State of the Art of Thermoelectric Generators Based on Heat Recovered from the Exhaust Gases of Automobiles

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Abstract

The recovering of heat from exhaust gases in automobiles is a typical application of electricity generation using thermoelectricity. This paper is focused on reviewing the main characteristics and evolution of the different investigations performed over the last three decades concerning the use of thermoelectric generation using the heat from the exhaust gases produced in the combustion process of an automobile. The use and evolution of different kinds of thermoelectric materials (silicon germanium, lead telluride and bismuth telluride alloys) will be presented. Also, several main characteristics of the different structures proposed for the thermoelectric generators (TEGs) will be compared. In the review included in this paper, it would be useful to update the potential of thermoelectric generation in the automobile industry nowadays. The results presented can be considered as references of the minimum goals to be reached. Better results can be expected due to the continuous improvement in thermoelectric, thermal and insulating materials.

1. Introduction

The electrical power used in automobiles is generated using part of the energy converted into a driving force with an alternator. The main problem of this energy transformation is that only part of the energy flow supplied by the fuel in an automobile is converted into brake power output and although the efficiency of the alternator is high, the ratio between the electric energy produced and the fuel consumed is very low. The efficiency of a modern internal combustion engine oscillates from 37% in a normal passenger car spark ignition engine to more than 50% in a low speed marine diesel engine. The energy dissipated is lost by transmission to the environment through exhaust gas, cooling water, lubrication oil and radiation. For instance, in a gasoline engine, about 30% of the primary gasoline energy is discharged as waste heat in the exhaust gases.

Furthermore the electric load of a vehicle is increasing due to improvements of comfort, driving performance and power transmission. In line with this tendency, the alternator size, load of engine power and engine weight are becoming larger. However, the engine room is becoming smaller in order to improve the aerodynamic characteristic and expand the passenger room. For this reason, the space for the alternator cannot be freely increased.

If approximately 6% of the exhaust heat could be converted into electrical power, more or less the same quantity of driving energy that demands the production of electrical power would be released and then, it would be possible to reduce the fuel consumption around 10%. This is the reason why thermoelectric generators (TEGs) can be profitable in the automobile industry.

2. Elements of a TEG

A thermoelectric generator basically consists of three components:

- **The support structure**, where the thermoelectric modules are located. The internal part of this structure normally is modified in order to absorb the most part of the heat accumulated in the exhaust gases.
- **The thermoelectric modules**, depending on the range of temperatures, silicon germanium, lead telluride, or bismuth telluride modules are used.
- **The heat dissipation system**, which favours the heat transmission through thermoelectric modules.

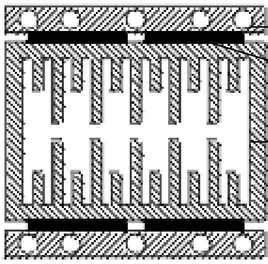

Figure 1. Scheme of a generic thermoelectric generator.

The following sections of this paper describe the ideas and designs proposed by the research community around the three elements mentioned of a TEG. A section summarising some experimental results follows to the previous ones mentioned, and finally some future prospects of automobile TEGs are included in the last section.

3. Support structure of the TEMs

This structure is extremely important in any thermoelectric generator oriented to be used in an automobile due to the following reasons and limitations:

- The heat transmission from the exhaust gases to the structure must be done normally in a short length. Usually it is necessary to introduce internal fin heat sinks, or other structures which increase the contact area between the gases and the support structure and raise the turbulence augmenting the average heat convection coefficient. However, the fin heat sinks or bundles are real obstacles in the way of the exhaust gases, generating a pressure drop. This can affect the engine efficiency, even causing a new design of the camshaft.

- The available space to mount a thermoelectric generator in an automobile is normally reduced because of the tendency to put more equipment in less space. There are mainly three possible locations for the TEG:
  - Just behind the exhaust manifold.
  - Between the manifold and the catalyst converter.
  - After the catalyst converter.
- The weight of the structure. Approximately it represents at least 50% of the total weight of the TEG. If the system is too heavy, the loss in the engine efficiency can surpass the electrical energy produced by the TEG making it completely inefficient.
- Variability of the exhaust gas temperature. The different working points of the engine cause the temperature of the exhaust gases at the same point of the exhaust pipe to vary. This affects the coefficient of performance of the TEG, and hence the electrical power generated. The structure must be designed in such a way that all the thermoelectric modules mounted are working near their optimum performance for the most common working point of the engine.

According to the previous paragraphs, the shape, size, weight, material, and the system used to enhance the thermal transfer from the exhaust gases, are important parameters to compare the different designs fabricated till now.

