# EXPERIMENTAL STUDY ON WASTE HEAT RECOVERY FROM AN INTERNAL COMBUSTION ENGINE USING THERMOELECTRIC TECHNOLOGY

by

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*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. A detailed experimental work was carried to study the performance of thermoelectric generators under various engine operating conditions. A heat exchanger with 18 thermoelectric generator modules was designed and tested in the engine test rig. Thermoelectric modules were selected according to the temperature difference between exhaust gases side and the engine coolant side. Various designs of the heat exchangers were modeled using computer aided design and analysis was done using a computational fluid dynamics code which is commercially available to study the flow and heat transfer characteristics. From the simulated results it was found that rectangular shaped heat exchanger met our requirements and also satisfied the space and weight constraint. A rectangular heat exchanger was fabricated and the thermo electric modules were incorporated on the heat exchanger for performance analysis. The study also 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.*

Key words*: thermoelectric generator, waste heat recovery, spark ignition, internal combustion engine, engine exhaust*

## Introduction

In order to meet the increasing electrical demands of modern automobiles, bigger and bulkier alternators are connected to engines. Bigger and bulkier alternators which operate at an efficiency of 50 to 62% consume around 1 to 5% of the rated engine output. However,

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due to the expansion of the passenger room and to improve the vehicle aerodynamics, the space for the alternator in engine room is becoming smaller. About 30% of the energy supplied to an IC engine is rejected in the exhaust as waste heat. If approximately 6% heat can be recovered from the engine exhaust, it can meet the electrical requirements of an automobile and it would be possible to reduce the fuel consumption around 10% [1]. Heat is rejected through exhaust gases at high temperature when compared to heat rejected through coolant and lubricating oil. This shows the possibility of energy conversion using a thermoelectric generator (TEG) to tap the exhaust heat energy. TEG is like a heat engine which converts the heat energy into electric energy and it works on the principle of Seebeck effect. Moreover TEG are highly reliable, operate quietly and are usually environmentally friendly [2]. Semi-conducting materials (in conjunction with copper inter-connecting pads), were found to offer the best combination of Seebeck coefficient, electrical resistivity, and thermal conductivity. Semi-conducting materials provide another benefit, the ability` to use electrons or "holes" (the absence of an electron in a crystal matrix) to conduct current [3]. Thermoelectric module (TEM) has a cold side and a hot side. At the hot side, heat is absorbed by electrons as they pass from a high energy level in the n-type semiconductor element, to a lower energy level in the p-type semiconductor element. The power supply provides the energy to move the electrons through the system. At the cold side, energy is expelled to a heat sink as electrons move from a high energy level element (n-type) to a lower energy level element (p-type) [4]. Bismuth telluride-based TEM are designed primarily for cooling or combined cooling and heating applications where electrical power creates a temperature difference across the TEM. By using the modules in reverse, where a temperature differential is applied across the faces of the module, it is possible to generate electrical power [5]. Although power output and generation efficiency are presently low, useful power often may be obtained where a source of heat is available.

## Thermoelectric generator

A single thermocouple produces low voltage and in order to obtain high voltage, a number of thermocouples are connected electrically in series and thermally in parallel to form a module. The module is heated at one end (hot side) and a temperature gradient is maintained with respect to the other end (cold side) [6]. Figure 1 shows the arrangement of "n" and "p" type material in a TEG module. In TEG, electrical charge carriers (electrons or holes) instead of lattice are the energy transport media. TEG offers several distinct advantages over other technologies involving no moving parts or bulk fluids, low maintenance, lightweight, no vibration, no optic and sonic signal, and flexibility on heat source [7]. Easy availability, low cost and low operating temperature range with a considerable efficiency makes the use of bismuth telluride as an effective module. The dimensions of the module are given in fig. 2.

