

STUDY OF THERMOELECTRIC POWER GENERATORS AND APPLICATION IN A SMALL SIZED CAR

Hatzikraniotis E.¹, Zorbas K.^{1,2}, Triandafyllis I.² and Paraskevopoulos K.M.¹

1- Physics Department, Solid State Physics Section, Aristotle University of Thessaloniki,
54124 Thessaloniki, Greece

2- Department of Vehicle Technology, School of Technological Applications, Technological
Educational Institute of Thessaloniki, 57400 Greece

Contact author: evris@physics.auth.gr

Abstract

Waste heat recovery from car's exhaust gases provides an opportunity to significantly improve the overall car engine efficiency. One approach for recovering energy from the exhaust gases is to generate electrical power through thermoelectric (TE) conversion. The economic competitiveness of this technology is determined by the capital investment (cost per watt) and reliability of the thermoelectric elements.

A thermoelectric device, using a commercially available thermoelectric generator module (TEG) was made, in order to measure the gained power and efficiency at different places of the exhaust pipe of a small size car (Toyota Starlet, 1300cc), for various engine loads. With the use of a modeling approach, we evaluated the thermal contact resistances and their influence on the final device efficiency. The methodology used can also be applied to thermoelectric elements with better "figure of merit" ZT and respectively higher power output. Furthermore, the repercussion on fuel consumption was examined and the principles and ways of implementation were discussed.

1. Introduction

Thermoelectric (TE) generators make use of the Seebeck effect in semiconductors for the direct conversion of heat into electrical energy, which is of particular interest for waste heat recovery [1]. A thermoelectric generator (TEG) usually consists of several pairs of alternating p- and n-type

semiconductor blocks, which are arranged thermally in parallel and connected electrically in a series circuit. Heating one side of the arrangement while the opposite side is cooled induces the heat flow, which is partly converted into electrical power.

The possible use of a device consisting of numerous TEG modules in the wasted heat recovery of an internal combustion (IC) engine can considerably help the world effort for energy savings. The use of a thermoelectric generator device will offload the alternator and thus will reduce its size. Generally, the wasted heat from IC engines is a great percentage of the fuel's energy. In gasoline fuelled IC engines, about 75% of the total energy of the fuel is rejected in the environment [2]. The recovery of a 6% of the exhaust's energy could lead to 10% saving of fuel [3].

Among the sources of rejected energy that exist in a petrol engine, an application of a thermoelectric device can be implemented at the exhaust pipe. The basic reason for this is the high temperatures that prevail there and the big rate of thermal power that goes through [4]. The exhaust gases exiting the engine contain up to 40% of the energy from the fuel burned by the engine. Typical operating exhaust gas temperatures at the exit of the catalytic converter are 400 to 600 °C, with excursions above (up to 1000 °C) and below this range. The average flow rate for a mid-sized car is about 1.13 m³/min [2]. The application of a TE device before the catalyst is considered to be undesirable, because it influences the proper operation of the catalyst and the oxygen sensor.

However, temperatures much higher than the desired operating range of the heat pipe could cause structural failure of the thermoelectric elements. The exposure of thermoelectric materials to such environments, causes generally, an increase in electrical resistivity, as well as a decrease in material “Figure of merit” Z [5, 6]. Furthermore, the continuous thermal cycling charge and the harsh environment under the vehicle, could lead to reduced efficiency and lifetime of the TEG [7].

This work focuses on investigating the temperature distribution along the exhaust pipe of a small sized car for various engine loads and the development and application of a measuring device at the exhaust pipe, in order to study the gained power and efficiency of a commercially available TEG module. A theoretical model has been developed [8], which allows the calculation of gained power and efficiency of a thermoelectric generator device under different electric charges and temperature gradients. With the use of this model we evaluated the thermal contact resistances and their influence on the final device efficiency.

2. Experimental

A commercial $2.5 \times 2.5 \text{ cm}^2$ Bi_2Te_3 module with $N=31$ thermocouples (Melcor HT9-3-25) was used. A semi-cylindrical aluminum piece was used as heater and was attached directly to the exhaust pipe and to the top of the TEG module. A $60 \times 68 \text{ mm}^2$ aluminum heat sink with 156 fins of 20 mm was used as cooler by the ambient air. All pieces were bonded together at a pressure on TEG’s surfaces of 4 MPa. (Figure 1). In order to reduce the thermal contact resistance, all surfaces were lapped and a thin layer of graphite thermal grease (Melcor GRF-159) was used.

For temperature monitoring three K-type thermocouples were mounted, one in a hole near the exhaust pipe, the second near the bottom surface of the heater and the third in a thin aluminum plate on the bottom of the TEG module. A total ohmic resistance of

0.45 Ohm (as near as the value of the internal TEG’s resistance at hot side temperature of $200 \text{ }^\circ\text{C}$) was used as load, in order to achieve the maximum power.