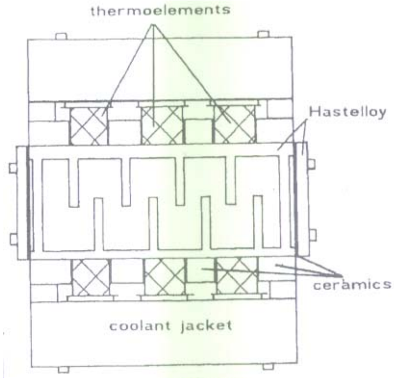

Figure 2. Support structure for a Birkholz generator, [2].

Birkholz, U. et al, in collaboration with Porsche proposed a structure with rectangular cross section, [2]. This thermoelectric generator was designed to be adjusted to the exhaust pipe of a 944 engine with a length of 500 mm and with a total maximum cross section of 300 x 300 mm^2. It was made of Hastelloy X (Ni 47, Cr 22, Fe 18, Mo 9). The free section 0,23 dm^2 of this channel was high enough to prevent a decreasing of the engine power. Some fin heat sinks were included in the interior part of the channel to improve the heat transmission through the thermoelectric pairs, see figure 2.

Serksnis, A. W. in [3] proposed a design which used the proper exhaust shape of the exhaust pipe. The thermoelectric generator would have a length of 460 mm and an internal diameter of 76 mm. The material used was stainless steel. No system was included to improve the heat transmission from the exhaust gases to the support structure.

The Nissan Research Centre has developed TEGs for different temperature ranges with a shape similar to the first one explained in this paper [4], [5], and [6].

The prototype using BiTe modules with a length of 455 mm and an internal cross section of 160 x 40 mm^2. This thermoelectric generator consists of 16 commercial HZ-20 modules. Inside the inner shell, heat exchanging fins with different area ratios (0.92, 1.21, 1.65, 1.99) along the length of the exhaust gas flow were located in order to reduce the temperature distribution on the hot side of the modules without overheating them.

The prototype using Si-Ge modules had a length of 440 mm and a cross section of 120 x 40 mm^2. In this TEG, 72 modules of a 20 mm square section each were mounted.

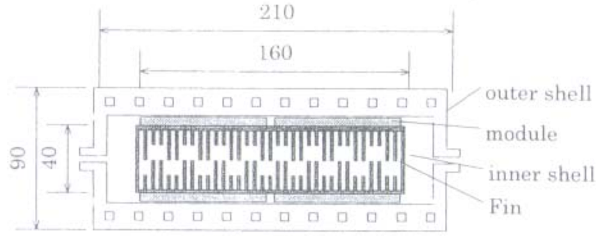

Figure 3. Structure of Nissan TEGs.

Takanose, E. and Tamakoshi, H. proposed in [1] a different structure where the TE modules were mounted inside a cylindrical structure with a diameter of 190 mm and a height of 180 mm. The total weight of the generator was 5.8 kg and 10 kg including accessories. Different diffusers were installed and tested inside this thermoelectric generator to improve the heat conduction creating turbulence in the exhaust gases. Experimental results show that a diffuser injecting the exhaust gas to inner wall of the TE modules performed better than systems which diffused exhaust gas spirally.

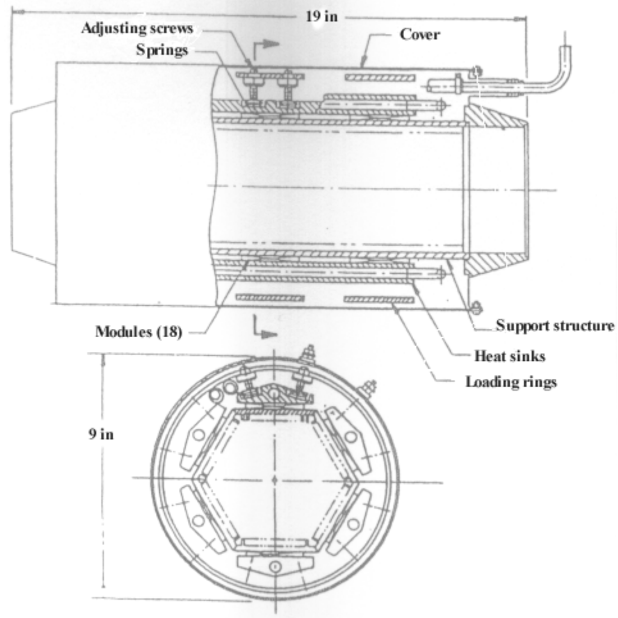

Figure 4. Cross Section of Hi-Z thermoelectric generator.

