THERMOELECTRIC GENERATOR FOR A PETROL ENGINE

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• *Results of computer simulation of thermoelectric generators (TEG) using waste heat from petrol internal combustion engines are presented. The simulation was done with regard to dynamic operating conditions of engine for real temperature dependences of thermoelectric material parameters. Results of experimental investigations of a generator using waste heat of 1.8 liter displacement automotive engine are given. Computer simulation is verified by test results.*

Introduction

The use of waste heat from the internal combustion engines is currently central task of thermoelectricity [1-6]. A lot of papers on this subject have been published. Year after year, at the international conferences on thermoelectrics the number of papers dedicated to exhaust heat recovery from the internal combustion engines goes up. Also, issue-related conferences are organized in the USA and Germany.

World producers of vehicles, as well as companies engaged in thermoelectricity, focus extensively on the development of efficient thermoelectric generators. Such works aim at increasing fuel economy up to 10% due to the use of engine waste heat for electric energy generation.

The largest companies making it their mission to create industrial prototypes of generators and their quantity production are *Hi-Z* [7], BSST [8] and General Motors [9] in the USA. In Japan, the problems of creating automotive generators are most widely addressed by Komatsu [10], Nissan [11] and Shiroki [12]. In Germany, Volkswagen and BMW together with DLR (German Airspace Centre) represented their developments of thermoelectric automotive generators [13].

As is evident, interest in creation of automotive thermal generators is growing. The generator samples created to date confirm the possibility of electricity generation from the exhaust gas heat, but none of the elaborated generators can be used for industrial production yet. The reason for that is modest generator efficiency. The generator efficiency relies heavily on the engine operating condition. The dynamic operating conditions of the engine in true life driving impose rather complicated requirements in the design and optimization of vehicular generators which cannot be met to the full extent today.

In Ukraine, the problems of creating efficient thermoelectric generators for the internal combustion engines are solved at the Institute of Thermoelectricity [14]. A series of thermoelectric generators have been created that utilize the exhaust gas heat both from stationary diesel plants and vehicular diesel engines [15]. The exhaust gas temperature of petrol engines is known to be much higher than in diesel engines and makes about 500 – 800ºC.

The purpose of this work is to develop a thermoelectric generator utilizing the exhaust gas heat from a petrol engine.

Optimization of a thermoelectric generator is done by computer-aided design [16] which consists in the following.

Computer-aided design procedure

Consider a physical model of a thermoelectric generator (TEG) represented in Fig. 1. In the general case the TEG consists of N sections connected in series with respect to the hot gas flux and the cold coolant.

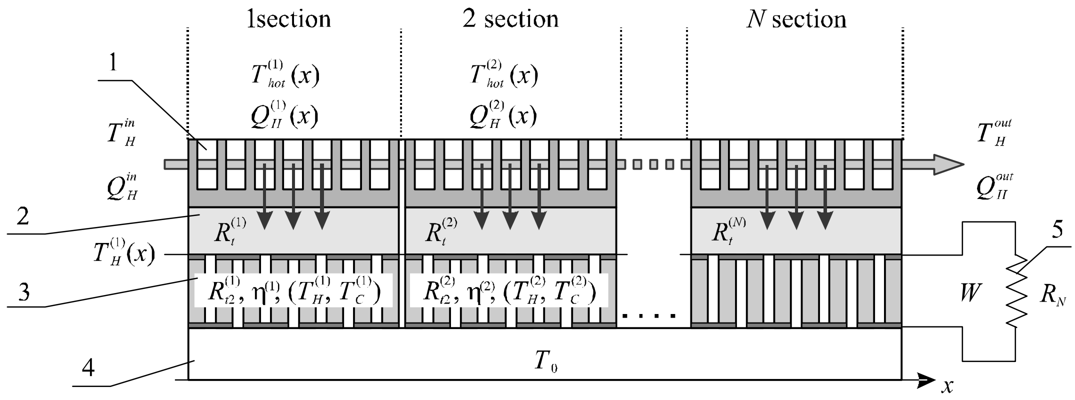

Fig. 1. Physical model of a thermoelectric generator:
1 – hot heat exchanger; 2 – thermal resistance between the hot heat exchanger and thermopile;
3 – thermopile; 4 – cold heat exchanger; 5 – matched electric load.

