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Power generation from waste heat of vehicle exhaust using thermo electric generator: A review

Mohd.Quasim Khan[1], S Malarmannan[2], G Manikandaraja[3]

[1]B.Tech Student, SRM Institute of Science and Technology, Chennai, Tamil Nadu
quasimk5@gmail.com[1],
[2,3] Assistant Professor, SRM Institute of Science and Technology, Chennai, Tamil Nadu,

*Corresponding author: quasimk5@gmail.com

Abstract. The internal combustion engines used in cars have maximum 25%-30% efficiency and rest of the heat energy burned in combustion chamber goes into the exhaust and then to the atmosphere. This led to the increase in harmful gases emission and increase in global warming and environmental problems. This has led to put efforts on improving the efficiency of any industrial process being a priority. In order to use the waste heat of car's exhaust thermoelectric generators are first priority. It is a solid state device which converts the heat energy available in car's exhaust into electrical energy which is then used to increase the performance of a car. The efficiency of a TEG is 4-5% which is quite low but it is not a big issue because this technology uses free heat ; heat energy of no cost as an input and due to the benefits of TEG's it has become a promising alternative green technology. The installation position and thermoelectric materials plays a vital role in improving the efficiency.

Abbreviation:

TEG	Thermoelectric generator
TEM	Thermoelectric module
ICE	Internal combustion engine
Be_2Te_3	Bismuth Telluride
T_C	Cold temperature
T_H	Hot temperature
PbTe	Lead Telluride
Z	Figure of merit
η	Efficiency
T	Average temperature
α	Seebeck coefficient
SiGe	Silicon germanium
TE	Thermoelectric
SrTe	Strontium Telluride

1. Introduction

Due to increase in the carbon dioxide level and other harmful gases specially which are contributing in increase in pollution and global warming, our automobile industries are one of the easy and clear target therefore many researches has been undertaken in this field [1]. Globally, it is estimated that about 1/3 of the total energy is utilized while remaining is rejected as waste heat. The maximum efficiency of an engine is around 25% which means that 75 % of the energy left is wasted in the form of heat from parasitic losses and friction which causes 30% waste in the engine coolant and 40% in the form of gases in exhaust [2]. TEG is a solid stated device which works on the principle of 'Seebeck effect'. The given figure shows the energy distribution in an ICE [1].

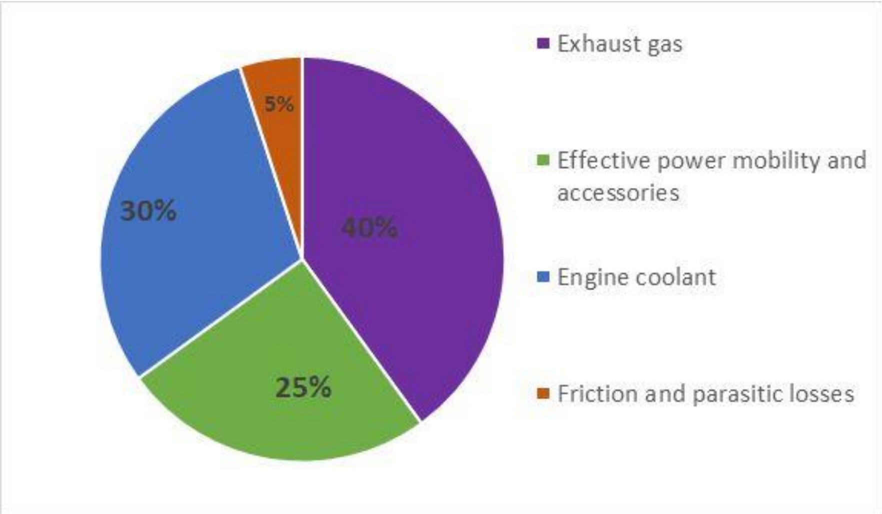

Figure 1. Energy distribution in an ICE.

They are found in solar energy systems like solar panels, solar hot water system, biomass power applications, energy power plants and solar pond systems [3]. Installing a TEG is easy and very beneficial as it has some advantages like small in size, it has no vibrations, makes less or no noise while operating, it generally requires less or no maintenance. And major advantage is that it is using free thermal energy and converting into useful electrical energy.

A thermoelectric module consists of many thermo elements connected in electrical channel in series to increase the operating voltage and to increase the thermal conductivity they are connected in parallel [4]. According to a research the conversion of this waste heat into electricity results to an increase of fuel efficiency about 20% [5]. A TEG works on the principle of a Seebeck effect. Two metallic strips, made of different metals and joined at the ends to form a loop. If the junctions are kept at different temperatures then there is an electric current in the loop and the emf developed is called the SEEBECK emf or thermo emf and the current can be used to power a load.