Another important contributions are coming from the different applications published by the Hi-Z company oriented to recover energy from the exhaust pipe of trucks. This company has a lot of experience in manufacturing TEGs ([7], [8], [9], [10], and [11]), and some of its publications include a small prototype that could be used inside the space available in a car. The structure proposed is a central support tube, circular in its inner part and hexagonal or octagonal in its outer surface, see figure 4. The inner part of the support tube also contained small fins (96 in the first prototype and 32 in the last one) to improve the heat transfer from the exhaust gases to the inner tube. The sides of the support structure were fabricated from flat steel strips with small fins machined on one side. They were welded together configuring the polygonal shape. In the small prototype each side supported three thermoelectric modules. The nominal electric power of the TEG was 180 W. The length was 483 mm and the internal diameter was approximately 110 mm.

4. Thermoelectric modules, materials, shape and size

The TE modules used in a typical TEG can be classified according to the semiconductor material used and the shape, size and configuration of their thermoelectric pairs.

The semiconductor material used in the fabrication of the pellets has been selected according to the position of the TEG in the exhaust pipe:

- **Just behind the exhaust manifold** where the temperature range of the exhaust gases is between 1000ºC and 750ºC. The thermoelements were fabricated on the basis of β-$FeSi_2$, with Co-doping for n-type and Al-doping for p-type in [2], while in [4] the pellets were based on Si-Ge alloys.
- **Between the exhaust manifold and the catalyst converter** where the temperature range of the exhaust gases is between 750ºC and 400 ºC. The model proposed in [3] uses lead telluride thermoelements, type 2P and type 3N/4N. The Nissan Research Centre used PbTe alloys in [5] and the same was also used by Takanose, E. in [1].
- **Just behind the catalyst converter** where the temperature range of the exhaust gases is between 400ºC and 200ºC. All the TEGs designed to be mounted in this position are based on bismuth telluride alloys, specifically Hi-Z commercial modules, [6], [10], and [12]. One important advantage is that it minimises the amount of heat transfer surface required, because the thermal flow required through the modules is lower. This decreases the pressure drop across the generator and results in a lower back pressure on the engine.

Nowadays, the automobile manufacturers are reticent to install any equipment before the catalyst converter because its performance can be negatively affected by a reduction of temperature previous to the inlet.

Another interesting classification of the TEGs is taking into account the shape, size and configuration of their thermoelectric pairs. The TEGs analysed can be classified into two groups:

- TEGs with **traditional square TE modules**. Each of these modules is composed of several thermoelectric pairs in series. This type of configuration requires flat surfaces in order to mount the modules, and has been used in many applications ([4], [6], [5], [10], [12]).
- TEGs with **linear shape TEMs**. In this case the thermoelectric pairs form lines which can adjust better to the circular shape of the exhaust pipe. Related to this theme, Taguchi, K. et al, have designed a linear shaped Si-Ge thermoelectric module in [13]. This configuration was used in [2] and [3].

The following paragraphs describe the main characteristics of thermoelectric pairs used in the different TEGs analysed.

The thermoelectric pairs used in [2] are shown in figure 5. The main characteristic of this thermoelectric pair was that the electrical hot junction contacts were included in the fabrication process of the pellets. The electrical cold junction contacts were made by soldering silver foils to the thermoelectric arms using a Pb/Ag alloy. This TEG used 45 thermoelectric pairs. located on opposite sides of the generator.

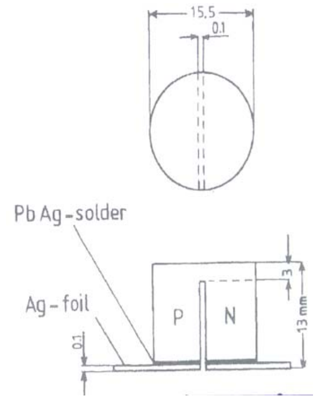

Figure 5. Shape of a $FeSi_2$ element including hot and cold junction contacts, [2]

The same concept of thermoelectric pair was used in [3], but in this case based on PbTe alloy. The dimensions of both P and N legs and the expected values for the power generated by the couple are summarised in table 1. The number of couples employed was 220.

Table 1. Thermoelectric characteristics of the thermoelectric pairs, [3].

Parameter	N leg	P leg	COUPLE
Diameter	1.45 cm	1.45	
Length	0.37 cm	0.35	
Voltage Output	32.4 mV	36.4 mV	68.8 mV
Power Output	1.18 W	1.33 W	2.51 W
Heat rate rejected	24.9 W	25.8 W	50.7 W
Heat rate supplied	25.7 W	26.7 W	52.4 W

The TEG described in reference [4] consists of 72 SiGe TE modules. Each one was formed by 8 thermoelectric pairs connected electrically in series using Mo electrodes. The pellets had a cross section of 3.5 mm^2 and height of 8.0 mm. The dimensions of the TE modules were 20 mm of square section and a height of 9.2 mm. Information about the performance of this type of module is reported in [14]. As a reference, using a ΔT of 563 K, (a hot side temperature of 853 K), the maximum electrical power and the internal resistance of the module were 1.2 W (0.7 V 1.8 A) and 0.4 Ω respectively.