Each TEG section consists of the following components (Fig. 1): hot heat exchanger (1), thermopile (3) with thermal resistance $R_t^{(i)}$ and efficiency $\eta(T_H, T_0)$; cold heat exchanger (4) with temperature T_0; thermal resistance between the hot heat exchanger and thermopile $R_t^{(i)}$ (3) which restricts the hot side temperature of modules. Thermopiles of each section are loaded for matched electric load R_i (5).

The inlet hot gas flux is characterized by temperature T_H^{in} and thermal power Q_H^{in}. The hot gas gives away part of heat $Q_H^{(i)}(x)$ at temperature $T_{hot}^{(i)}(x)$ to the hot heat exchanger. At the outlet of the TEG the temperature of gas is T_H^{out} and the thermal power is Q_H^{out}. From the hot heat exchanger through thermal resistance $R_t^{(i)}$ the heat is transferred to thermopile, heating its hot side to $T_H^{(i)}(x)$.

To prevent thermoelectric modules from overheating, we will supplement the physical model with a bypass through which the excess exhaust gas will be rejected in such a way as to maintain the temperature of modules on maximum permissible level.

For the optimization of the TEG it is necessary to find the distribution of temperatures and heat fluxes in thermopiles of each section. Such calculation for the represented model is made using the numerical computer methods.

To calculate the electric power of the TEG, we will use the energy balance equation in the form

$$W = \sum_{i=1}^{N} \left[\int \left(Q_H^{(i)}(x) - Q_C^{(i)}(x) \right) dx \right]. \quad (3)$$

The necessary temperatures and heat fluxes are found from thermal conductivity equation:

$$-\nabla \left(\kappa_{TE}(T) \nabla T \right) = Q_J, \quad (4)$$

where κ_{TE} is the effective thermal conductivity of a thermopile, Q_J is the Joule heat released in the bulk of a thermopile.

The boundary conditions for (4) will be of the form

$$Q_H^{in(1)} = Q_H^{in},\ Q_H^{in(i+1)} = Q_H^{out(i)},\ Q_H^{out(N)} = Q_H^{out}, \quad (5)$$

$$Q_H^{(i)}(x) = \left(T_H^{(i)}(x) - T^{(i)}(x) \right) / R_t^{(i)}, \quad (6) \qquad Q_C^{(i)}(x) = \left(T_0(x) - T^{(i)}(x) \right) / R_{t2}^{(i)}, \quad (7)$$

A combination of relationships (3)-(7) allows finding the distribution of temperatures $T_H^{(i)}(x)$ and heat fluxes $Q_H^{(i)}(x)$ in each of the sections.

To restrict the hot temperature of module, the thermal resistance $R_t^{(i)}$ between the hot heat exchanger and thermoelectric module is found from equation (6).

The power of each section and total TEG efficiency can be determined from equations

$$W^{(i)} = \int Q_H^{(i)}(x)\eta(T_H^{(i)}(x), T_0))dx, \quad (8)$$

$$\eta_{TEG} = \frac{1}{Q_H^{in}} \sum_{i=1}^{N} W^{(i)}. \quad (9)$$

A system of equations (3) – (7) is solved by numerical methods on a two-dimensional finite element mesh [10].

Computer-aided design outputs

To design a thermoelectric generator in dynamic conditions, the input parameters of exhaust gas (temperature and flow rate) were obtained on 1.8 liter displacement petrol engine UMZ-3318 (Russia) in operating mode which simulates vehicle driving in the New European Driving Cycle (NEDC) (Fig. 2). This cycle of duration 1220 s consists of two parts. The first part is Urban Driving Cycle (UDC) with a maximum speed 50 km/h which includes four consecutive driving cycles and simulates vehicle driving conditions in the city. The second part is ExtraUrban Driving Cycle (EUDC) with a maximum speed 120 km/h which simulates vehicle driving conditions along the highway.

