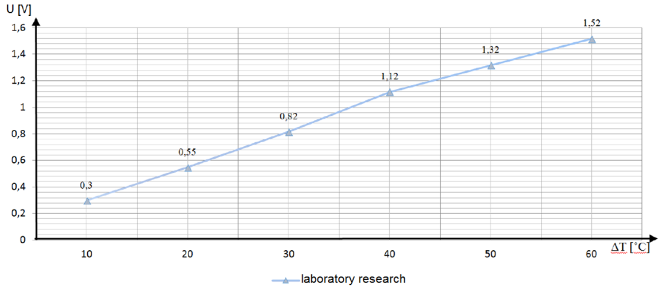


Figure 11: Results, Voltage (laboratory measurements)

A Spartan HE923 radiator with a fan was used, to absorb heat from the surface of processors in PCs. After preliminary tests it was observed that heat energy should be discharged from the generator's hot side, which was used for cooling the tested generator. This results from the heat balance of the energy delivered to the generator with the purpose of cooling the cold side of the tested generator. This explains the necessity of using the radiator to cool the hot side.

A Lutron TM-909 infrared thermometer was used to read the temperature values. A Kazemaster Pro temperature and rotational speed fan controller was also used. It is an electronic system originally used to control the temperature inside stationary computer units (PC). The Kaze Master set consists of a 6-channel electronic controller (allowing for simultaneous change of speed of two fans and for temperature reading from two thermocouples, attached to the tested surface), wires for connecting the fans, and thermocouples. Unfortunately, the electronic controller and the selected thermocouples were designed so as not to exceed 100°C on the surface of the tested element of the PC motherboard, and after exceeding the temperature of 75°C a sound alarm is activated, indicating heat hazards for PC elements. During tests at the laboratory stand, a pyrometer was used for reading temperatures above 75°C.
The basis for the tests were voltage measurements at the determined (constant) temperature of the cold side, and at the gradual increase of the temperature of the hot side (T_C=40°C). The results of the performed tests are shown in Fig. 11.

4. Summary/Conclusions

Recapitulating: the aim of the performed calculations and simulations was to verify their compliance with real tests and results. Upon comparison, it was seen that the theoretical calculations results and the FEM (computer) simulations were very similar. The comparison of the calcula-

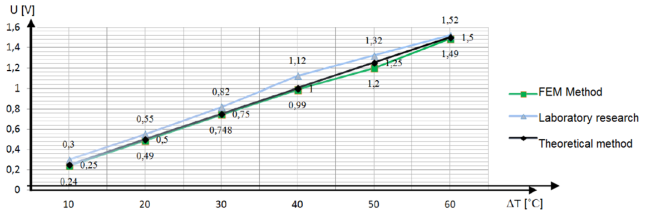


Figure 12: Characteristic of voltage electricity values

Table 1: Summary of results obtained by electric energy voltage

T_z,°C	T_g,°C	ΔT,°C	U, V, Test Bed	U, V, FEM	U, V, Analytical model
40	50	10	0.3	0.24	0.25
40	60	20	0.55	0.49	0.5
40	70	30	0.82	0.748	0.75
40	80	40	1.12	0.99	1
40	90	50	1.32	1.2	1.25
40	100	60	1.52	1.49	1.5

tions, simulations, and test results is illustrated in Fig. 12. Table 1 shows the electric energy voltages, obtained from three different methods of tests and analysis.

Analyzing the results, it can be stated that increasing the temperature difference between the hot and cold sides could make it possible to obtain and infinitely large voltage value of the concurrently achieved electric power. Unfortunately, due to the occurrence of Joule's heating and the phenomenon of heat conductance, thermogenerators should be employed in the defined scope of temperature difference. The simulations presented in this article justify the practical possibilities of module modeling, by means of the finite element method. Special emphasis should be placed on the boundary conditions, the number of mesh elements and the shape of the finite element used for modeling. All these elements significantly affect the process of modeling the thermoelectric phenomena observed in TEG.

Acknowledgments

This research was made possible through funding from the Office of the Marshal of the Mazowieckie Region in Warsaw, Poland. We express our sincerest gratitude.

References

[1] A. Piętak, S. Radkowski, Biofuels-opportunities and challenges, Journal of KONES 18 (2011) 347–358.

[2] A. Piętak, S. Radkowski, Methane-a fuel for agriculture, Journal of KONES 18 (2011) 357–386.

[3] S. Wierzbicki, Laboratory control and system of dual-fuel compresion ignition combustion engine operating in cogeneration system, Solid State Phenomea 210 (2014) 200–205.

[4] M. Śmieja, S. Wierzbicki, Influence of content of methane in biogas on emission of toxic substances in diesel engine supplied with bifuel, in: The 9th International Conference ENVIRONMENTAL ENGINEERING, 2014.

[5] K. Lubikowski, S. Radkowski, K. Szczurowski, M. Wikary, Analysis of possibility of use peltier module in task of energy scavenging, Key Engineering Materials 588 (2014) 1–11.

[6] M. Smieja, S. Wierzbicki, The concept of an integrated laboratory control system for a dual - fuel diesel engine, Journal of KONES Vol. 19, No. 3 (2012) 451–458.

[7] E. Antonova, C. David, Finite elements for thermoelectric device analysis in ANSYS, ANSYS Release 9.0 Documentation, ANSYS Release 9.0 Documentation (2004).

[8] M. Lubieniecki, T. Uhl, Thermoelectric energy harvester for a smart bearing concept, Proceedings of the 13th IFToMM World Congress in mechanism and machine science (2011) 1–9.

[9] D. Salerno, Ultralow voltage energy harvester uses thermoelectric generator for battery-free wireless sensors, Journal of Analog Innovation 20 (2010) 1–12.

[10] P. Ramade, P. Patil, M. Shelar, C. Sameer, S. Yadav, S. Trimbake, Automobile exhaust thermo- electric generator design & performance analysis, International Journal of Emerging Technology and Advanced Engineering 4 (2014) 682–691.

[11] S. Priya, D. Inman, Energy Harvesting Technologies, Springer, 2009.

[12] A. Chmielewski, K. Lubikowski, S. Radkowski, K. Szczurowski, Research and simulation work of teg in cogeneration task of the exhaust system, Journal of KONES Powertrain and Transport 20 (2013) 41–47.

[13] Information on www.lairdtech.com.

[14] R. C. Kumar, A. Sonthalia, R. Goel, Experimental study on waste heat recovery from an ic engine using thermoelectric technology, Thermal science 15 (4) (2011) 1011–1022.

[15] S. Angrist, Direct energy conversion, 3rd Edition, Allyn and Bacon, Boston (1976) 140–166.

[16] P. P. Silvester, R. L. Ferrari, Finite elements for electrical engineers, 3rd Edition, University Press, Cambridge.

[17] L. D. Landau, E. M. Lifshitz, Electrodynamics of continuous media, 2nd Edition, Butterworth- Heinemann, Oxford.

[18] E. Kelner, T. E. Owen, D. L. George, A. Minachi, M. G. Nored, C. J. Schwartz, Development of a low-cost inferential natural gas energy flow rate prototype retrofit module, Topical report, for the reporting period: September 2000–january 2002, Southwest Research Institute (March 2004).