A Survey on Waste Heat Recovery from Internal Combustion Engine Using Thermoelectric Technology

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Abstract

A major part of the heat supplied in an internal combustion engine is not realized as work output, but dumped into the atmosphere as waste heat. If this waste heat energy is tapped and converted into usable energy, the overall efficiency of an engine can be improved. The percentage of energy rejected to the environment through exhaust gas which can be potentially recovered is approximately 30-40% of the energy supplied by the fuel depending on engine load. Thermoelectric modules which are used as thermoelectric generators are solid state devices that are used to convert thermal energy from a temperature gradient to electrical energy and it works on basic principle of Seebeck effect. This paper demonstrates the potential of thermoelectric generation. The use and evolution of different kinds of thermoelectric materials 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..

***Keywords*— Thermoelectric generator, waste heat recovery, internal combustion engine, engine exhaust**

1. Introduction

Heat engines are predominantly designed to produce useful work only. Waste energy in the form of heat is normally a byproduct resulting from the irreversibility of the processes involved in the conversion of primary energy to mechanical or electrical energy. The efficiency of a modern internal combustion engine is about 37% in a normal passenger car spark ignition Engine whereas 50% in low speed marine diesel engine. The energy dissipated is lost by transmission to the environment through exhaust gas, cooling water, lubrication oil and radiation. The electric power used in automobile is generated by taking part of useful mechanical energy. Due to improvements of comfort, driving performance and power transmission the electric load of a vehicle is increasing day by day. Due to this tendency, the alternator sizes, load of engine power and engine weight are becoming larger. However, the engine room is becoming smaller in order to expand the passenger room. For this reason, the space for the alternator cannot be freely increased. With the help of TEG fuel consumption can be reduced by 10% by converting only 6% of waste heat into electrical power. In this way the overall efficiency of the internal combustion engine can be increased.

2. Elements of Thermoelectric Generator

Thermoelectric generator basically consists of three elements these are thermoelectric module, support structure and sink.

a. *Thermoelectric module* – Depending upon the range of temperature different thermoelectric modules are selected like Silicon Germanium, Bismuth Telluride, Lead Telluride also many new material like Zinc Antimonides, Thermoelectric oxide material NaxCo2O4, Thin Films Materials etc.
b. *Support structure* – It is the very important part of the TEG, where the thermoelectric modules are mounted. The internal part of this structure normally is modified in order to absorb the most part of the heat accumulated in the exhaust gases.
c. *Sink* – It is nothing but the heat dissipation system which favors the heat transmission through thermoelectric module.

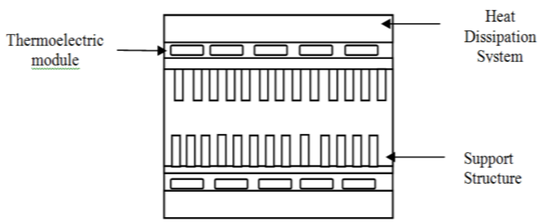

Figure 1.Schematic of generic Thermoelectric generator

The following section of these paper summaries the ideas and designed proposed by research community on these three components.

3. Thermoelectric module

The Thermoelectric module used in a typical TEG can be classified on the basis of material used, shape and size and configuration of their thermoelectric pair.

The semiconductor material used in fabrication of TEG is dependent on maximum temperature obtained and hence location of TEG mounting on the exhaust pipe. There are three positions for TEG mounting

1) *Just behind the exhaust manifold*- The temperature range of the exhaust gases obtained is in between 1000^0 c and 750^0 c. The thermo elements were fabricated on the basis of β-$FeSi_{2,}$ with co-doping for N type and Aluminium doping for P type. Si-Ge alloys are also used.
2) *Between the exhaust manifold and the catalytic convertor*- In this region the temperature range of exhaust gases is in between 750^0 c and 400^0c.The lead telluride material is generally used for this temperature range.
3) *Just behind the catalyst convertor*- The temperature range obtained in this region is in between 400^0 c and 200^0c.All the TEGs designed to this temperature range are based on Bismuth Telluride alloys.