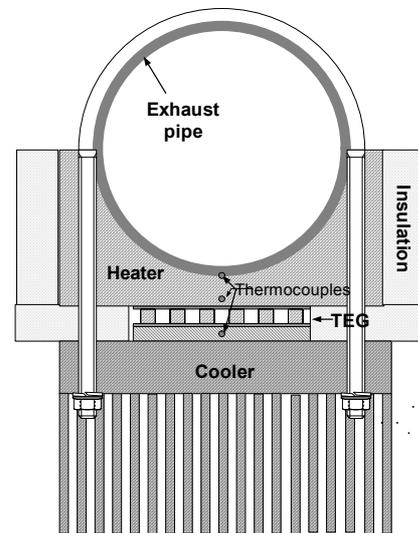


Figure 1. The experimental device

All measurements were made at the exhaust pipe of a Toyota Starlet 1300cc car.

3. Results and discussion

In order to measure the temperatures evolved on the several positions of the exhaust pipe for various engine loads, the car initially was set on a chassis dynamometer which provides simulated road loading.

In Figure 2 it can be seen that at all engine loads except idle, the exhaust pipe temperatures were very high for direct thermoelectric applications with the commercially available TEG modules. Also, the exhaust pipe temperatures after the catalyst are higher than the temperatures before the catalyst. This condition can be attributed to the fact that the engine on dynamometer runs at full load, which means that the fuel-air mixture in the engine’s combustion chamber is rich and the oxidation-reduction reactions in the catalyst cause elevated temperatures. Furthermore, the dynamometer fan, that cools the engine, was not fully capable to cool enough the rear parts of the exhaust pipe.

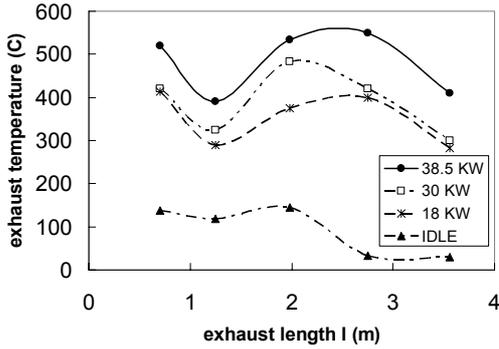


Figure 2. Temperature distribution along the exhaust pipe for various engine loads (measurements on chassis dynamometer)

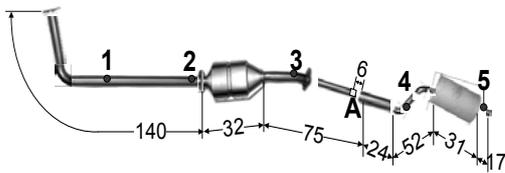


Figure 3. Schematic of the exhaust pipe (Toyota Starlet, 1300 cc.)

As the engine full load is not the most frequent situation in normal driving conditions, we decided to measure the exhaust pipe temperatures and to apply our experimental device under real road conditions. The experimental device was mounted at the position A (Figure 3), a place after the catalyzer and just before the front muffler. The measurements were made at an even highway, simulating normal driving at speeds from 70 to 130 km/h, with IV and V gears engaged.

Figure 4 shows the measured temperatures in the experimental device at position A, versus vehicle speed. T_{exh} is the exhaust pipe temperature and T_1 , T_2 are the measured heater and cooler temperatures near the TEG module, respectively. Dashed curves represent the calculated by our theoretical model temperatures TH_{calc} , TC_{calc} at the hot and cold side of the TEG's legs respectively.

It can be seen that in such driving conditions, the TEG's hot side temperature TH slightly exceeds the TEG's maximum operating temperature ($225^{\circ}C$) at the 130 Km/h vehicle speed. Also, the thermal inertia of the aluminum heater mass eliminates the quick temperature changes of

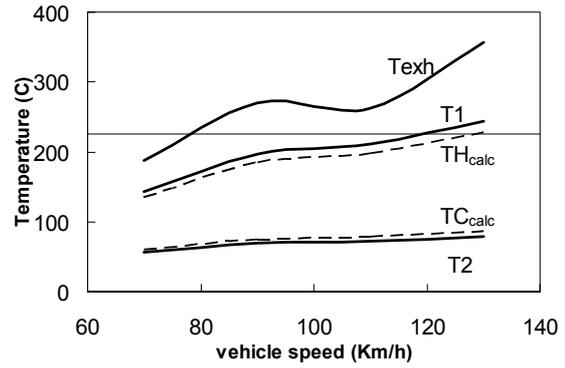


Figure 4. Temperatures in the experimental device at position A, for various vehicle speeds. (Even road, environment temperature $20^{\circ}C$)

the exhaust pipe, ensuring a smoother TEG operation. Furthermore, it is noticeable that the natural funless air cooling seems to be fairly efficient, as the TEG's cold side temperature TC does not exceed the $80^{\circ}C$ (at an ambient temperature of $20^{\circ}C$).