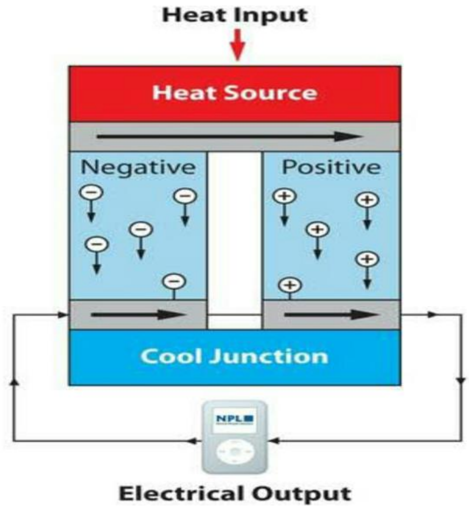

Figure 2. Layout of a TEG.

The TEG structure is sandwiched with the thermoelectric material which is then sandwiched by the heat exchanger plates at their ends respectively. The two heat exchangers remains at different temperatures, one at high temperature and the other at lower temperature and called the hot side and cold side. A thermally insulated layer is present between metal heat exchanger and material of a TEG. The p type and n type materials are connected by the metal electrically. A TEG consists of a two sides, one is cold and other is hot side. The hotter side derives the electrons in n type leg towards the cold side which pass through the metallic connection and then passes into the p type leg, hence develops current. Larger the temperature difference between cold side and hot side, larger value of emf will produce.

2. Experimental Setup

Speed of the vehicle is the most important factor for the power generated by a TEG. For better performance of TEG, speed of vehicle should be greater. As the exhaust temperature is higher, more energy is available for the conversion into electrical energy. There is increase in optimal length and reduction in optimal width based on dynamic optimization simulations when the temperature of the exhaust increases [6]. The efficiency and power of a TEG remarkably depends on the temperature. Given figure shows the temperature of inlet and outlet when the engine is operated between 2500 rpm to 3400 rpm. As the engine speed increases, the temperature difference between the surfaces of TEM increases rapidly, hence the output power also increases [4]. It was found that there is a possibility of generating 1.4 kW of electricity form the heat recovery system in the exhaust of the car if the power produced by the engine is 150 kW and also found that it is possible to produce electricity of 5.9 MW by a waste heat energy recovery system of 500 MW of gas turbine power plant [2].

Another experiment has been performed for checking the power output of TEG by changing the speed of vehicle. The speed of the vehicle were 48.3, 80.6 and 112.7 km/hr and the result was the output power increased as speed of vehicle increases correspondingly mass flow rate of exhaust and inlet temperature increased as per the speed [7]. At the speed of 80 km/hr, the power output with 72 mm * 4 mm TEM was 75 W [17].

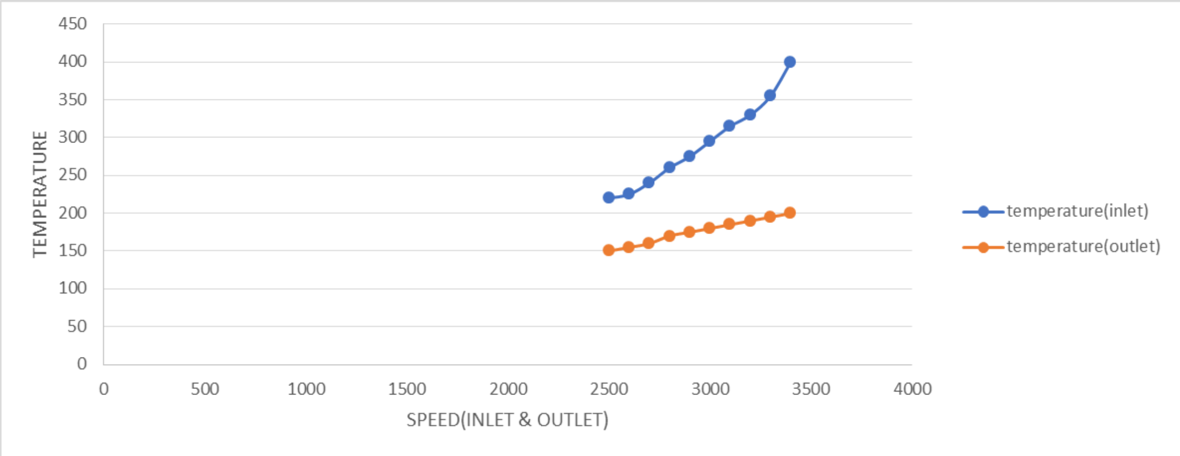

Figure 3. Variation in temperature due to variation in speed.