Another interesting classification of the TEGS is based on the shape and size thermoelectric module. The TEG analyzed can be classified into two groups

Traditional square Thermoelectric module:- Each of these modules is composed of several thermoelectric pairs in series. This type of module require flat surface for mounting.

Linear shape thermoelectric module:- In this case, the thermoelectric pairs form lines and therefore they can adjust better to the circular shape of the exhaust pipe.

4. Support structure

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

- The heat transmission from the exhaust gases to the structure must be done normally in a short length. Therefore it is necessary to use fins or other structure to maximize the surface area and to raise the turbulence so that convective heat transfer coefficient should increase. However fins and other structure may cause the problem of backpressure and hence decrease the efficiency of the engine.
- Variation in the exhaust gas temperature. The varying speed causes 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.

By considering these things research community designed the different structure for TEG. These designs are explained below

Birkholz, U. et al, in collaboration with Porsche proposed a structure with rectangular cross section.[1] 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 dm2 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. Model designed is shown in figure.

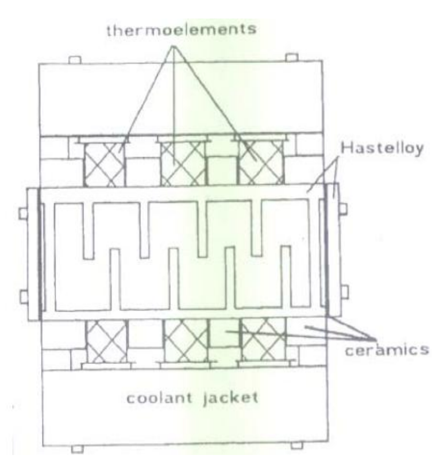

Figure 2.Support structure for a Birkholz generator

TEG was located just behind the exhaust manifold. The thermo elements used are β-$FeSi_2$, with co-doping for N type and Aluminium doping for P type. The linear shape TEMS with 45 thermoelectric pairs was used. The temperature in the exhaust channel was T_1=870^{o}c at maximum engine power, and the temperature of the cooling water was T_0=70^{0}c.The main parameters which characterized the performance of the TEG were an open circuit voltage of 22 v, an internal electrical resistance of 2 ohm and a maximum electric output power of 58w.

The Nissan Research Centre has designed TEGs for different temperature ranges with a shape similar to first one i.e. rectangular cross section[2],[3],[4]. The prototype using BiTe modules with a length of 455mm and an internal cross section of 160 x 40 mm^2 was designed. In this different material like Si-Ge alloy, PbTe alloy and Bismuth Telluride alloy were selected for the different temperature range obtained in just behind the exhaust manifold, between manifold and catalyst convertor and just behind the catalyst converter respectively. 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. The best working point of the TEG designed based Si-Ge TE module was 35.6 w at a speed of 60 km/h hill climb mode in gasoline engine. For Bi-Te modules TEG best result obtained under the condition at a speed of 60 km/h up a 3-5% hill using a 2-3 liters gasoline engine vehicle. Power generated was 193 w.

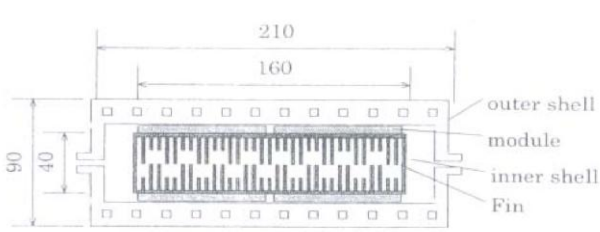

Figure 3.Structure of Nissan TEGs

Takanose, E. and Tamakoshi, H. proposed different structure for TEG[5]. In this structure 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. TEG was located in between exhaust manifold and catalyst converter and the material used is lead telluride.The maximum power generated 131.5 w at 65km/h ascent speed.

