



## Experimental analysis of an automotive thermoelectric generator under different engine operating regimes

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### Abstract.

Thermoelectric generators (TEGs) have become a promising technology for vehicle exhaust heat recovery. In this paper, a novel prototype with reduced thermal inertia, low size and capable to withstand the exhaust highest temperatures has been proposed. A small-scale prototype has been built and tested for further study. Results of experiment show the reasonability for exhaust heat recovery. The prototype can generate a maximum power output of about 111 W when operating at exhaust temperatures of 700 °C. The vehicle speed is a significant factor affecting the TEG performance for waste heat recovery. It can be found that the higher the vehicle speed is, the better the performance of the ATEG is. Also the temperature of the cooling system strongly affects the ATEG performance. Higher water cooling temperatures reduce temperature difference between hot and cold side of TEGs and cause a reduction on ATEG efficiency.

### Key words

Automotive, Thermoelectric, Generator, Waste, Heat.

### 1. Introduction

Internal combustion engines waste through the tailpipe about the same amount of thermal power they produce mechanically, around 35-40% of the fuel energy supplied, even when operating at top efficiency[1–4]. It is therefore advantageous to recover a portion of this wasted energy by converting it into electricity[5]. This electric recovery will be especially useful in the case of vehicles having a high degree of electrification, synergistically increasing the efficiency potential.

A significant number of researches in cooperation with several vehicle manufacturers have been done for exhaust manifold, exhaust piping and catalytic converter

packaging design for automotive exhaust system to improve performance based on heat transfer analysis of exhaust system. The most interesting results of this research have been described in Table I, which summarizes the achievements reported.

Bismuth Telluride is the most popular thermoelectric material. However, its use is limited because its maximum operating temperature is relatively low. As they are widely used and mass produced, their cost is low compared to other thermoelectric materials. Other materials and techniques have been used to improve the power generation and efficiency of TEGs. Due to the high temperatures achieved on the exhaust line, the most promising and practical materials to be used for TEGs in exhaust heat recovery systems would be materials rated for a high temperature. This means a larger temperature difference can be present and potentially more power and higher efficiency can be achieved. Lead telluride and calcium manganese have been used as materials in TEGs due to their ability to handle higher temperatures. Some TEGs have been manufactured with segmented material. A material with a high ZT at higher temperatures is used on the hot side (i.e.: lead telluride) and a material with a high ZT at lower temperatures is used on the cold side (i.e.: bismuth telluride). More power would be produced compared to a TEG made of just the high temperature rated material. Other materials such as skutterudites and other manufacturing techniques such as quantum well structures have been investigated to improve TEG power generation efficiency but they are still very expensive and not commercially available.

The objective of this study is to test and analyze the performance of a new concept of ATEG under different stationary regimes. This new thermoelectric generator

makes use of a hot side heat exchanger geometry that reduce the thermal inertia and guarantees TE material will

resist the highest exhaust temperature.

Heat source	ATEG power	Exhaust Temperatures	Cooling temperature	TE material	Exhaust flow rate	Pressure loss	Ref.
Cummins NTC350 14l 300HP Diesel truck engine	1068	-	-	BiTe	-	-	[6]
Toyota 2l	266	650	25	Skutterudites/BiTe	-	-	[7]
Ruston 3YDA 3,6l	12,2	650	-	BiTe	-	-	[8]
Ford Lincoln BMW X6	700W	625	20 / 80	Skutterudites	45g/s	-	[9]
Combustor bench	35,6	595	25	SiGe	58g/s	-	[10]
GMC Sierra 5.3l	177	550	88	BiTe	-	-	[11]
Chevy suburban	235	600	-	Skutterudites/BiTe	-	-	[12]
Engine simulator	350	600	10	BiTe	-	-	[13]
Experimental rig	250	600	-	Silicide	-	<30mbar	[14]
Light Duty Truck 2.3l diesel engine	500	450	-	BiTe	-	<30mbar	[15]

Fig. 1. Most significant ATEGs build and tested to date.