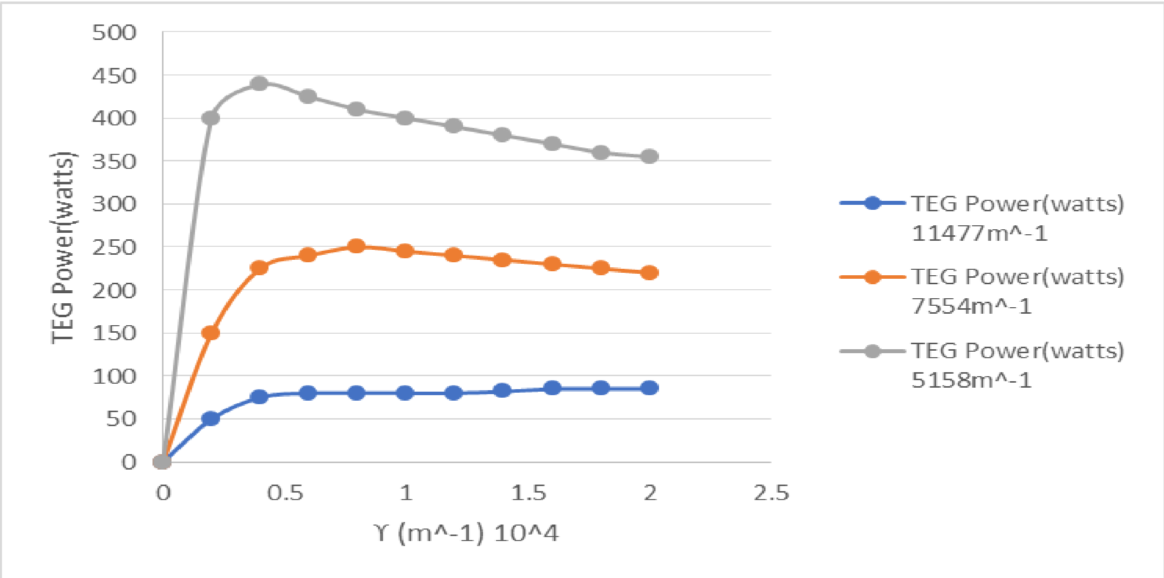

Figure 4. Variation in power production.

3. TEG Power Generation Calculation

The equation involved in calculation of the performance of a TEG is (8,9,10)

$$Z = \alpha^{2/} kR \,, \tag{1}$$

Z is a figure of merit of thermoelectric material, R is the electric resistivity
k is a thermal conductivity and
α is a Seebeck coefficient which is

$$\alpha = \Delta V / \Delta T, \tag{2}$$

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$\bar{T}$ is the average temperature of cold and hot plate of a TEM and when multiplied by Z it makes it dimensionless.

$$Z\bar{T} = \alpha^2 \bar{T} / KR \quad (3)$$

$$\text{and } \bar{T} = (T_H + T_C) / 2 \quad (4)$$

As per the second law of thermodynamics,

$$\eta = T_H - T_C / 2 \quad (5)$$

The maximum efficiency of conversion of a TEG can be found using

$$\eta = \{(1 + Z\bar{T})^{1/2} - 1/ (1 + Z\bar{T})^{1/2} + (T_C / T_H)\} \quad (6)$$

The output efficiency of a TEG mainly depends on two variables: the temperature and MFR of exhaust. Maximum power output and corresponding heat transfer can be obtained by maximizing the MFR ratio [7-8]. As the size of a TEG increases, the output power also increases [11].

4. Thermoelectric Materials

Thermoelectric materials are used in automobiles, power plants, space satellite, etc. Thermoelectric materials can be characterized according to the structure and composition. They can be classified as - chalcogenide , clathrates, skutterudites, half-heusler, oxides and silicides.

The most common thermoelectric materials are the alloys of chalcogenide. The calcogenide materials are popular for their use with (Bi2Te3) and (PbTe).Thermoelectric materials made with Bi2Te3, Se and Sb for temperature use are economical. PbTe has better thermo electric properties at temperature range 500-600 ^{0}C and has been used by NASA as a radioactive thermo electric generator (RTG's) [12]. The stability of a TE material is very important as it should not oxidize within the operating temperature when exposed in air [11]. But nowadays, automobile industries are focusing on bismuth telluride for constructing a TEG.