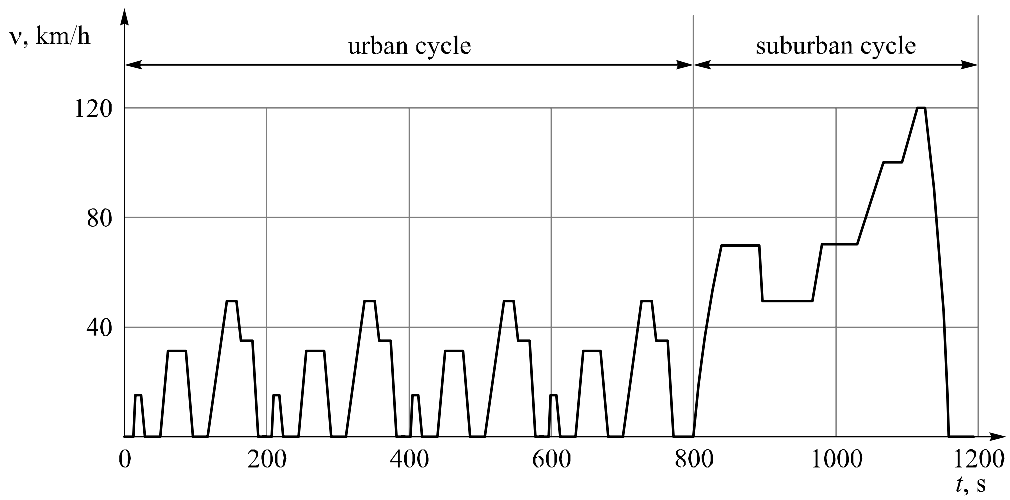

Fig. 2. New European Driving Cycle (NEDC).

To design the generator, thermoelectric modules Altec-1061 [17] based on *Bi-Te* were selected which outperform the known world analogs.

Generator design optimization consisted in finding the minimum number of modules needed for the generator to achieve maximum average electric power during the NEDC. The results of such optimization are shown in Fig. 3. As we can see, for the task set the optimal number of modules is 48. With a deviation from the optimal value to the smaller side, the hot temperature of modules can be raised to higher values, but the total electric power of the TEG decreases due to a small number of modules. A drop in the electric power of the TEG is also observed with a deviation from the optimal number of modules to the larger side. It is due to a reduction of total thermal resistance of thermopile, and, as a consequence, a reduction of temperature difference on the modules.

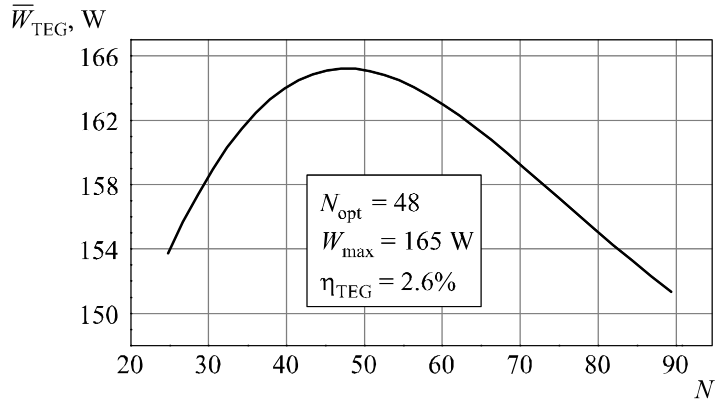

Fig. 3. Dependence of the average electric power of the TEG on the number of modules

Fig. 4 *a* shows time dependences of the hot side temperature of modules with the engine operated in the NEDC. The cold side temperature is assumed as T_0 = 60ºC.

Fig. 4 *b* shows time dependence of the electric power of the TEG. As can bee seen from the figures, in the time range of 1060 – 1160 s the temperature on the modules is maximum permissible, and a bypass is switched on which maintains the temperature on a set level.