Serksnis,A. W. proposed a design which used proper exhaust pipe shape[6]. The TEG would have length of 460 mm and an internal diameter of 76 mm. The material used was stainless steel. No any specific arrangement was provided for heat transfer enhancement. The TE module used is linear shape made up of lead telluride and mounted in between exhaust manifold and catalyst converter. The number of couples employed was 220.The dimension of both P and N legs and expected values of power generated is given as follows.

Parameter	**N Leg**	**P Leg**	**Couple**
Diameter	1.45cm	1.45cm	
Length	0.37 cm	0.35 cm	
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	52.4 w

Table 1. Specification of the test setup

Other important contributions are coming from the different applications published by the Hi-Z company oriented to recover energy from the exhaust pipe of trucks[7],[8]. This company has a lot of experience in manufacturing TEGs 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.

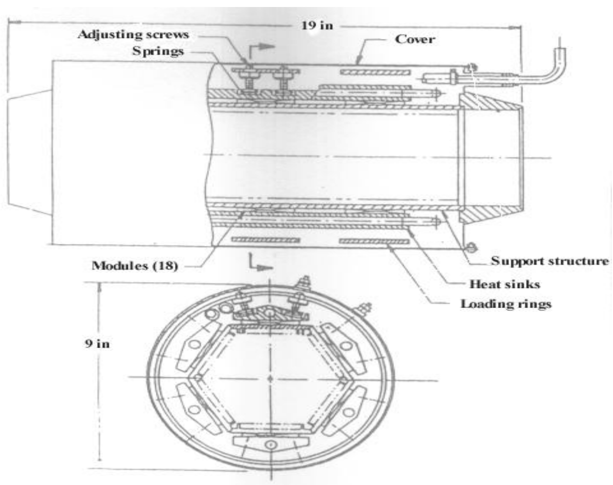

Figure 4.Cross Section of Hi-Z thermoelectric generator

Jihad G. Haidar and Jamil I. Ghojel proposed Thermoelectric generator modules HZ-14 manufactured by HI-Z Technology[10]. The HZ-14 is a thermoelectric module which uses bismuth telluride based alloys and consists of **98** couples. The module requires **a** heat **flux** of about **8** W/cm2. With temperature difference of 200°C (Design hot-side temperature 330"C), the module converts **5%** of the thermal energy that passes through it into electrical energy generating 14 W of electrical power. To provide uniform temperature distribution across the face of the module aluminium was chosen as the thermal spreader between the two faces of the module and the heat source and sink. The system was designed so that it can be mounted between the exhaust manifold and exhaust tube, water cooled heat sink is used for heat dissipation.

Thermoelectric power generation system using waste heat recovery from motorcycle has been demonstrated by the consortium (Project leader: Prof. Y. Nishino, NIT) of Nagoya Institute of Technology, ATSUMITEC Co., Ltd, AIST and other three companies supported by METI [11]. The surface temperature of motorcycle muffler is about 473 K. Although *Bi-Te* class element is suitable to this temperature range application, in this project *Fe*2*VAl* class Heusler alloy has been selected because of potential supremacy from safety, robustness, resource and cost. At present *Fe*2*VAl* alloy has very high power factor ($S2\sigma$, S – thermo power, and σ – electrical conductivity) at 300 K, that is, 5.4 m W/m2·K, but thermal conductivity is very high, that is, 24 W/mK for *p*-type, and 18 W/m K for *n*-type respectively. In the project the performance has been improved about 1.5 times due to the reduction of thermal conductivity. The module size is 35 mm×35 mm. The element size is 5 mm2 × 5 mm. The power output is obtained 0.94 W at 573 K in high temperature. The power density is estimated 0.1 W/cm2. Figure 5 shows the power generation system of 12 improved modules mounting the surface of motorcycle muffler. The power output is obtained about 12 W at 6 V under the driving condition of 60 km/h to charge a battery.