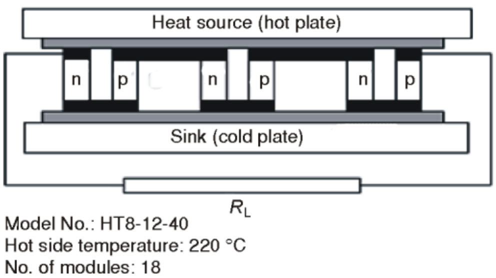


**Figure 1. TEM connected to the load**

With no load ($R_L$ load not connected), the open circuit voltage as measured between points is:

$$V = \alpha \Delta T \tag{1}$$

where $V$ is the output voltage from the couple in volts [V], $\alpha$ [V°C$^{-1}$] – the average Seebeck coefficient, and, $\Delta T$ [°C] – the temperature difference across the couple

$$\Delta T = T_h - T_c \tag{2}$$

where $T_h$ [°C] is the hot side of the couple and $T_c$ [°C] – the cold side of the couple.

When a load is connected (fig. 1) to the thermoelectric couple the output voltage (V) drops as a result of internal generator resistance. The current through the load is:

$$I_{load} = \frac{\alpha \Delta T}{R_c + R_L} \tag{3}$$

where $I_{load}$ [A] is the generator output current, $R_c$ [Ω] – the average internal resistance of the thermoelectric couple, and $R_L$ [Ω] – the load resistance.

The total heat input to the couple ($Q_h$) is:

$$Q_h = \alpha T_h I - 0.5 I^2 R_c + K_c \Delta T \tag{4}$$

where $Q_h$ [W] is the heat input and $K_c$ [W°C$^{-1}$] – the thermal conductance of the couple.

Most TEG contain a number of individual modules which may be electrically connected in either series, parallel, or series/parallel arrangement. A typical generator configuration is illustrated in fig. 3. This generator has a total number of modules NT with a number of modules connected in series NS, and a number of modules connected in parallel NP. The total number of modules in the system is:

$$NT = NS \cdot NP \tag{5}$$

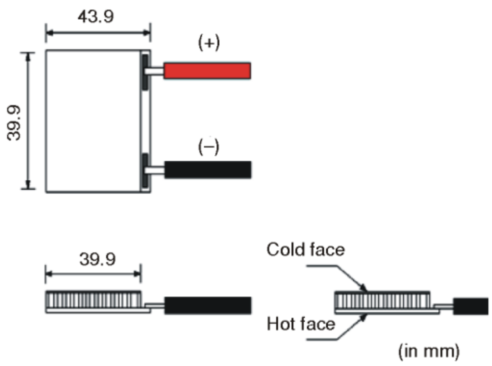


**Figure 2. Dimensions of the TEM**

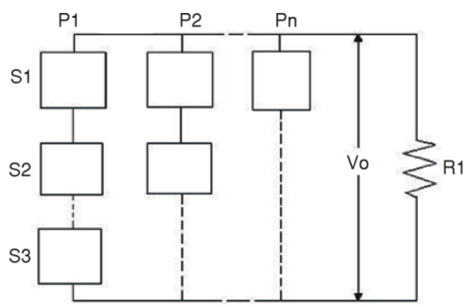


**Figure 3. Connection of TEM**

## Heat exchanger

It was planned to implement TEG in a small car, where weight and space are crucial factors for implementation. The weight and space occupied by the hexagonal model is more than the rectangular one. As the number of sides in hexagonal heat exchanger is more, more cooling chamber will be required and the amount of coolant to be pumped to the chamber will also be more. In triangular shaped TEG the number of modules will be less as compared to rectangular shaped model, as a result the amount of power produced will be less which makes the use of triangular TEG monotonous. Two designs of the heat exchangers, rectangular and hexagonal shape have been proposed by [1]. Moreover, researchers [8] have used hexagonal shaped TEG but only few worked on rectangular TEG [9]. In this study rectangular, hexagonal, and triangular shaped heat exchangers were modeled using computer aided design (CAD). The computational fluid dynamics (CFD) analysis of the models was done using FLUENT. The flow in the heat exchanger was considered to be unsteady and turbulent and traditional wall law was applied. The governing equations were solved iteratively with simple algorithm. The velocity contours and temperature distribution of the models are shown in figs. 4 and 5, respectively. Using CAD software weight of these models were predicted utilizing properties of the materials used for construction of TEG. The predicted weights are 12.4, 14.1, and 21.3 kg for triangle, rectangle, and hexagonal designs.

