

# Design of Exhaust Heat Recovery Power Generation System Using Thermo-Electric Generator

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**Abstract:** A number of irreversible processes in the engine limit its capability to achieve a highly balanced efficiency. The rapid expansion of gases inside the cylinder produces high temperature differences, turbulent fluid motions and large heat transfers from the fluid to the piston crown and cylinder walls. These rapid successions of events happening in the cylinder create expanding exhaust gases with pressures that exceed the atmospheric level, and they must be released while the gases are still expanding to prepare the cylinder for the following processes. By doing so, the heated gases produced from the combustion process can be easily channeled through the exhaust valve and manifold. The large amount of energy from the stream of exhausted gases could potentially be used for waste heat energy recovery to generate power. Various methods to harness the waste heat to produce power effectively had ended up in vain. This paper proposes and implements a thermoelectric waste heat energy recovery system for internal combustion engine automobiles, including gasoline vehicles and hybrid electric vehicles. The key is to directly convert the surface heat energy from automotive waste heat to electrical energy using a thermoelectric generator (TEG), which is then regulated by a DC-DC Cuk converter to charge a battery using maximum power point tracking. Hence, the electrical power stored in the battery can be maximized. The experimental results demonstrate that the proposed system can work well under different working conditions, and is promising for automotive industry.

**Keywords:** Combustion process, Heat transfer, Exhaust gas, Heat energy recovery, Cuk converter, Thermo Electric Generator.

## 1. Introduction

Even a highly efficient combustion engine converts only about one-third of the energy in the fuel into mechanical power serving to actually drive the automobile. The rest is lost through heat discharged into the surroundings or, quite simply, leaves the vehicle as “waste heat”. Clearly, this offers a great potential for the further reduction of CO<sub>2</sub> emissions which the BMW Group’s engineers are seeking to use through new concepts and solutions.

The current research is focusing on a technology, which is able to convert the thermal energy contained in the exhaust gas directly into electric power. Taguchi [1] invented an exhaust gas-based thermoelectric power generator for an automobile application. In this invention, the exhaust gas gases in the pipe provide the heat source to the thermoelectric power generator, whereas the heat sink (cold side) is suggested to be provided by circulation of cooling water. An experimental study was conducted at VIT [2] wherein a heat exchanger with 18 thermoelectric generator modules was designed and tested in the engine test rig. This study revealed that energy can be tapped efficiently from the engine exhaust and in near future thermoelectric generators can reduce the size of the alternator or eliminate them in automobiles.

A typical total waste heat recovering technology, using thermoelectric generators (TEGs), coupled with a gasoline engine was investigated in this study conducted at Ambrose Alli University, Nigeria [5]. According to the experimental analysis conducted by Suryawanshi et al. [6] the temperature of pipe surface of exhaust gases flowing through exhaust gas pipe is very high and it is around 200<sup>o</sup>C to 300<sup>o</sup>C so a heat

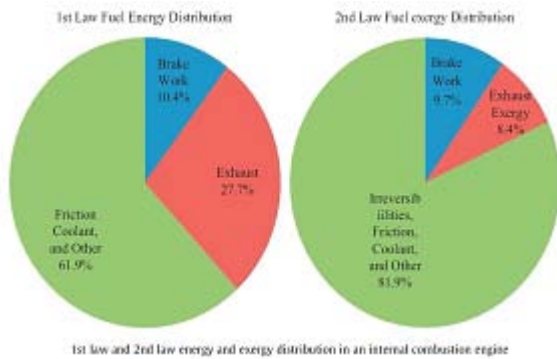
exchanger is made, which conducts heat from exhaust pipe to thermoelectric modules, one surface of these modules is in contact with the surface of hot side heat exchanger and other is in contact with the surface of cold side heat exchanger and thus potential difference is created and power is produced due to Seebeck effect.

Baskar et al. [7] did an experiment to study and analyze the feasibility of retrofitting the waste heat recovery system to a two stroke petrol engine. The experimental performance testing has shown that the overall efficiency of two stroke petrol engine installed with and without the waste heat recovery system is 29.67% and 29.2% respectively when the power extraction was 90W. Jadhao et al. [8] in his paper had analyzed the possibility of heat recovery from an IC engine and the various ways to achieve it. He has compared the various possibilities like the Thermo electric generation, Thermo Ionic Generation and Piezoelectric Generation. He found that in Thermo Electric generation, optimal temperature difference is sufficient to produce the required power.

