THE ISSUE OF ENERGY CO-GENERATION USING THERMOELECTRIC GENERATORS

ADRIAN CHMIELEWSKI[1], KAMIL LUBIKOWSKI[2], STANISŁAW RADKOWSKI[3], MICHAŁ WIKARY[4], JĘDRZEJ MĄCZAK[5]

Warsaw University of Technology

Summary

The development of the renewable energy sources technologies and the energy policy emphasise the energy co-generation systems. In the automotive industry, investments are located in the development of heat pumps, Stirling engines, energy accumulators, gas turbines, piezo mats, suspensions and enfeeblements, linear motors, and other energy retrieval systems retrieving energy that is expelled in the process of the combustion of the fuel and air mixture in conventional combustion engines [1,2] and lost irretrievably. The energy co-generation systems increase efficiency in the use of the energy contained in the fuel and air mixture. Currently, there is a tendency of combination of the energy micro-cogeneration systems with other vehicle systems, e.g. motor control systems, motor power supply systems, safety systems, etc. [3-8]. One of such ways is the retrieval of heat energy thanks to thermoelectric generators (TEG) using the Seebeck effect.

Keywords: co-generation of energy, thermoelectric generators, Seebeck effect, Stirling engine

1. Introduction

The article presented the issue of energy co-generation from heat dissipated in the exhaust system of the combustion engine using thermoelectric generators commonly called "Peltier Modules" [9]. The publication presents the results of analyses and computer simulations of phenomena occurring in the thermoelectric Peltier modules. Then, the results of the analyses conducted in the ANSYS computer programme were compared with the results of the calculations from the adopted mathematical model and the results from the bench test. The laboratory tests were conducted in the Environmentally Integrated Mechatronic Systems Laboratory [Zintegrowane Środowiskowo Laboratorium Systemów Mechatronicznych Pojazdów i Maszyn Roboczych] at the Faculty of Automotive and Construction Machinery Engineering of the Warsaw University of Technology located in at Narbutta 84 street in Warsaw.

[1] Warsaw University of Technology, the Faculty of Automotive and Construction Machinery Engineering, the Institute of Vehicles, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: a.chmielewski@mechatronika.net.pl, tel.+48 22 234 8118

[2] Warsaw University of Technology, the Faculty of Automotive and Construction Machinery Engineering, the Institute of Vehicles, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: k.lubikowski@mechatronika.net.pl, tel. +48 22 234 8118

[3] Warsaw University of Technology, the Faculty of Automotive and Construction Machinery Engineering, the Institute of Vehicles, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: ras@mechatronika.net.pl, tel. +48 22 234 8118

[4] Warsaw University of Technology, the Faculty of Automotive and Construction Machinery Engineering, the Institute of Vehicles, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: m.wikary@mechatronika.net.pl, tel. +48 22 234 8118

[5] Warsaw University of Technology, the Faculty of Automotive and Construction Machinery Engineering, the Institute of Vehicles, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: jma@mechatronika.net.pl, tel.+48 22 234 8118

It should be mentioned that, in the laboratory, in the study of issues concerning the process of co-generation of energy, piezoelectric devices, the Stirling engine, and, recently, the thermoacoustic engine are used.

The energy policy of the European Commission's goal is to reduce the EU countries' dependence on imported oil and to produce their own local energy sources, which can be biofuels [1]. In issues of renewable technologies and the energy policy, emphasis is put on the co-generation systems. In the Directive 2009/28/EC of April 2009, the requirements for the member states of the European Union on the promotion of the use of energy from renewable sources were clearly defined. Investments are located in the development of heat pumps, Stirling engines [2], energy accumulators, and gas turbines in the automotive industry, as well as energy retrieval systems retrieving energy that is expelled in the process of the combustion of the fuel and air mixture in conventional combustion engines [9]. One of such methods is the retrieval of thermal energy thanks to the thermoelectric generators (TEG) [10-12] using the Seebeck effect.

Conducting scientific and research works on thermoelectric generators as energy converters, thermoelectric generators' operating parameters in a retrieval of electricity from thermal energy dissipated in a combustion engine in the exhaust system were developed.

In order to model and conduct computer simulations, the finite element method (FEM) was used [13-14].

In the mathematical description of a continuous medium, an object is regarded as a model in the Euclidean space, whose points are identified with the material particles of a body. Continuity [15] is modelled mathematically, and continuity of internal discontinuities separating continuous areas appearing in the theory of functions, with an acceptable exception on a limited number is assumed.