High charge mobility and small band gaps are the properties of two heavy elements Bi and Te and Bulk alloys of PbTe have a zT value of 0.7 at 467 ^{0}C. When SrTe and PbTe are doped with Na, zT value was 2.2 at 642 ^{0}C [18]. Skutterudites (MX_3) have a lower thermal conductivity due to its complex crystal structure has large voids. $CoSb_3$ based skutterudites are versatile in accepting various actinides, lanthanides, alkalis and alkaline earth metals to be used in void filling and thermal conductivity of skutterudites lowers as the size decreases [18].

Compounds of half heuslers are intermetallic compounds which are thermally stable, having high thermal conductivity and corresponding seebeck coefficient. The lattice thermal conductivity of these compounds reduces having nano structures due to phonon scattering [18]. SiGe alloys are used for high temperature applications because of having very low degradation upto 1000 ^{0}C. When compared to their bulk alloys, nanostructured SiGe alloys have higher zT value. Bulk $Si_{0.8}Ge_{0.2}$ have zT value of 1 and 0.6 for n type and p type respectively. There is an improvement in zT value when nanocomposite thermoelectric materials are used [18].

5. Cost Considerations of Thermoelectric Materials

Commonly, Be_2Te_3, PbTe and SiGe forms the basis of TEG material and among these, Be_2Te_3 is generally used. For manufacturing a TEG material cost is kept into consideration. Cost of the material completely depends on the composition of material and the cost can be varied by doping an expensive and inexpensive material. Given figure 5a and 5b shows the cost of TE materials based on raw materials and there cost of constituent elements respectively. Table 1 shows the detail list of materials and its cost.

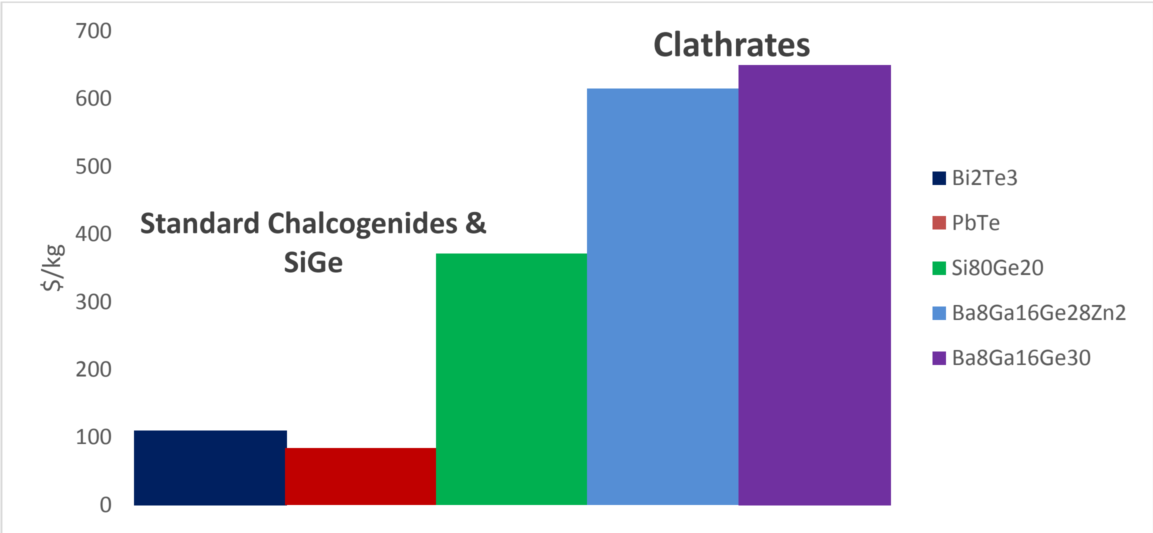

Figure 5 a. Material cost.