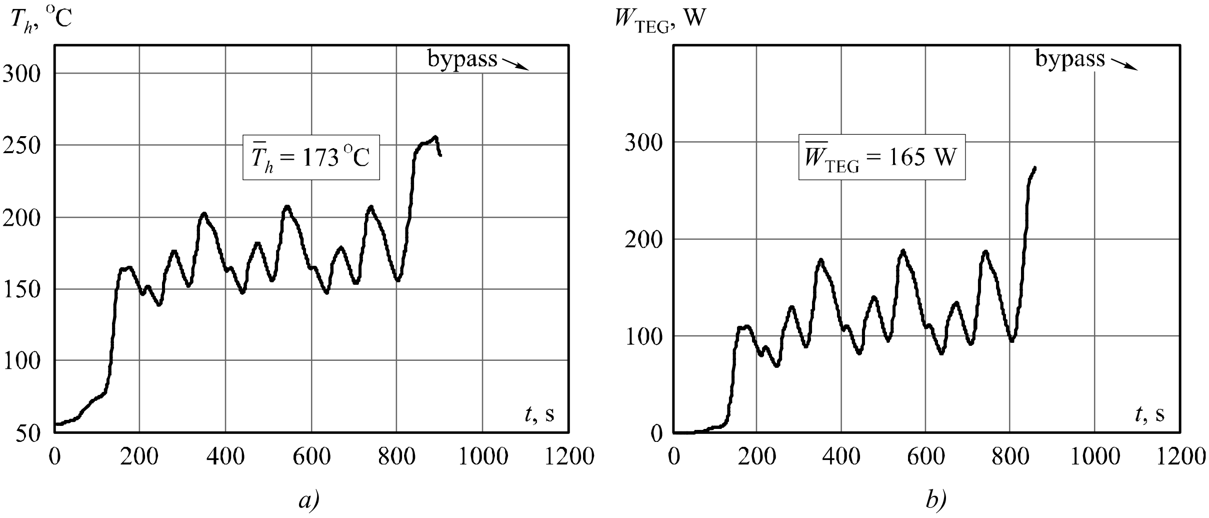

Fig. 4. Time dependences of the hot side temperature of modules (a) and the electric power of the TEG (b) with the engine operated in the NEDC.

At this time the electric power of thermal generator achieves its maximum value 365 W.

The average electric power of thermal generator with the engine operated in the NEDC is 165 W, which is quite sufficient for charging the accumulator.

In so doing, the average efficiency of a thermoelectric generator during one NEDC came up to 2.6%.

As is clear from Fig. 4, as a result of generator optimization for a full NEDC and considerable difference in the temperatures and powers of gas in the urban and suburban driving cycles, the way the generator converts gas thermal energy into electric energy is not the most efficient one.

The generator optimization for the urban or suburban driving cycle yielded the following results. Fig. 5 *a* shows a dependence of the electric power of the TEG optimized for the urban driving cycle.

Such a generator comprises 22 thermoelectric modules and develops the average electric power 110 W in the urban driving cycle. On the whole, during the NEDC such a generator develops the average electric power 138 W. Such a low value is due to the fact that considerable part of thermal energy is lost through a bypass in the suburban phase of the cycle Fig. 5 *b* shows a dependence of the electric power of the TEG optimized for the suburban driving mode. Such a generator comprises 74 modules and develops the average electric power 350 W in the suburban mode. On the whole, during the NEDC it develops the average electric power 162 W. Such a low value, as is seen from Fig. 5 *b*, is caused by inefficient generator operation in the urban phase of the NEDC.