In comparison to continuous models, discrete models allow modelling of discontinuities and fragmentation of the material through an approach to the model as the assembly of a finite number of discrete objects. Currently, the discrete models can be built at different levels of observation (macro/micro/nano) from the point of view of the structure of the material.

2. Analysis of thermoelectric generator (steady-state condition)

The main task of the experiment is the analysis of the commercial Peltier module using the finite element method and the comparison with the mathematical model and results of empirical and commercial parameters of the module.

A typical task of thermoelectric generators (from the commercial point of view), which is visible nowadays, is generation and maintenance of the required temperature at the appropriate level (either positive or negative one) by means of the electricity supplied to the system. For the purposes of the analysis, the process was reversed providing a stream of thermal energy with the observed result of energy values collected at the terminals of the thermoelectric generator.

The model consists of 142 p- and n-type semiconductor components, which creates 71 p-n pairs. Semiconductor objects are connected together with thin copper connectors, as it was shown in Figure **1.** The model does not include sockets, which means that it does not create additional connections. Ceramic tiles were not modelled.

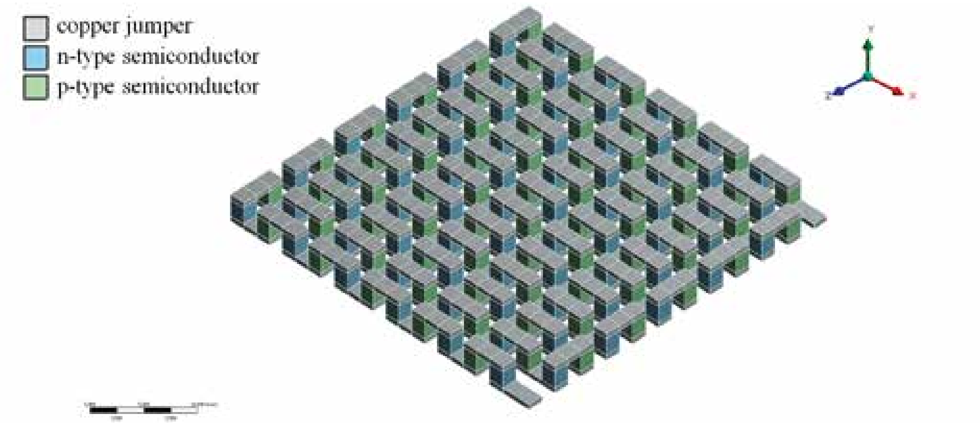

Fig. 1. Geometric model

3. Results

In this part of the paper, the results of the analysis of the model discussed earlier were presented. Figure 2 shows the values of voltage of retrieved energy (and its distribution) in the last step of the analysis (for the temperature difference of 60°C). The maximum value that was recorded is **1.497 V**. The voltages that were obtained during the "n" steps are presented in Table 1.

Table 1. Voltage values

Time [s]	Max. [mV]	Time [s]	Max. [mV]
0.2	7.79E-07	3.2	798.14
0.4	5.19E-07	3.4	848.03
0.73333	8.65E-08	3.7333	931.17
1	249.42	4	997.68
1.2	299.3	4.2	1047.6
1.4	349.19	4.4	1097.4
1.7333	432.33	4.7333	1180.6
2	498.84	5	1247.1
2.2	548.72	5.2	1297
2.4	598.61	5.4	1346.9
2.7333	681.75	5.7333	1430
3	748.26	6	1496.5