Birkholz et al. [9] have implemented the same TEG principle to recover the heat and to generate power, but the material they used was FeSi<sub>2</sub>. Yu and Chau [10] has proposed and implemented an automotive thermo-electric waste heat recovery system by adopting a Cuk converter and a maximum power point tracker (MPPT) controller into its proposed system as tools for power conditioning and transfer. They reported that the power improvement is recorded from 7.5% to 9.4% when the hot-side temperature of the TEG is heated from 100<sup>o</sup>C to 250<sup>o</sup>C. Also, when the hot-side temperature of the TEG is fixed at 250<sup>o</sup>C, the power improvement as much as 4.8% to 17.9% can be achieved.

According to the research paper published by Narumanchi et al [11] TIMs (Thermal Interface Materials or Thermal Grease) pose a significant bottleneck to heat removal from a device.

In internal combustion engines a huge amount of energy is lost in the form of heat through the exhaust gas. Conklin and Szybist investigated that the percentage of fuel energy converted to useful work only 10.4% and also found the thermal energy lost through exhaust gas about 27.7%. The second law (i.e., energy) analysis of fuel has been shown that fuel energy is converted to the brake power about 9.7% and the exhaust about 8.4% as shown in Figure 1.



**Figure 1:** Percentage of fuel energy distribution

So, this project proposes and implements a thermoelectric waste heat energy recovery system from the exhaust heat from the internal combustion engine automobiles, including gasoline vehicles and hybrid electric vehicles. The key is to directly convert the heat energy from automotive waste heat to electrical energy using a thermoelectric generator.

While the electric power generation by such a system is able to generate is still relatively small at a maximum of 10 W from a single TEG module, rapid progress in materials research can make the ambitious objective of generating higher watts by all means of feasible proposition.

## 2. Working Principle

### 2.1 Seebeck Effect

The Seebeck Effect is the conversion of temperature differences directly into electricity. It is a classic example of an electromotive force (emf) and leads to measurable currents or voltages in the same way as any other emf. Electromotive forces modify Ohm's law by generating currents even in the absence of voltage differences (or vice versa); the local current density is given by,

$$\mathbf{J} = \sigma (-\Delta V + \mathbf{E}_{emf})$$

Where,  $V$  the local voltage and  $\sigma$  is the local conductivity. In general the Seebeck effect is described locally by the creation of an electromotive field.

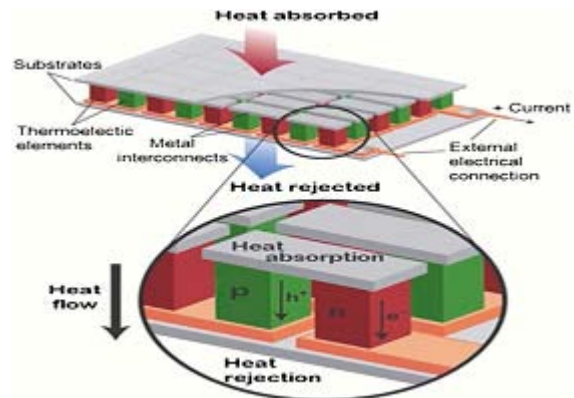
$$\mathbf{E}_{emf} = -S \Delta T$$

Where  $S$  is the Seebeck coefficient (also known as thermopower), a property of the local material, and  $\Delta T$  is the gradient in temperature  $T$ .

### 2.2 Thermoelectric Principle of Operation

Thermoelectricity means the direct conversion of heat into electric energy, or vice versa. According to Joule's law, a

conductor carrying a current generates heat at a rate proportional to the product of the resistance ( $R$ ) of the conductor and the square of the current ( $I$ ). A circuit of this type is called a thermocouple; a number of thermocouples connected in series are called a thermopile.



**Figure 2:** Thermionic Principle of Operation

Jean C. A. Peltier discovered an effect inverse to the Seebeck effect: If a current passes through a thermocouple, the temperature of one junction increases and the temperature of the other decreases, so that heat is transferred from one junction to the other. The rate of heat transfer is proportional to the current and the direction of transfer is reversed if the current is reversed.

## 3. Description of the Equipment

### 3.1 Peltier Module

A thermoelectric (TE) module, also called a thermoelectric cooler or Peltier cooler, is a semiconductor-based electronic component that functions as a small heat pump. By applying a low voltage DC power to a TE module; heat will be moved through the module from one side to the other. One module face, therefore, will be cooled while the opposite face is simultaneously heated.