Information about commercial Hi-Z modules is included in [15]. The HZ-14 and HZ-20 TE modules have a 62.7 mm and 75 mm square section respectively and a thickness of 5 mm in both cases. When a thermal flow of 9.54 W/cm^2 crosses the modules, a maximum electric power of 13 W and

19 W is produced for a designed hot an cold side temperature of 230ºC and 30ºC respectively.

3. Heat dissipation system at the cold side.

All the TEGs analysed are based on the same system to dissipate the heat. The heat sink system uses aluminium coolant jackets connected to the water circulation system of the automobile. It tries to maintain a temperature close to 100ºC at the cold side of the TE module. Different shapes are used for these liquid cold plates depending on the particular TEG.

Only the theoretical model in [3] proposes to use fin heat sinks at the cold side of the TEG. This option would take advantage of the proper movement of the automobile to create a turbulent flow at the bottom of the exhaust pipe. An estimation was done in order to obtain the number and shape of the fins required to dissipate the heat power which crosses the thermoelectric modules. The fins would be rectangular with a thickness of 3 mm, a height of 25 mm and a length of 457 mm. A theoretical analysis concluded that the TEG must have 90 fins around all the perimeter of the exhaust pipe considering an air speed of 9 m/s (32.4 km/h) to dissipate a thermal flow of 60.300 W/m^2.

4. Mounting methods, thermal and electrical insulation of the TEGs

The mounting details of the TEGs are extremely important to obtain its correct behaviour. A list of them follows:

- **Mounting method**. It must assure a good mechanical contact between the thermoelectric modules, the support structure and the heat dissipation system, but at the same time it has to be elastic in order to compensate the different thermal expansion coefficients. Furthermore, this mechanism does not have to increase the thermal resistance between the TE modules and the heat dissipation system neither to represent a thermal by-pass between the heat source and the cold sink.
- **Electrical insulation.** Typically the support structure and the heat dissipation system are metallic. Also the thermoelectric modules used in the TEGs are skeleton type and for this reason it is necessary to insulate electrically the surface contacts in order to avoid short circuits.
- **Thermal insulation.** The thermal insulation of TEG is very important in order to reduce the thermal bypass losses between the heat source and the cold sink, including both, the free space between the pellets of the thermoelectric pair and the space among the TE modules.

In [2], the electrical insulation between the heat source and thermoelements was provided by a mica foil (0.1 mm thick). At the cold side, an elastic system with good thermal conductivity was developed. This system is shown in figure 6. Each thermoelectric pair was pressed against the heat sink by the force of a spring (15 N). An aluminium peg served as thermal conductor between thermoelement and water circulation and an elastic stainless steel foil (thickness of 0.05 mm) separated the water from the thermoelements allowing for vertical displacements of ±1 mm. The electrical insulation on the cold side was obtained by oxidation of the aluminium pegs. In this arrangement, the thermal resistance per thermoelement in respect to the heat source was 5 K/W and 3 K/W in respect to the heat sink. A similar concept was used in the theoretical model included in [3].

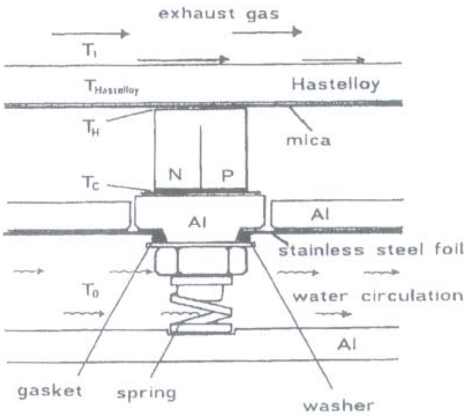

Figure 6. Strain relief construction with a stainless steel foil [2]

The aluminium water cooled heat sink assemblies in [10], were held against the flat surface of the support structure by a pressure of about 200 lb/in^2. The force required was provided by stacks of Belleville springs located at positions which coincide with the centre of each thermoelectric module. Each spring stack was individually adjusted to the same load being between the back side of the heat sink assembly and one of three floating aluminium support rings which surround the TEG, see figure 4.

In order to provide an uniform temperature distribution across the face of the TE modules, aluminium was normally chosen as the thermal spreader between the two stages of the TE module and the hot and cool sinks. The thermoelectric modules of the TEG in [12] were mounted ensuring a compressive pressure of 200 psi (1.38 MPa) as recommended by Hi-Z. In this prototype, instead of using ceramic to avoid short circuit, aluminium hard anodised coatings were used on the surface of the heat spreaders.

5. Experimental results

The TEGs analysed were mounted in different engines or test bench, so the comparison of results is difficult. When the cases studied include experimental tests, their conditions and results achieved are summarised.