## 2. ATEG

The automotive thermoelectric generator (ATEG) presented in Fig. 2 is designed for exhaust pipes of automobiles. The purpose of these kind of systems is to turn the wasted energy into a useful one. In this case, into a source of electrical power, in order to feed many electrical parts of the vehicle, leading to fuel and greenhouse emissions savings.

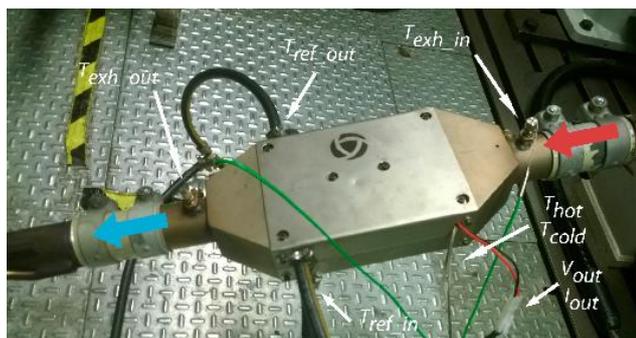


Fig. 2. ATEG installed on the engine exhaust.

The working mode is based on the conversion of heat into electricity. Thermoelectric materials generate a voltage while in a temperature gradient on their junctions. In such case, electrons flow from hot to cold by Seebeck effect.

A thermoelectric module (TEM) is a circuit containing two different thermoelectric materials. One, a negative charged semiconductor, called n-type, and the second, a positive charged semiconductor, called p-type. These two semiconductors form a thermoelectric couple. Then, concatenating several thermoelectric couples wired electrically in series a thermoelectric module is obtained.

The objective of this ATEG is to get a high temperature gradient on the both sides of the thermoelectric modules using the energy contained in the exhaust fumes of a combustion engine. The gases flow internally through the device and transfer a portion of its heat through the thermoelectric modules to the cold plates. Then, the cooling circuit, that uses water as a coolant, takes the heat and dissipates it using a forced convection exchanger. The more heat flows through the thermoelectric modules, the higher the power generated.

The size of the device is 160x500x60mm (WxLxH) with a total weight of 6,97kg. It is composed by 12 thermoelectric modules connected electrically in series but thermally in parallel. TEMs are constructed with Lead Tin Tellurium and Bismuth Tellurium and stuck with high thermal conductivity graphite sheet on their both sides to

provide low contact thermal resistance. These modules are arranged on the both surfaces of a copper heat exchanger (2), through which the exhaust gas is passed, and two aluminum cold plates (3). Fig. 3 shows the schematic diagram of the experimental ATEG.

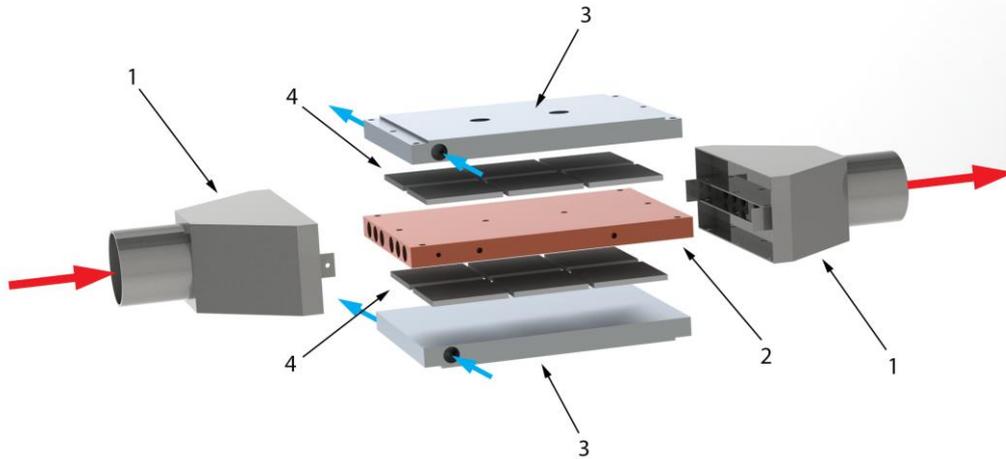


Fig. 3. Exploded view of prototype. 1) Exhaust fumes inlet and outlet. 2) Heat exchanger. 3) Cold plates. 4) Thermoelectric modules. In red, exhaust gases. In blue, cooling system's water.