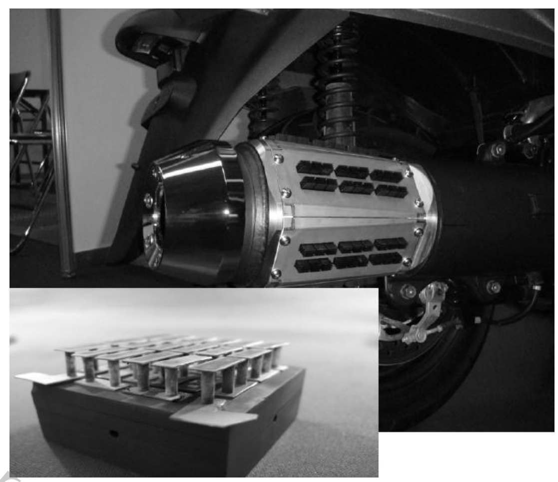

Figure 5. TEG module and system mounted on muffler of a motorcycle

C. Ramesh Kumar designed the model for TEG [12]. On the basis of result obtained in CFD analysis i.e. the surface temperature attained in rectangular model is less compared to that of other two (hexagonal and triangular) models, which suits the TEM requirements (max. hot side temp 220 °C).In this designed the TEG consists of an exhaust gas heat exchanger, counter flow coolant cooling chamber and 18 TEM connected in series. Cast iron of 5 mm thickness was used to make the frame of the heat exchanger. Figure shows the cast iron frame. Two plates were used for the TEM: hot plate and cold plate. Modules were placed on the top side of the hot plate and the exhaust gas (flowing through the frame) was in direct contact with the bottom side of the plate. The cold plate was assembled with the cooling chamber and was placed over the modules with spacer block in between them. The spacer block was used to increase the distance between the hot and cold plate, so as to maintain the temperature difference. Silicon foam was used around the modules to provide necessary insulation and also to eliminate the problem of water condensation. Aluminum plates of 5 mm thickness were used as hot plate and copper plates of 3 mm thickness were used as cold plates. Thermal grease was used to increase the thermal conductivity between the hot plate and the modules. Figure shows the aluminum plate with TEM attached to it. Asbestos gasket was placed in between the hot plate and the frame to arrest the exhaust gas leakage at the junction. The total weight of the TEG was 14.6 kg which is 0.5 kg higher than that of the predicted. The excess weight may be due to welded joints and additional bolts and nuts used during fabrication. The test was carried out on an engine dynamometer, details of which are given in table. No modifications were made on the engine.

Make	Maruti 800
Type	Three cylinder, 4-stroke SI engine, water cooled SOHC
Displacement	796 cm3
Maximum power	37 Bhp at 5000 rpm
Maximum torque	59 Nm at 2500 rpm
Dynamometer make	Dynaspede
Maximum torque	80 Nm at 3000 rpm
Maximum power	25 kW
Controller	PC/manual based

Table 2 Specification of the test setup

Megha Tak *et al* also used potential of Thermoelectric to convert waste heat from automobile to electric energy [13]. They used 2.0engine car for a BMW petrol car with 2000 cc volume. The temperature outside the insulation of the car is 120 c .They used a Thermoelectric convertor having two parallel plates likes a capacitor ,one just near to engine insulation having temperature of 120c and another at a distance of 30 cm inside the car bonnet itself. The plate materials used are Silicon for engine insulation cover and copper at the cold side. Output voltage obtained is 0.0628v.Final amp-hr rating (considering 6% convertor efficiency) is 35.261 amp hr. This energy would be good to efficiently light up the headlights, use for charging other batteries like that of motorcycle.

5. Conclusions

The performance of TEG is mainly depend upon heat transfer from the exhaust gas to TE module, material of TE module, location of TEG. 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. Several improvements can be done to reduce Thermal resistance.

TE module is basically a heat conduction problem. The materials used in all the paper for support structure are Hastelloy and aluminium. The use of Copper for support structure can give better result as the thermal properties of copper are better than this two. Locations of TEG behind exhaust manifold is the best condition as it gives more exhaust temperature provided that TEG design should be such that it should not diversely affect the engine performance. In this way we can increase the efficiency of TEG.

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.

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