In case of the TEG mounted in a 944 Porsche engine [2], the temperature in the exhaust channel was T_1=870ºC at maximum engine power, and the temperature of the cooling water was T_0=70ºC. The temperature difference between the hot and cold side of the thermoelectric pairs in these conditions was 490ºC. The main parameters which characterised the performance of the thermoelectric generator under these conditions were an open circuit voltage of 22 V, an internal electrical resistance of 2 Ω and a maximum electrical output power of 58 W. The electrical output power obtained was quite low because the temperature drop along the generator was only 30 K, so the support structure did not extract a lot amount of heat from the exhaust gases.

Figure 2 shows that the distance between the different thermoelectric pairs was around the same size than this of the thermoelectric pairs. In that situation, the thermal bypass through the thermal insulation can achieve high values. Also, the number of thermoelectric pairs could be increased considerably using the same surface. Another aspect is that the thermal resistances at the cold and hot sides were quite high, therefore a duplication of the output power would seem feasible by reducing these thermal resistances. At the hot side the best option to do this would be the substitution of the material used in the exhaust channel because the Hastelloy X has a thermal conductivity varying from 9.1 W/mK at 21 ºC to 27.2 W/mK at 927ºC. These values are very far from the average thermal conductivity of pure copper (400 W/mK) or even pure aluminium (237 W/mK). The use of alloys with higher thermal conductivity would considerably reduce this thermal resistance, always taking into account the melting point of the alloy. Another factor that can help to reduce the thermal resistance at the hot side can be the modification of the interior fins, increasing their number and possibly changing their shape but always maintaining a free section enough for not affecting the performance of the engine.

The reduction of the thermal resistance at the cold side is more complex, taking into account that the material of the peg in contact with the thermoelectric pair is aluminium. Perhaps efforts could be focused on improving the contact between the water and the aluminium peg, something quite difficult to achieve because of the watertightness required.

The best working point of the TEG designed by the Nissan Research Centre based on SiGe TE modules was 35.6 W at a speed of 60 km/h hill climb mode in a gasoline engine (3000 cc). At this working point, the efficiency of the generator heat exchanger was 11% of the primary exhaust gas energy flux being the generated power just only 0.9% of the heat flux through the generator. For the conditions expressed above, the temperature and the heat power of exhaust gas at the inlet of the catalyst were 868 K and 37.3 kW. The temperature drop of the exhaust gas was about 65 K between the inlet and the outlet of the generator with an exhaust gas flow of 58 g/s. The increment of the cooling water temperature was 4.5 K passing through the generator at a water flow rate of 14.2 l/min.

The temperature difference between the hot and cold sides of the first row of the thermoelectric modules located at the most upper stream of the exhaust gas flow was 396 K with a temperature at the hot side of 772 K. The temperature difference decreased to 372 K at the lower stream of the exhaust gas flow.

However, the ratio between the temperature difference in the thermoelectric module and the temperature difference between the exhaust gas and the cooling water was almost constant in all rows of thermoelectric modules, 72 % for all module blocks, assuming a linear relationship for temperature variation of both, the exhaust gas and the cooling water. This result suggests that the heat resistance of the thermoelectric modules represented the 72% of the total thermal resistance from the exhaust gas to the cooling water. In these conditions, the ratio of electrical power generated to the area of hot sides of all the modules was 1.2 kW/m^2.

The total efficiency of the generator can be defined as:

$$\eta = \eta_s \cdot \eta_{mh} \cdot \eta_{me}$$

where:

η_s : is the efficiency of heat exchange of the generator

η_{mh} : is the ratio of heat flux through the elements in the modules to that from the inner shell to outer shell

η_{me} : the thermoelectric conversion efficiency of the elements.

Considering the results, the primary exhaust gas energy ~37.3 kW, the heat transfer from the exhaust gas to the cooling water through the generator ~4 kW and the generated power 35.6 W, the η_s and η_{mh} x η_{me} are estimated as 11% and 0.9%, respectively. Consequently, the total efficiency of power generation (η) became 0.1 %.

The authors considered that the electrical efficiency of this type of modules in normal conditions is 1~2 %, and therefore the efficiency of the total heat transmission through the thermoelectric modules (η_s x η_{mh}) would be 5~10%. So, a further improvement on heat transfer around the module would be necessary. The paper suggested that if η_s x η_{mh} and η_{me} could be improved to 50% and 5%, respectively, the generated power would rise up to 950 W under the same 60 km/h hill climb mode.

The inner shell of this thermoelectric generator was made of SUS 304 ,which is stainless steel (Japanese nomenclature). Another problem of this prototype is the distance among the different rows of thermoelectric modules. The proportion of area occupied by modules to the faces of the inner shell was only 55%. In this situation, the thermal bypass is considerable, and it becomes critical when the temperature is in the order of 800-900 K, because the thermal conductivity of the insulation materials normally increases with temperature.