### 3. Results and discussion

Fig. 4 to 9 shows the data obtained from the stationary study. On the whole, four stationary points were established: three standard engine regime points at 2000rpm and acceleration rate of 15%, 45% and 85%, and a final point at maximum engine regime of 4000rpm and 85% of acceleration. It can be observed that all electrical parameters such as voltage in Fig. 4, current in Fig. 5 and power in Fig. 6 increase with the engine load.

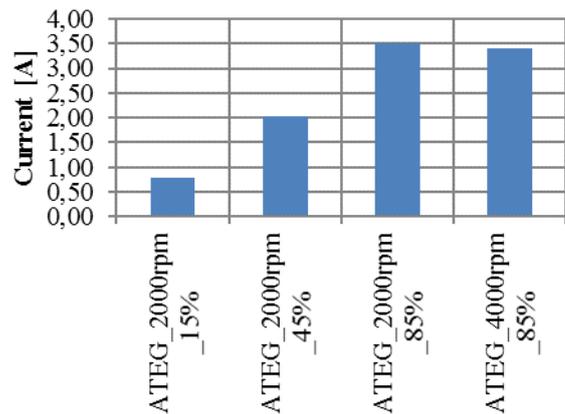


Fig. 5. ATEG current at MPP at various stationary regimes.

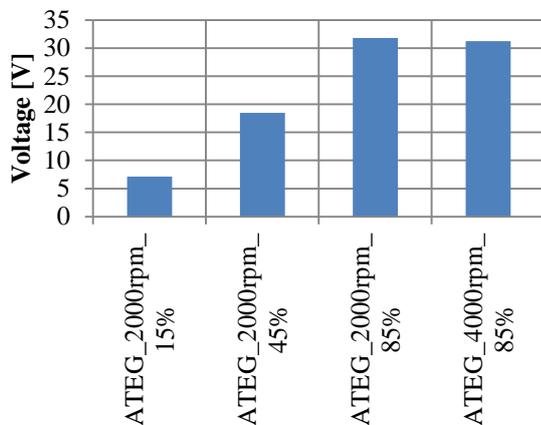


Fig. 4. ATEG voltage at MPP at various stationary regimes.

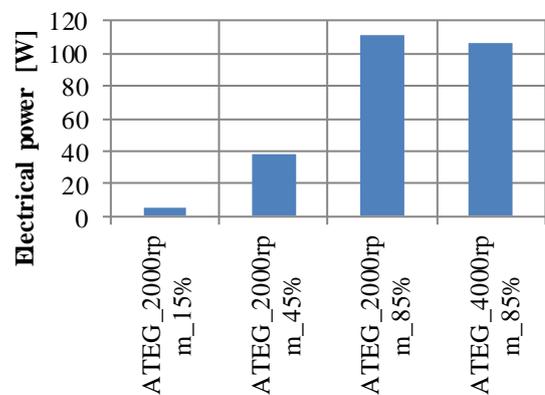


Fig. 6. ATEG electrical power at MPP at various stationary regimes.

As can be seen in Fig. 7, the more the engine load, the higher is the exhaust gas temperature and flow rate and consequently, the more the power generated by the ATEG.

On the last stationary point, it can also be observed that, in spite of having a highest exhaust temperature, the power production is lower than expected. That is because of the higher temperature on the cooling system that causes a  $\Delta T$  decrease on TEGs, Fig. 9. The exhaust temperature lost through the ATEG remain constant throughout all the tests.