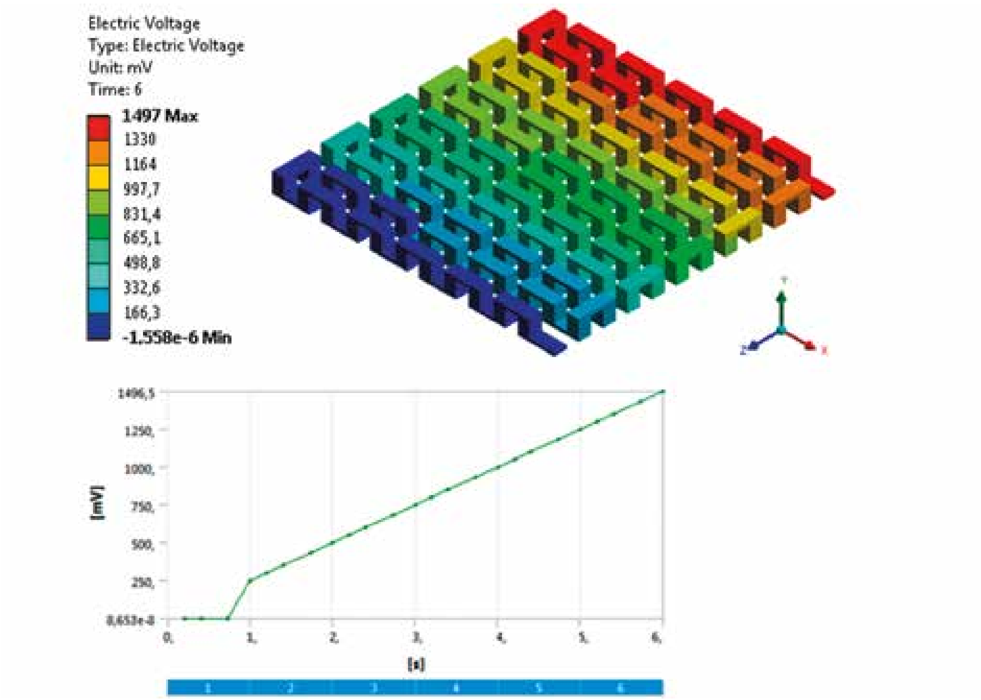

Fig. 2. Voltage distribution

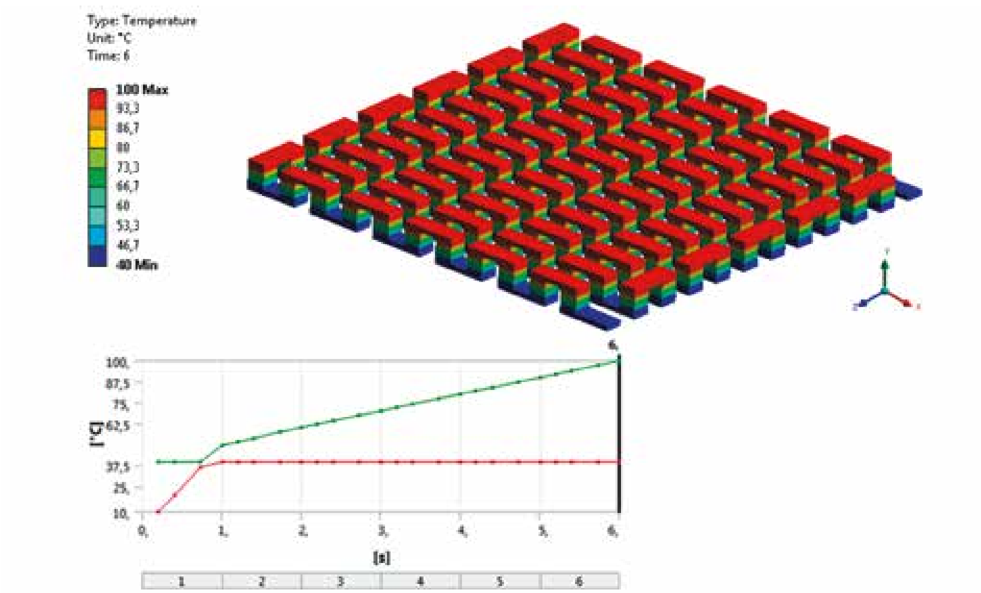

Fig. 3. Temperature distribution. The red line shows the simulated temperature on the cold side of the TEG, while the green line shows the temperature of the heated side of the TEG

Figure 3 presents the temperature distribution in the semiconductor junctions in the modelled TEG.

Table 2. Temperature values

Time [s]	Min [°C]	Max [°C]	Time [s]	Minimum [°C]	Maximum [°C]
0.2	10	40	3.2	40	72
0.4	20	40	3.4	40	74
0.73333	36.667	40	3.7333	40	77.333
1	40	50	4	40	80
1.2	40	52	4.2	40	82
1.4	40	54	4.4	40	84
1.7333	40	57.333	4.7333	40	87.333
2	40	60	5	40	90
2.2	40	62	5.2	40	92
2.4	40	64	5.4	40	94
2.7333	40	67.333	5.7333	40	97.333
3	40	70	6	40	100

The computer analysis results were compared with the results of the laboratory tests. These results have already been presented at various conferences and symposia [1,5]. The figure below shows pictures of the benches, where the tests were conducted.