The TEG based on BiTe modules [6] obtained its best results under the conditions at a speed of 60 km/h up a 3-5% hill using a 2-3 litres gasoline engine vehicle. The electric power generated was 193 W. The efficiency of the generator was estimated of 37% of the primary exhaust gas energy flux, being that the electric power generated the 2.9 % of the heat flux through the generator. Some aspects included in this reference are summarised in table 2. The meaning of the different variables is the following:

- T_{is}: surface temperature of inner shell.
- T_{os}: surface temperature of outer shell.
- T_{mh}: temperature of hot side surface of module calculated from the generated power and the data of Hi-Z catalogue.
- $T_{gas\text{-}in}$, $T_{gas\text{-}out}$: gas temperature at the entrance and the exit of the inner shell.
- $T_{water\text{-}in}$, $T_{water\text{-}out}$: water temperature at the entrance and the exit of the outer shell.

It is important to observe the high values of the temperature at the input of the TEG, 583ºC compared to the optimum steady temperature at the hot side of the TE modules, 250ºC. Despite this high temperature, the hot side temperature of the module was not optimum because in all the steps it was approximately 50ºC lower than the optimum value recommended by the manufacturer. Possibly, this fact is related to the material used to build the inner shell, and with the system used to joined the thermoelectric modules on the outer surface of it, increasing the thermal resistance.

Another important fact is that the temperature of the cooling water was 26ºC. This temperature would require a secondary water circuit because the steady temperature in a radiator is close to 100ºC. The average electrical power generated by each thermoelectric module was approximately 12 W, while the maximum electrical power produced by a HZ-20 module is 19 W, 58.3% higher.

Table 2. Generation power and conversion efficiency of the BiTe TEG [6].

Exhaust gas					
T_{gas-in}	583 ºC				
$T_{gas-out}$	377 ºC				
ΔT_{gas}	206 ºC				
Flow rate	30 g/s				
Q_{gas-in}	18 kW				
ΔQ_{gas}	6.7 kW				
Cooling water					
$T_{water-in}$	26 ºC				
Flow rate	0.0015 m^3/min 0.025 l/s				
$T_{water-out}$	65 ºC				
Generator	**Nº 1**	**Nº 2**	**Nº 3**	**Nº 4**	**Total**
T_{is}	255 ºC	252 ºC	223 ºC	220 ºC	
ΔT_{shell}	200 ºC	201 ºC	172 ºC	174 ºC	
Electric power	43 W	40 W	110 W		**193 W**
T_{mh}	193 ºC	185 ºC	201 ºC		
Efficiency					
Stack efficiency			37 %		
Module efficiency			2.9 %		
Total efficiency			1.1 %		
Power performance					
Power Volume of Stuck			25 kW/m^3		
Power Area of Modules' surface			3.0 kW/m^3		

The physical characteristics of Hi-Z TEGs are summarised in table 3. One problem was encountered with the operation of the engine during the first tests [8] because the temperature of the coolant water delivered to the generator was much higher than expected, ranging between 87.5 ºC and 120 ºC depending on the revolutions and the power developed by the engine. As the power output of a thermoelectric device changes roughly as the square of the temperature difference across the device, the maximum generated power in the small prototype in the first test was only 120 W. The thermoelectric generator functioned quite well during these first tests without suffering any mechanical or electrical problems as a result of operating on the engine exhaust.

Table 3. Physical characteristics of Hi-Z generators.

Physical Characteristics	**Model 1 kW**	**Model 180 W**
Nominal Power	1000 W	180 W
Voltage	28 V	12 V
Size		
Diameter	279 mm	222 mm
Body length	762 mm	472 mm
Overall length	------	838 mm
Weight	44 kg	13.6 kg
Te material	BiTe	BiTe
Number of thermoelectric modules	72	18
Coolant	Liquid	Liquid
Engine	Cummins H-14	Cummins L-10

The results of the first 1 kW experimental TEG obtained in 1992 were quite poor since the system was only able to achieve a maximum of 400 W, when it was designed for 1000 W. It was suspected that there was a boundary layer problem with the heat transfer from the exhaust gas to the support structure. The original heat transfer fin design used 90 fins, each about 0.25 inches high, which were continuous from the inlet to the outlet. As an order of magnitude, the temperature difference between the first row of thermoelectric modules and the last one was 60ºC, being the first one at 180ºC and the last one at 120 ºC

The first modification of the casting structure was to reduce the number of fins to 32, and to lengthen them to maintain the required heat transfer area. Furthermore, the fins were also made to be discontinuous by placing 0.375 inch gaps about 1.5 inch intervals to aid in breaking the laminar boundary layer. The open circuit voltage temperature profile through the modules showed some improvement from the first test series, however, it still indicated that there was a problem with the gas boundary layer. It was suspected that the heat transfer problem was associated with a lack of turbulence in the exhaust gas.