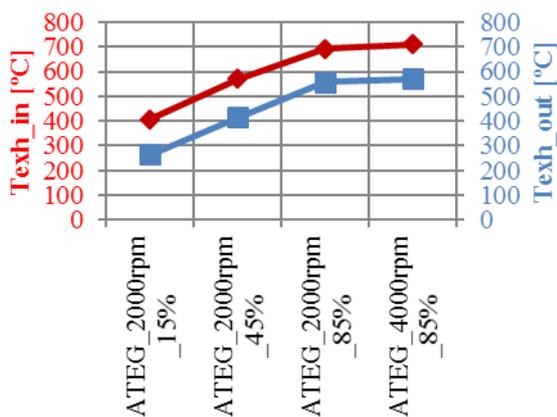


Fig. 7. ATEG inlet and outlet exhaust temperature at various stationary regimes.

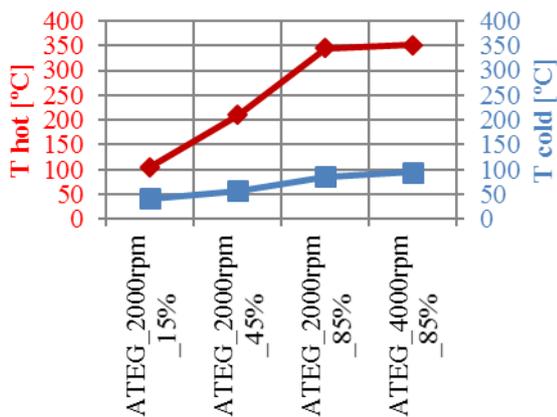


Fig. 8. TEGs hot and cold side temperature at various stationary regimes.

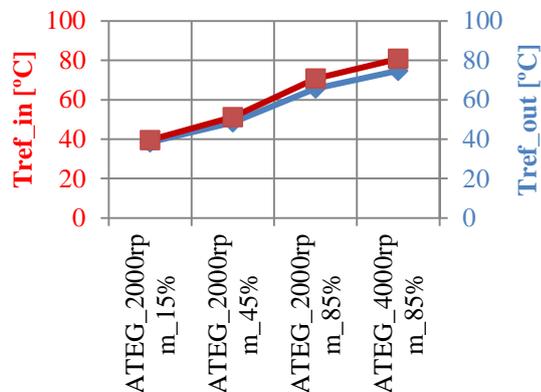


Fig. 9. ATEG inlet and outlet water cooling temperature at various stationary regimes.

Considering the data obtained from the experiments, the way in which the vehicles are driven is a significant factor affecting the ATEG performance for waste heat recovery. Most of the ATEGs developed in literature have been designed to withstand the maximum temperature of the exhaust gases. In this case, the ATEG was designed to withstand the maximum allowable temperature of TEGs, which was 350°C at 700°C of exhaust gases. Taking into account that during normal driving conditions this working point is rarely achieved, it can be stated that the majority of ATEGs will work below its MPP.

#### 4. Conclusion

In this study, an automotive thermoelectric generator ATEG based on vehicle waste heat recovery has been developed. The ATEG system behavior is investigated for constant and dynamic driving conditions. It is found that the vehicle speed is a significant factor affecting the ATEG performance for waste heat recovery, the higher the vehicle speed is, the higher the temperature of the exhaust gases and the better the ATEG performance is. In stationary conditions, the maximum power output is 5.52 W at 2000rpm at 15% acceleration, and it reaches 111.22 W at 2000rpm at 85% acceleration. Transitory tests have demonstrated that the way in which the vehicle is driven is also a significant factor affecting the ATEG performance for waste heat recovery.

All ATEGs developed in literature have been designed to withstand the maximum temperature of the exhaust gases. However, during normal driving conditions this working point is rarely achieved. Additionally, the high thermal inertia of the ATEG prevent thermoelectric materials from achieving its MPP when it is subjected to transitory conditions such as present in a NEDC driving cycle. Consequently, the results suggest that the majority of ATEGs will produce significantly less energy than expected from stationary analysis. Highly frequent change of driving condition may have a negative effect on the ATEG performance. Only vehicles that work in a very constant regime such as high-duty vehicles will take advantage of this kind of energy harvesters.

#### Acknowledgement

This work has been partially funded by the University of Girona under grant MPCUdG2016-4.

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