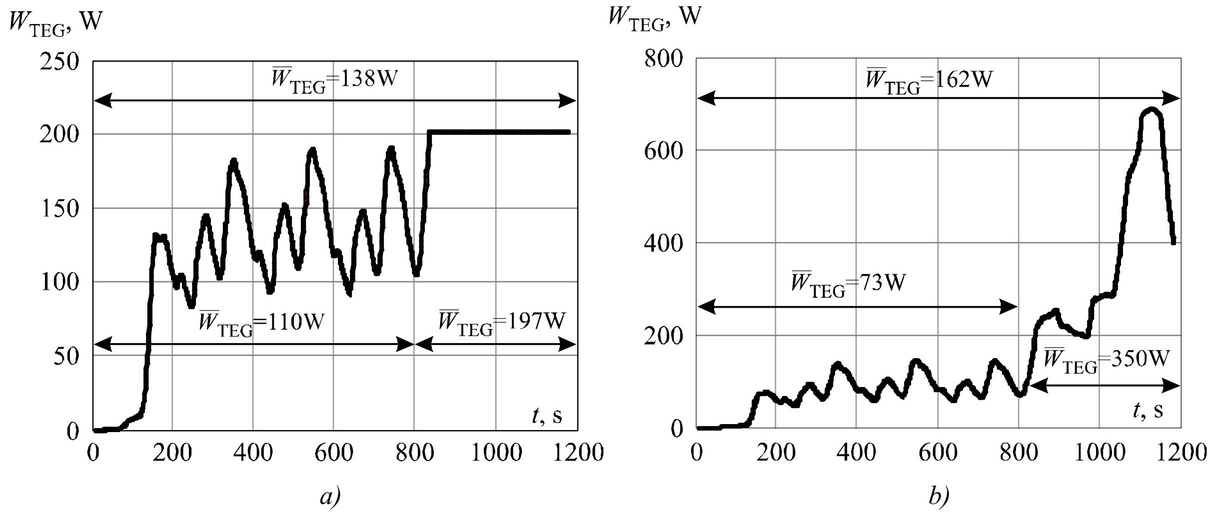

Fig. 5. Dependence of the electric power of generators optimized for the urban (a) and suburban (b) driving cycles.

As is evident from the foregoing, the use of one generator with a bypass is not the optimal variant of exhaust gas recovery from engine operated in a dynamic mode. In the time interval 0 ÷ 800 s of the NEDC the hot temperature of modules is much lower than maximum permissible. Accordingly, the modules work with a low efficiency. Hence it can be concluded that a model comprising 2 generators optimized for the operation in the urban and suburban cycles, respectively, will be more efficient (Fig. 6). At low temperatures and powers of the exhaust gas, only TEG 1 will be included into operation. On reaching maximum permissible temperature on the modules, a portion of gas will be rejected to TEG 2.

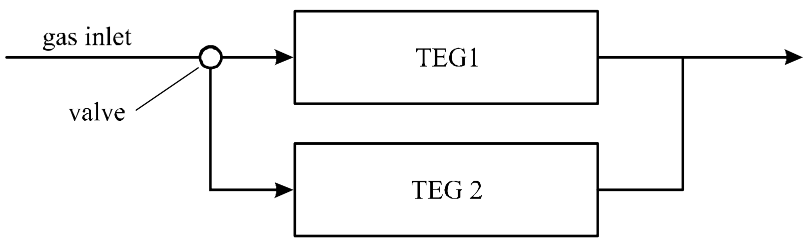

Fig. 6. Model with two generators.

The results of such model optimization are given in Fig. 7. For this case TEG 1 comprises 22 thermoelectric modules and TEG 2 – 52 modules.

As is evident from Fig. 7, in this model the hot temperature of TEG 1 modules is in the region of optimal temperatures and TEG 1 works with maximum efficiency. In the NEDC phase corresponding to suburban mode part of the exhaust gas is rejected to TEG 2. The average electric power of this system came up to 205 W which is 25% greater compared to the model where one generator with a bypass is employed. Maximum generator power is 675 W.