As heat transfer fins in the cast had been made discontinuous and were placed in line because of the cost of changing the casting core mould to offset the fins. It was decided to install swirl fins on the centre displacement body to increase the gas turbulence. This was accomplished by welding two types of fins to the shell of the hollow displacement body. The first row was a single set of curved blades to start the swirl and the second type consisted of four rows of angled straight blades to sustain the swirl.

With these modifications, the generator was tested on both Cummins NTC-325 and NTC 350 engines. The results of the final test on the NTC 350 showed that with an engine output of 300 hp and 1700 rpm, a maximum generator output power of 1068 W was achieved. Using the same structure of the first prototypes, the thermoelectric modules have been substituted by the new version of HZ-13 modules, called HZ-14 in [16], which features better mechanical properties as well as higher electric power output. Also a new high temperature thermally conductive grease was formulated and tested. It has demonstrated superior performance at the TEM hot side operating temperature (about 250-275 ºC) and has been selected for the TEG assembling. In the first test of this prototype, it was found that power strongly depends on engine loading and less on engine speed. These results were in agreement with the previous one. The highest electric power output from the TEG (over 900 W) was recorded at engine load close to 300 HP. The test engine could not reach its designed output which limited the power produced by TEG.

The maximum power generated in the Takanose TEG was 131.5 W, obtained at 65 Km/h (ascent) speed. Under these conditions, the engine worked at 3244 rpm, the temperature of the exhaust gases just in the exhaust manifold was 868ºC, at the entrance of the TEG 866ºC, and at the outlet 716ºC with an efficiency of 2.3 % calculated as the quotient between the generating power and the sum of this power plus the heat dissipated in the cooling water. Under these conditions, the hot side of the TEG was at 750ºC and the cooling water at

91ºC."Normal" and "idling" working points resulted in low performance as 10~20 W and 1 W respectively, making it necessary to improve the generated power under "normal" and "idling" conditions which are frequent working points of the engine. In both cases, the temperature of the exhaust gases was down to 400ºC, low temperature for PbTe modules.

The test results show a good correlation between the generating power and the engine revolutions. More than 3000 r.p.m were required to obtain 100 W or more. The heat transmission from the exhaust gas to the thermoelectric generator could also be improved because the temperature difference between the inlet and outlet of the TEG was only 100ºC approximately.

The total electrical power generated by the TEG mounted in a Ruston 3YDA engine, [12] was 42.3 W when the temperature of the exhaust gases was more than 600ºC being the maximum exhaust pipe temperature 285 ºC. Possibly the reason for this bad heat transmission from the exhaust gases to the support structure was the lack of fins in the internal part of the exhaust pipe.

Recommendations to build TEGs and conclusions

After a through analysis of the results published in different papers, it is possible to extract some important features and recommendations in order to design and build a TEG. These are summarised in the following paragraphs.

<u>Heat transfer from the exhaust gas to the TE modules</u>

This is the essential part to take into account in the design and building of an optimum TEG. The critical parameter is the heat flux which crosses the TE modules. In order to achieve that the TE modules work close to their best conditions of power, it is necessary to reduce the thermal resistance from the exhaust gas flow to the hot surface of the modules. This thermal resistance is the contribution resulting from both the thermal resistance from the exhaust gases to the inner wall of the exhaust pipe, and the thermal resistance from the inner wall of the exhaust pipe to the hot surface of the module. Several improvements can be made to diminish both thermal resistances. One of them is the use of fins in the inner part of the exhaust pipe in order to improve the heat transmission in a turbulence regime. The fins can have different areas along the exhaust gas flow in order to uniform the temperature at the hot sides in all the TE modules. Another option is the use of a hollow displacement body in order to redirect the gas flow to the support structure.

Table 4. Thermal properties of different alloys.

Properties	HastelloyX	Steel	Stainless steel	Copper	Duralumin
Type		AISI 1010	AISI 302	99.9 Cu+Ag	
Melt point (ºK)	1533	1670	1670	1293	755
Density [kg/m^3]	8300	7830	8055	8950	2770
λ [W/mK]					
T=294 K	9.1				
T=300 K		64	15	386	174
T=473 K	14.1				
T=500 K		54	19	----	188
C_p[J/kgK]					
T=294 K	486				
T=300 K		434	480	385	875

The heat transmission from the inner wall to the hot surface of the TE modules is basically a heat conduction problem. The most common materials used in the construction of the support structure of the TEG are steel, stainless steel and in one case Hastelloy, and aluminium. Table 4.shows the thermal properties of these alloys. According to these properties, the best material to be used for the contact of the TEG with the exhaust pipe is copper because it is 6 times and 25 times better as a thermal conductor than carbon and stainless steel respectively, while the maximum gain in weight compared to the lightest steel is only 14.3 %.