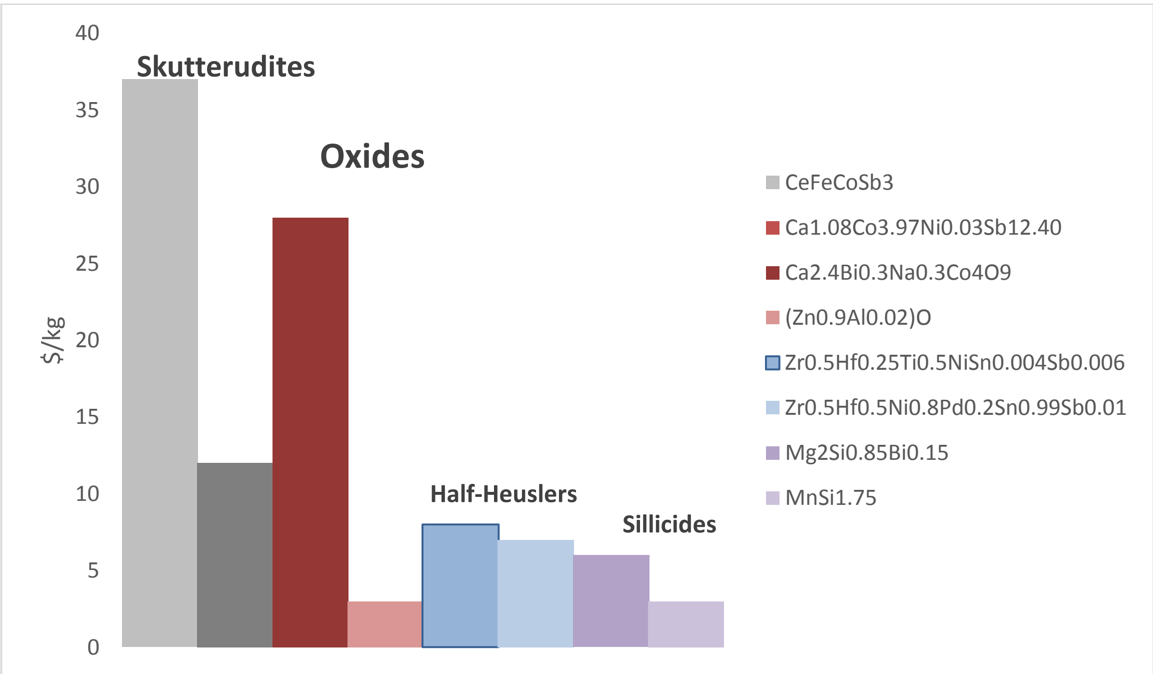

Figure 5 b. Material cost.

Table 1. Cost of materials [12]

Material Type	Material Cost (Raw) ($/kg)	Material Cost (Pure) ($/kg)
Chalcogenide	110	806
SiGe	371	7081
Skutterudite	24	204
Silicide	7	191
Oxide	2	50

6. Installation Position of TEG:

Installing a TEG at an appropriate position is an important task as it determines the output power generated by exhaust heat. In an experiment by [13] TEG was assigned three different position and then examined the net performances. 1. TEG is positioned at the end of exhaust system. 2. TEG is positioned between catalytic converter and muffler. 3. TEG is positioned upside of catalytic converter and muffler.

Among three cases, case 2 was found to be better than case 1 and 3 because in case 2, the heat exchanger obtained a high temperature at the surface and the pressure drop of catalytic converter, muffler and heat exchanger was relatively low, which met with the requirement of exhaust gas system [13].

7. Applications

In steam power plant by installing 60W TEM near the boiler section, achieved a conversion of 4.4% [9].The FORD system heat exchanger uses number of small parallel channels which are lined with thermo electric material for the exhaust gases to pass. The system produces a power of 400W when 4.6 kg of thermoelectric material used [14].In March 2009, BMW launched a prototype vehicle with a TEG in which bismuth telluride material was used. The power produced around 200W-210W at the driving speed of 130km/hr [15].Renault applied it on a diesel truck engine and the system produced a power of 1 Kw [14].Honda system uses a model of flat rectangular boxes with TEG present on upper and lower surface. The maximum power produced 500W [14]. In industrial cogeneration system, the data collected from 27000 factories from different sectors like textiles, oil refining, food processing, chemical factories. It was found that diesel engines and gas turbine cycle produced electricity at 40% and 3% respectively. The useful waste heat from the exhaust cogeneration system was around 10%-11% for diesel cycle and 18%-20% for gas turbine cycle. The net power generation was 100MW [9].The TEG produces electric power of 10-30kw/cylinder. The total electric power which was generated from all cylinders was approximately 200KW as in case of Porche918 and Le Ferrari hybrid vehicles [3].

8. Conclusion

A dynamic model of TEG is presented in this paper. Research has found an appropriate way of exhaust heat to convert into electricity and efficiency of the fuel in a vehicle can be improved. TEG is a promising technology for recovering waste heat of the vehicle exhaust as it is small in size, possess very less vibration and noise, requires very low maintenance and have a long life. Automobile industries are introducing TEG as next step for the contribution towards green earth. Performance of a TEG can be varied according to the change in vehicle speed, engine rpm and installation position. The average efficiency of a TEG IS 3 -4% and the maximum efficiency achieved is 5% in automobile field.

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Be_2Te_3 is widely used by automobile industries for manufacturing of TEG but researches are being done for improving the material properties and efficiency of TEG.

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