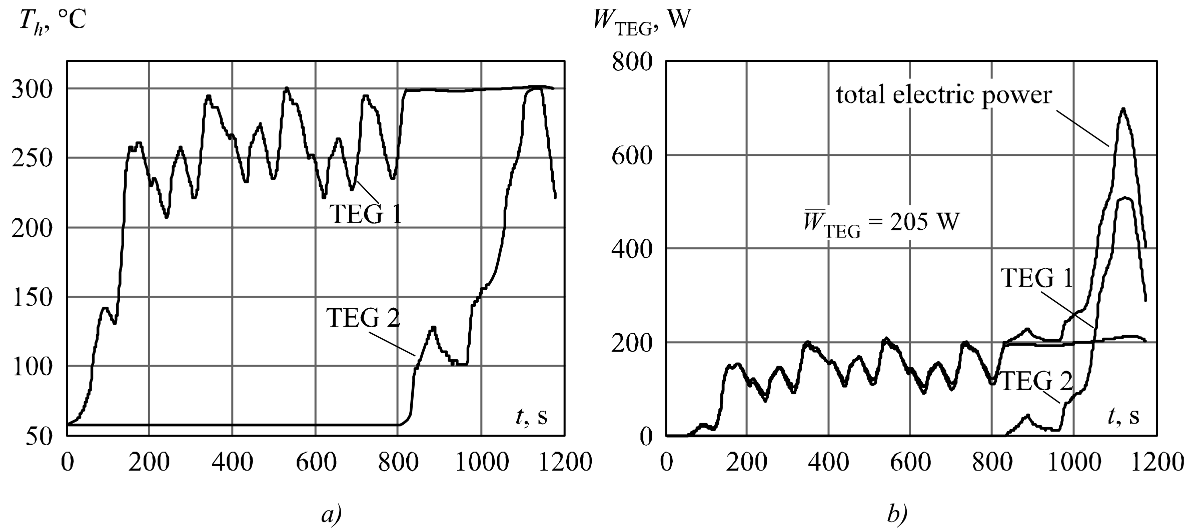

Fig. 7. Time dependences of the hot side temperature of modules (a) and electric power (b) of two generators with the engine operated in the NEDC.

Thermoelectric generator test

According to design outputs, a thermoelectric generator was designed that comprises 74 thermoelectric modules Altec-1061, the hot gas heat exchangers and the cold liquid heat exchangers.

For the purpose of generator testing, a test bench using a four-cylinder 1.8 liter displacement petrol engine was created. Exhaust gas delivery from the cylinders to thermoelectric generator is provided by special stainless-steel collector.

The test bench is used for recording:

- temperature of gases at the inlet to generator ± 5°C;
- temperature of gases at the outlet of generator ± 3°C;
- surface temperature of each heat exchanger at the beginning and end thereof ± 13°C;
- inlet cooling water temperature;
- outlet cooling water temperature ± 0.3°C;
- gas flow rate, l/s ± 5%;
- gas pressure at the inlet to generator ± 5%;
- gas pressure at the outlet from the generator ± 5%;
- number of engine rotations 100 ÷ 5300 rpm. ± 5%;
- TEG EMF ± 0.1 V;
- electric current on matched load with series connected modules ± 0.05 A;
- electric power on matched load with series connected modules ± 0.5%;
- electric power on matched load with the use of electronic converter with the output of 12 V ± 1%.

The optimal values are selected by load resistances for the achievement of maximum electric power of the TEG.

Results of testing the thermoelectric generator in a steady-state operating mode on maximum engine power are given in Table 1.

As is clear from the results obtained, the electric power value of thermoelectric generator is in good agreement with the results obtained by computer simulation.

Table 1

Parameter	Value
Exhaust gas temperature, °C	740 – 770
Exhaust gas flow rate, kg/hour	< 200
Exhaust gas thermal power, kW	< 50
Inlet cooling liquid temperature, °C	+ 60
Outlet cooling liquid temperature, °C	+ 80 ÷ 90
Electric voltage with conversion, V	12 ± 1
Current, A	51 ± 1
Electric power, W	630 ± 20
Electric power with electronic conversion, W	540 ± 20
Mass, kg	26
Gas pressure as the inlet of generator, mbar	10
Gas pressure at the outlet of generator, mbar	7

Conclusions

1. Thermoelectric generator for 1.8 liter displacement petrol engine was designed. For the steady-state operating mode according to design outputs the possibility of producing up to 675 W of electric energy was shown. For engine operation in the NEDC, the average electric power of the TEG is ~ 165 W for a model with one generator with the average efficiency 2.6%, and 205 W with the efficiency 3.2% for a model with two generators.
2. The obtained design results were verified experimentally. In the steady-state operating mode about 630 W of electric energy was produced. With regard to electronic conversion of voltage, the electric energy produced was 540 W.
3. The use of one thermoelectric generator is not the optimal method for conversion of the exhaust gas thermal energy in dynamic operating mode, since the hot side temperature of modules is considerably less than the working one, which makes their use inefficient. For the NEDC the average electric power of the TEG is about 45% of maximum generator power.
4. The use of a model with two generators optimized for the urban and suburban driving modes, respectively, allows producing ~ 25% more electric power as compared to a model where only one generator is employed.