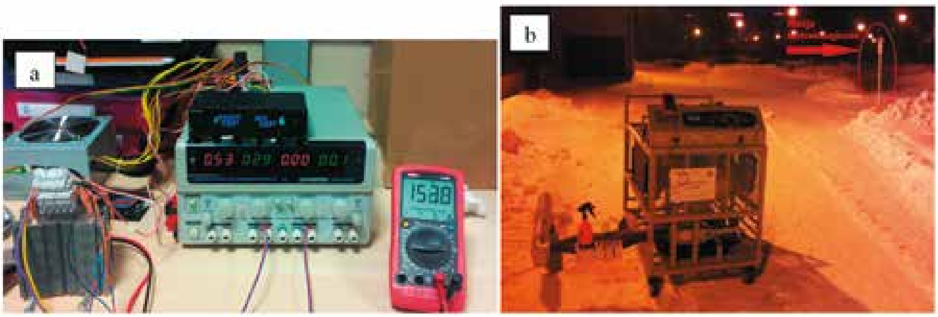

Fig. 4. The bench tests of the TEGs: a) The bench for tests of the TEGs' properties, b) The bench for tests of the TEGs on the ECOTEC X18XE engine

The laboratory tests were conducted on laboratory benches at the Faculty of Automotive and Construction Machinery Engineering (SiMR) of the WUT, in the Environmentally Integrated Mechatronic Systems Laboratory [Zintegrowane Środowiskowo Laboratorium Systemów Mechatronicznych Pojazdów i Maszyn Roboczych] in two stages. First, the TEGs' properties were researched by means of heating and cooling sides of the cell, as well as reading values describing electricity i.e. voltage, current, and electric power on the measuring apparatus. Next, measurements were conducted on the real bench, both at room temperature (conditions in the laboratory) and ambient temperature during the winter that is –12ºC. On the bench built on the ECOTEC X18XE petrol engine rebuilding its exhaust gas system. Initially, the measurements of the surface temperature of this system were conducted in order to determine a suitable place for mounting the TEGs. In the selected place, the system was separated and the double tube of rectangular cross section was incorporated in order to mount the TEGs easily using their entire surface. In addition, the system with the rectangular pipe was equipped with the running wheel of the waste gas stream. At the time of supplying energy to the TEGs, the waste gas stream was directed into this part of the pipe, on which the TEGs were mounted. At the boundary limit of the exceedance of temperatures, which could damage the semiconductor structure, waste gas stream was directed to the free tube (the bypass without TEGs).

The measurements results are presented in Table 3.

Table 3. Comparison of the energy retrieved in the different environmental conditions [5]

	At temp. of +28 [ºC]		At temp. of -12 [ºC]	
	800 [rpm]	2000 [rpm]	800 [rpm]	2000 [rpm]
Without the exhaust gas flow	1.4 [V]	2.5 [V]	0.9 [V]	1.44 [V]
With the exhaust gas flow	1.9 [V]	3.15 [V]	1.14 [V]	2.24 [V]

Ultimately, the results of the research were compared with the results of the computer simulations and model calculations. The results of the comparison are shown below, in Figure 5, and summarized in Table 4.

Table 4. Comparison of the value of the voltage of electricity from the laboratory measurements (the first column), the FEM simulation (the middle column), and the mathematical calculations (the column at the right)

C – the cold side	H – the hot side	ΔT – the temperature difference	U – voltage	U – voltage	U – voltage
Temp (ºC)	Temp (ºC)	-	Voltage (V), empirically	Voltage (V), FEM	Voltage (V), manual calculations
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

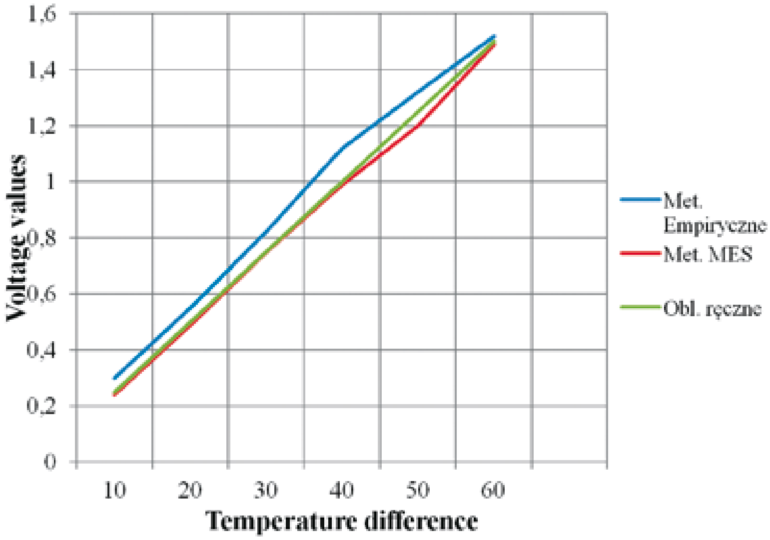

Fig. 5. TEGs energy retrieval characteristics

5. Conclusions

The conducted research enabled to claim that despite the low efficiency of the TEGs, they work perfectly as passive components retrieving energy irretrievably dissipated in the exhaust gas system of the combustion engine. Then, it was further found that the use of the TEGs in the exhaust system requires the preparation of the surface – it must be flat (most vehicles on the roads are equipped with circular exhaust systems) and appropriately cleared of debris.