Both N-type and P-type Bismuth Telluride  $\text{Bi}_2\text{Te}_3$  thermoelectric materials are used in a thermoelectric cooler.



**Figure 3:** Peltier Module

### 3.2 TE- Generator

Based on the Seebeck effect, thermoelectric devices can act as electrical power generators. A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect.

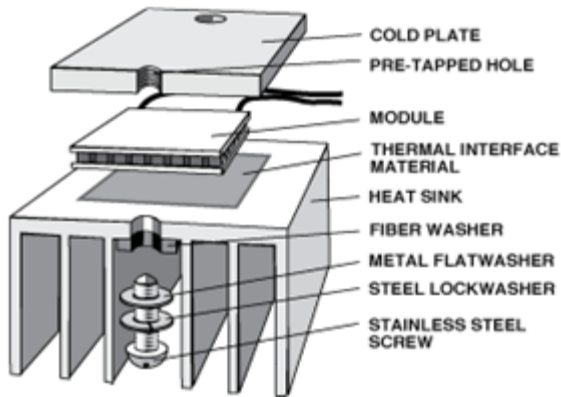


Figure 4: TE-Generator

### 3.3 Thermal Grease

Thermal grease (also called thermal gel, thermal compound, thermal paste, heat paste, heat sink paste or heat sink compound) is a viscous fluid substance, originally with properties akin to grease, which increases the thermal conductivity of a thermal interface by filling microscopic air-gaps present due to the imperfectly flat and smooth surfaces of the components; the compound has far greater thermal conductivity than air (but far less than metal). In electronics, it is often used to aid a component's thermal dissipation via a heat sink.

### 3.4 Booster Circuit

This is based on the theory that inductor holds current and passes in opposite direction. This is a DC to DC converter and it has a poor efficiency of 60-80%. So we can't use it for a large project. We can use it for low power consuming models like 12 V and 3 V models which requires 250 mA current. We have to spend 650 mA with 80% efficiency. In this circuit we are going to put DC pulse of around 2V through TEG and amplifying to 12 V as output. We need to follow the below for expected voltage range.

- 6 V to 12 V @1 A: 80 turns of 24swg wire in a 0.5 mm ferrite core.
- 6 V to 12 V @500 mA: 60 turns of 36swg wire in a 0.5 mm ferrite core.



Figure 6: Booster Circuit

The main purpose of using the Booster Circuit is to amplify the voltage obtained from TEG. From TEG we can get a maximum of 2V and 500mA current. The Booster circuit will amplify the voltage to 12V and there is a digital display is provided in it which can display the amplified voltage.

### 3.5 Battery

In isolated systems away from the grid, batteries are used for storage of excess thermal energy converted into electrical energy. In fact for small units with output less than one kilowatt, Batteries seem to be the only technically and economically available storage means. Since both the TEG system and batteries are high in capital costs, it is necessary that the overall system be optimized with respect to available energy and local demand pattern.

## 4. Identification of Hot Spot in the Silencer



Figure 6: Silencer Model

A model of silencer is developed using Ansys and it is subjected to analysis in Fluent to identify the hot spot zone in the silencer.

The meshed file is subjected to analysis using the Fluent. The physics is set up and the flow of gas is made to take place in the silencer with an average velocity of 40 m/s and the hot gas inlet temperature was given to be 100°C. The result obtained is shown in the figure below. It is observed from the contour that the hot region is concentrated around the elbow region where the colour variations are shown (Red and Yellow coloured spots).



Figure 7: Contours of Temperature

Hence it is in agreement with the practical case. The thermal stress is more concentrated in the Elbow region and the base region of the silencer because the hot exhaust gas will directly strike the elbow region and take a diversion and so the velocity of gas will be reduced at those spots and this leads to the accumulation of more exhaust gas in those

regions. Hence more amount of heat is said to be produced in those regions. So if we place the TEG at this portion of the silencer then there would be maximum heat transfer leading to steady production of electric power.