References

1. L.I. Anatychuk, Yu.Yu. Rozver, K. Misawa and N. Suzuki, Thermal Generators for Waste Heat Utilization, *Proc. 16th International Conference on Thermoelectrics* (Dresden, Germany, 1997).
2. T. Kajikawa and T. Onishi, Development for Advanced Thermoelectric Conversion Systems, *Proc. 26th International Conference on Thermoelectrics* (Jeju, Korea, 2007).
3. Clay W. Maranville, Peter Schmitz, Thermoelectrics for Waste Heat Recovery and Climate Control in Automobiles, *Thermoelectrics Goes Automotive* (Expert Verlag, Germany).
4. G. Min, D.M. Rowe, Conversion Efficiency of Thermoelectric Combustion Systems, *IEEE Transactions on Energy Conversion* **22**, 528-534 (2007).
5. K.M. Sacr, M.K. Mansour and M.N. Mussa, Thermal Design of Automobile Exhaust Based on Thermoelectric Generators: Objectives and Challenges, *J.Thermoelectricity* **1**, 64-73 (2008).
6. X. Zhang, K.T. Chau and C.C. Chan, Overview of Thermoelectric Generation for Hybrid Vehicles, *Journal of Asian Electric Vehicles* **6**(2), 1119-1124 (2008).
7. N.E. lsner, J. Bass, S. Ghamaty, D. Krommenhoek, A. Kushch and D. Snowden, *Diesel Truck Thermoelectric Generator, Advanced Combustion Engine Technologies. – FY 2005 Progress Report*.
8. D. Crane, L. Bell, Progress Towards Maximizing the Performance of a Thermoelectric Power Generator, *Proc. 25th International Conference on Thermoelectrics* (Vienna, Austria, 2006).
9. Jihui Yang, F. Seker, R. Venkatasubramanian, G.S. Nolas, C. Uher and H. Wang, *Developing Thermoelectric Technology for Automotive Waste Heat Recovery. Advanced Combustion Engine Technologies. FY 2006 Progress Report*.
10. T. Kajikawa, Current Status of Thermoelectric Power Generation Technology in Japan, *J Thermoelectricity* **2**, 21-31 (2007).
11. K. Ikoma, M. Munekiyo, K. Furuya, M. Kobayashi, T. Izumi and K. Shinohara, Thermoelectric Module and Generator for Gasoline Engine Vehicles, *Proc. 17th International Conference on Thermoelectrics* (Nagoya, Japan, 1998).
12. E. Takanose, H. Tamakoshi, The Development of Thermoelectric Generator for Passenger Car, *Proc. 12th International Conference on Thermoelectrics* (Yokohama, Japan, 1993).
13. *Thermoelektrik-Eine Chance Fur Die Atomobillindustrie*, Berlin, 2008.
14. L.I. Anatychuk, O.J. Luste and R.V. Kuz', Theoretical and Experimental Studies of Thermoelectric Generator for Vehicles, *J .Electronic Materials* **40**(5), 1326-1331, (2011).
15. L.I. Anatychuk, R.V. Kuz', Computer Designing and Test Results of Automotive Thermoelectric Generator, *Thermoelectrics Goes Automotive* (Berlin, 2010).
16. Comsol multiphysics. http://www.comsol.com.
17. L.I. Anatychuk, R.V. Kuz', Materials for Vehicular Thermoelectric Generators, *Proc. 30th International Conference on Thermoelectrics* (Traverse City, Michigan, USA, 2011).

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