Furthermore, the tests of increased number of generators were conducted. The TEGs should be mounted in packages connecting them serially and parallel. Each retrieved watt means saving and the better use of the lost energy in the form of joules discharged to the environment.

In the future, the construction of the complex energy recovery bench at the SiMR faculty of the WUT is planned. The building-in of the cooler with the Peltier tiles, mounting the TEGs on the cover of the engine valves, and the building-in of the exhaust system with the high-temperature TEG cells are anticipated.

References

[1] Lubikowski K., Radkowski S., Szczurowski K., Wikary M.: *Analysis of possibility of use Peltier module In task of energy scavenging*, Key Engineering Materials, Vol. 588, 2014, pp. 1-11.

[2] Chmielewski A., Gumiński R., Lubikowski K., Radkowski S., Szulim P.: *Bench testing and simulation model of a cogeneration system with a Stirling engine*, Journal of KONES Powertrain and Transport, Vol. 20, No. 3, 2013, pp 97-104.

[3] Wierzbicki S.: *Laboratory Control and Measurement System of a Dual-Fuel Compression Ignition Combustion Engine Operating in a Cogeneration System*. Solid State Phenomena Vol. 210 (2014), 200–205. Priya S, Inman D. J., „Energy Harvesting Technologies", Springer, ISBN 978-0-387-76463-4.

[4] Wierzbicki S., Śmieja, M.: *Visualization of the Parameters and Changes of Signals Controlling the Operation of Common Rail Injectors*. Solid State Phenomena Vol. 210 (2014), 136-141.

[5] Śmieja M. & Wierzbicki S.: *Influence of content of methane in biogas on emission of toxic substances in diesel engine supplied with bifuel*. International Conference on Environmental Engineering (2014).

[6] Śmieja M., Wierzbicki S., Mamala J.: *Sterowanie dawką wtryskiwanego paliwa w układzie Common Rail z wykorzystaniem środowiska LabView*. Combustion Engines 123 CD (2013).

[7] Wierzbicki S., Śmieja M., Grzeszczyk R.: *Zintegrowane sterowanie stanowiskiem badawczym silników o ZS w środowisku fast prototyping.* Combustion Engines 123 CD (2013).

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

[9] Kumar C. R., Sonthalia A., Goel R.: *Experimental study on waste heat recovery from an internal combustin engine Rusing thermoelectric technology*, Thermal Science, 2011, Vol. 15, No. 4, pp. 1011-1022.

[10] Chmielewski A., Lubikowski K., Radkowski S., Szczurowski K..: *Research and simulation work of TEG in cogeneration task of the exhaust system*, Journal of KONES Powertrain and Transport, Vol. 20, No. 2, 2013, pp 41-47.

[11] Wojciechowski K., Merkisz J., Fuć P., Lijewski P., Schmidt M., Zybała R.: *Study of recovery of waste heat from exhaust of automotive engine,* 5th European Conference on Thermoelectrics, Odessa, Ukraine, September 10-12, 2007, pp. 194-198.

[12] Antonova E.E., David C.: *Finite Elements of Thermoelectric Device Analysis In ANSYS*, Looman ANSYS Inc, ANSYS Release 9.0 Documentation, 2004.

[13] Angrist S. W.: *Direct Energy Conversion*, 3rd Edition, Allyn and Bacon, Boston, 1976, pp. 140-166.

14] Silvester P.P., Ferrari R.L.: *Finite Elements for Electrical Engineers,* 3rd Edition, University Press, Cambridge, 1996.

[15] Landau L.D., Lifshitz E.M.: *Electrodynamics of Continuous Madia*, 2nd Edition, Butterworth-Heinemann, Oxford, 1984.

[16] Chmielewski A.: *Modelowanie procesu kogeneracji energii z wykorzystaniem badań stanowiskowych na silniku Stirlinga*, Praca Magisterska, Warszawa 2013.

The work was conducted within the research project: N N509 520940 entitled: "*The co-generational increase of the energy efficiency of the multi-combustion engine using the criteria of minimizing the vibro-acoustic activity and environmental threats*" [*Kogeneracyjne zwiększenie efektywności energetycznej wielopaliwowego silnika spalinowego z wykorzystaniem kryteriów minimalizacji aktywności wibroakustycznej i zagrożeń środowiskowych*] – The project was funded by the National Science Centre.