### 5. Working Procedure

The vehicle is started and the acceleration is to be given, so that the amount of heat leaving the exhaust will be increased. Due to this heat, the surface of the exhaust pipe and the silencer will be heated to very high temperatures. These hot surfaces will try to liberate the heat to the atmosphere, which acts as a Heat Sink. Since the atmospheric temperature is less than that of the silencer surface, a temperature difference is created and hence the surface tries to attain the equilibrium state through the heat transformation process. But this will take much longer time. Hence in order to increase the rate of heat transfer the Thermal Grease is used. The Thermal Grease is coated on the hot surface of the silencers and also in the inner surface of the fins which are present in the upper part. The fins are also used to increase the heat transfer rate. As the vehicle moves, the air flow will take place between the fins and it acts as the sink.

As the surface of the silencer gets more and more heated the heat transfer rate will increase due to the increase in the temperature difference. The Peltier module is placed between the Heat Source (Hot Silencer Surface) and the Heat Sink (atmosphere) and the fins are placed above the module. The module is made of semiconducting materials. Hence by the principle of Seebeck Effect, the temperature difference can be directly converted into voltage by using some thermoelectric materials. Based on this effect, when the surface heat of the silencer is passed on to the atmosphere, the electrons and holes of the thermo electric semiconductors will try to move towards the junction and make the flow of electric current to be possible.



**Figure 8:** Experimental Setup – Two Wheeler Silencer with TEG

The voltage developed due to this effect can be increased by using some Booster circuit like DC-DC Cuk Converter. This will step up the voltage generated to some nominal value. So that we can get the sufficient amount of voltage. For this converter the general formula used to measure the approximate voltage for the given temperature is

$T=V/10mV$ . Hence this voltage can be connected to some battery and stored, or else it can be given directly to some electric appliances which uses DC. If we need AC voltage, it can be converted using the rectifier.

The voltage generated can be increased by placing more number of modules and connecting them with one another to meet the demand of the required voltage. This voltage can then be supplied to the suitable electrical appliances.

### 6. Design Calculations

#### 6.1 Specification of Petrol Engine

Type	Two stroke
Cooling System	Air cooled
Bore/Stroke	50 X 50 mm
Compression Ratio	98.2 cc
Piston Displacement	6.6 : 1
Maximum Torque	0.98 kg-m at 5500RPM

#### 6.2 Calculation for Voltage generated

From the equation of Seebeck effect,

$$V = \alpha (T_h - T_c)$$

Where,

V – Voltage Generated in Volts

$\alpha$  – Seebeck coefficient in  $\mu V/K$

$T_h$ -temperature of hot surface (silencer) in Kelvin

$T_c$ -temperature of cold surface (atmosphere) in Kelvin

$\alpha$  of Bismuth Telluride - 287 $\mu V/K$

$T_c = 303$  k

A few temperatures of the hot silencer is taken into consideration and the corresponding voltages that are expected to be generated according to the Seebeck equation is calculated as follows,

$$V = \alpha (T_h - T_c)$$

**Case 1:**

$T_h = 403$  k

$$V = (287 * 10^{-6}) * (403 - 303)$$

$$= (287 * 10^{-6}) * (100)$$

$$= 0.0287 \text{ V}$$

**Case 2:**

$T_h = 453$  k

$$V = (287 * 10^{-6}) * (453 - 303)$$

$$= (287 * 10^{-6}) * (150)$$

$$= 0.04305 \text{ V}$$

These voltages are meager in value .This can be boosted up using the booster circuit. The experimental results obtained are tabulated as follows:

**Table 1:** Voltage generated and boosted for different temperatures

Temperature difference $\delta t$ (k)	Voltage without boosting (volt)	Voltage after boosting (volt)
80	0.02296	1.44
100	0.02870	2.53
120	0.03444	3.21
140	0.04018	3.85
150	0.04305	4.43
160	0.04592	4.94
180	0.05166	5.37
200	0.05740	6.10

## 7. Conclusion

In this paper we have successfully fabricated an exhaust gas heat recovery power generator. Thus the eco-friendly power generation method can be implemented for domestic and commercial use at an affordable cost. The efficiency of the engine will not be affected because only the surface heat of the silencer is drawn out. The main objective of this paper is to recover the surface exhaust heat to avoid the accidents (Burn-outs) caused by the overheated silencers, and to convert the recovered heat to useful electric energy. This objective has been successfully accomplished in this paper. The output could be increased by connecting a number of TEGs in series, so that the voltage gets added up leading to increased power. The energy produced from this system could be used to power any auxiliary devices in an automobile directly or it could be stored in a battery and then used later.

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## References



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