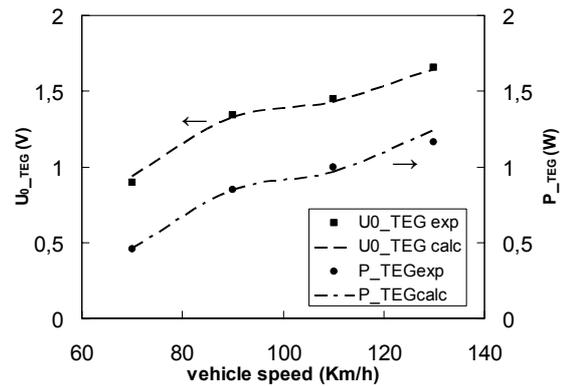


Figure 5. TEG's emf U_{0_TEG} and gained power P_{TEG} , versus vehicle speed.

Figure 5 depicts the measured values of the TEG's emf U_{0_TEG} and gained power P_{TEG} , along with the calculated ones, versus vehicle speed. With our theoretical model we have calculated that the TEG's efficiency varies from 2.5% to 3.2%, being normal at these temperatures for this type of TEG. Unlike, according to our model, the gained power could be about 18 % higher if the experimental device had about 40 % smaller thermal resistances and with a better adaptation of the load resistance.

It can be seen that at cruising driving situations (with a vehicle speed around 110

Km/h) a power of 1 W is easily obtained. Assuming a total covering of this part of the exhaust pipe (from the catalyst to the front muffler) with a device with a single row of TEGs, a total power of 30 W could be achieved. This power is enough to offload the car's alternator by 7.1 % (as the nominal alternator power at this car is 420W at 2000 rpm).

As there is enough available space at the exhaust pipe part mentioned before, TEGs with bigger dimensions or double row of TEGs could be used, resulting into a more efficient device.

In order to have a measurement of a possible TEG's material degradation, as it was exposed to elevated temperatures, a "Z-meter" device type DX4065 of RMT Ltd was used. With this device we measured the material "Figure of merit" Z and the TEG's electrical resistance, before assembling and after the experiment. The measurements showed a reduction of 5.5 % at Z , with no significant change at TEG's resistance. Brittleness at TEG's solderings after the operation was observed. This implies the TEG's susceptibility at temperatures above the maximum operating temperature.

4. Conclusions

It is investigated the temperature distribution along the exhaust pipe of a small sized car for various engine loads. An experimental device was developed, which allows the measurement of the gained power of a commercially available TEG at normal driving situations in a position after the catalyst. With the use of a theoretical model, the device's thermal resistances and the TEG's efficiency are evaluated.

From the results, it seems that a significant amount of power could be gained with the use of a properly designed device consisting of numerous TEGs. The natural cooling of the device seems to be efficient, as the use of an electric fan should reduce the overall efficiency of the thermoelectric device.

Acknowledgments

It is acknowledged the financial support of the project entitled "Application of Advanced Materials Thermoelectric Technology in the Recovery of Wasted Heat from automobile exhaust systems" by the Greek Secretariat of Research and Development under the bilateral framework with Non-European countries (Greece-USA)

References

- [1] D. M. Rowe (editor), CRC Handbook of Thermoelectrics: CRC Press, Boca Raton, FL, 1995
- [2] Francis Stabler, "Automotive applications of High Efficiency Thermoelectrics," DARPA/ONR Program Review and DOE High Efficiency Thermoelectric Workshop, San Diego, CA, March 24 – 27, 2002.
- [3] J. Vazquez, R. Palacios, M.A. Sanz-Bobi, A. Arenas, "State of the art of thermoelectric generators based on heat recovered from the exhaust gases of automobiles," Proceedings of the 7th European Workshop on Thermoelectrics, Paper #17. Pamplona, Spain, 2002
- [4] K.T. Zorbas, E. Hatzikraniotis, and K.M. Paraskevopoulos. Power and Efficiency calculation in commercial TEG and application in wasted heat recovery in automobile. Proc. of the 5th ECT; Paper #30, September 10-12, 2007, Odessa, Ukraine
- [5] L.B. Yershova, G.G. Gromov I.A. Drabkin. Complex Express TEC Testing. RMT Ltd, Moscow.
- [6] G.G. Gromov, L.B. Yershova, I.A. Drabkin. Complex Method to Control the Quality of Construction and Performance Reliability of Thermoelectric Modules in Optoelectronic Devices. RMT Ltd, Moscow.
- [7] E. Hatzikraniotis, K.T. Zorbas, K.M. Paraskevopoulos. Material degradation of Thermoelectric Power Generators (TEG) for use in automobile, Presented in E-MRS 2008 Spring Meeting, (symposium M) Strasbourg (France) May 26 - 30, 2008 (Appl. Energy, submitted 2008)
- [8] K.T. Zorbas, E. Hatzikraniotis, K.M. Paraskevopoulos. Power and Efficiency calculation and evaluation of material properties in Thermoelectric Power Generators, Mater. Res. Soc. Proc. vol. 1044 p.1044-U09-15 (2008)