Another possibility, could be an aluminium alloy, that is 3.5 times lighter than copper. In this case it is necessary to have a very good control of the temperatures because the melting point of duralumin is only approximately 500ºC, and in some cases is surpassed by the exhaust gas temperatures.

<u>Heat sink type</u>

The most common cooling systems for a TEG are based on water cold plates made of aluminium. They have the best heat dissipation capacity, allowing for a uniform temperature at the cold side of the TE modules and minimising the weight.

The use of the cooling water circuit of the car is possible when the TEG is designed for working with high exhaust gas temperatures (SiGe or PbTe modules). When the TEG has to use BiTe modules, the temperature of the water (normally close to 90 ºC), can be too high for an optimum working point of the TE modules. Possibly, a secondary water circuit would have to be used to diminish the water temperature.

<u>Configurations</u>

Normally two types of TEG configurations are used:

- **Axial configurations.** The thermoelectric pairs are located along the exhaust pipe and using thermoelements with big dimensions, 1 cm of diameter and a height of 1 cm, approximately.
- **Radial configurations.** They are based on the use of TE modules with traditional shape located around the exhaust pipe, normally in prismatic structures.

<u>Location of the thermoelectric generator</u>

Usually the TEG is mounted just behind the exhaust manifold in order to use the most part of the heat accumulated in the exhaust gases. A possible better option is the location of the TEG before the catalyst. Nowadays, the automobile manufacturers are contrary to this option because it can affect to the performance of the catalyst converter.

<u>Important mounting aspects</u>

The TEG mounting procedure is key to obtaining the best performance. The most important recommendations follow:

- It is necessary to allow vertical displacements of the components because of the thermal gradients and the different thermal expansion coefficients of the materials. A good practice is soldering the TE module to the heat dissipation system to minimise the thermal contact resistance in that part, and using a grease on the hot side. The union must be done controlling the applied pressure through traditional or Belleville springs.
- Sometimes it is difficult to build a TEG that is watertight. If this is required, it is important to take into account that the electrical circuit is very close to the water system. It is

also necessary to eliminate the problem of air condensation. The best way to do this is insulating the gaps between modules using some type of silicone. Normally these silicones lose their thermal insulation properties when the temperature increases, so the space between different thermoelectric modules must be minimised.

- Because of the vibrations which are produced in a TEG mounted in a real exhaust pipe, some type of system must be designed in order to eliminate possible movements of the modules with regard to the bases where they are mounted. A good way of doing this is to make a small groove on the base of the heat sinks.

Experimental results

The maximum electric power generated in TEGs for cars oscillates between 43 W and 193 W, except in the TEGs designed by HI-Z to be mounted in trucks. This electrical power has been only achieved normally in a car running at 65 km/h (ascent hill). The same TEGs have been inefficient for other working conditions, like idling point because the temperature range of the exhaust gases did not match with the optimum working temperatures of the thermoelectric materials.

Future prospects

All the projects developed until now are the basis for getting TEGs which match with the automobile requirements.

Improvements in the efficiency must be achieved to make the TEGs profitable for the use in cars and trucks. The efficiency of the TEG is mainly a function of the thermoelectric materials used, but also depends on a good design which minimises both weight and size, and allows for operating in a greater range of temperatures.

A TEG with a 20% efficiency would allow for a reduction in fuel consumption, incrementing the useful power from 44% to 51.8 %, [16]. This performance would greatly reduce payback time and emissions, in addition to fuel savings.

Once TEGs achieve an optimum efficiency, despite the high cost of thermoelectric modules, their use in the automobile industry will become a reality because the world's largest and most efficient cost reduction systems would be in operation, and this would certainly lower the overall cost.

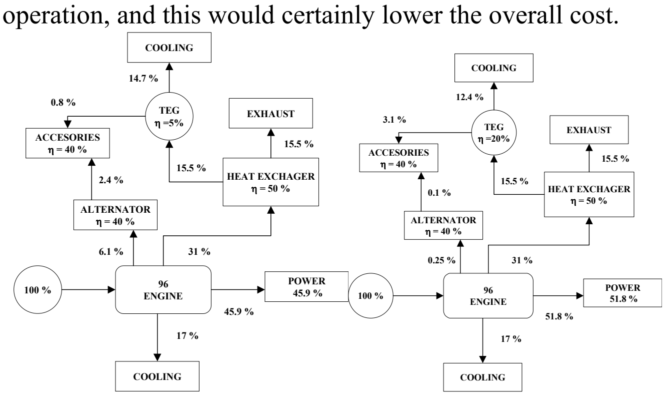

Figure 7. 96 Engine with 5% TEG (present technology) and 20% TEG (future technology), [16]

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