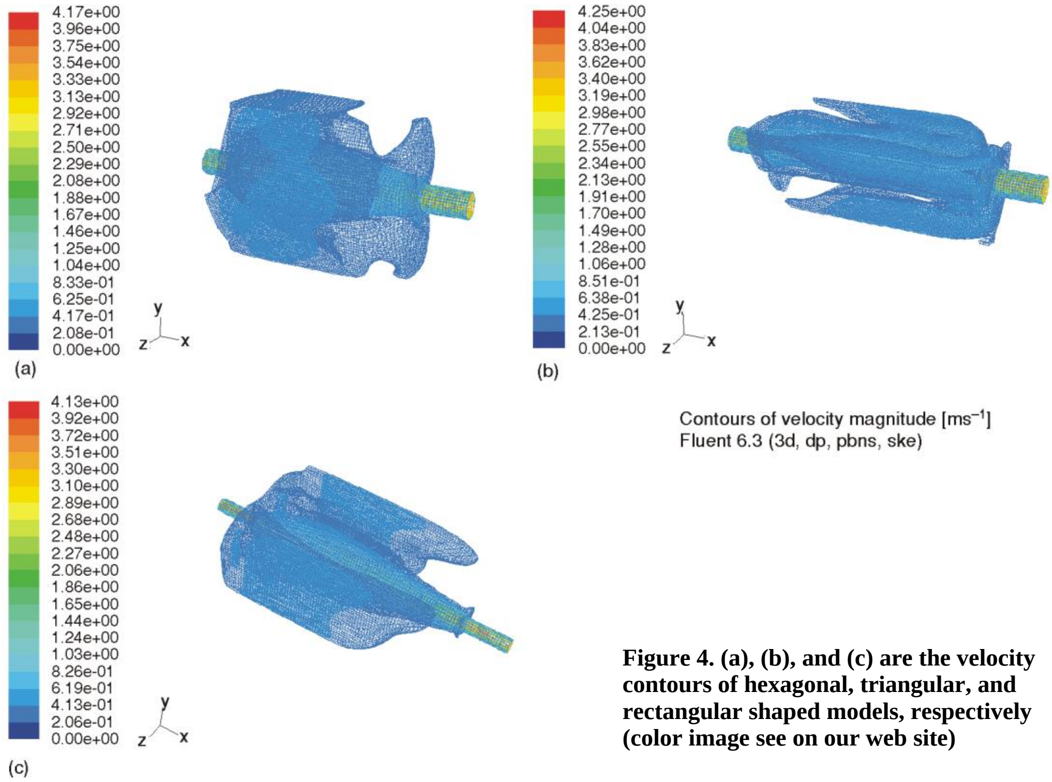


**Figure 4. (a), (b), and (c) are the velocity contours of hexagonal, triangular, and rectangular shaped models, respectively (color image see on our web site)**

The results of the CFD analysis revealed that the surface temperature attained in rectangular model is less compared to that of other two models, which suits the TEM requirements (max. hot side temp 220 °C). From the velocity contour it is very clear that in rectangular shaped TEG the exhaust is distributed uniformly over the profile. Therefore, it led to the conclusion that rectangular shaped TEG was better for our study and it was fabricated. The heat transmission from the exhaust gases to the exchanger must be done normally in a short length and in order to increase the average heat transfer coefficient, it is necessary to introduce internal fins in the heat exchanger. When the heat exchanger was tested using internal fins, back pressure in the exhaust increased and the engine performance got deteriorate. To avoid this, fins were removed but this resulted in decrease in effectiveness of the TEG.

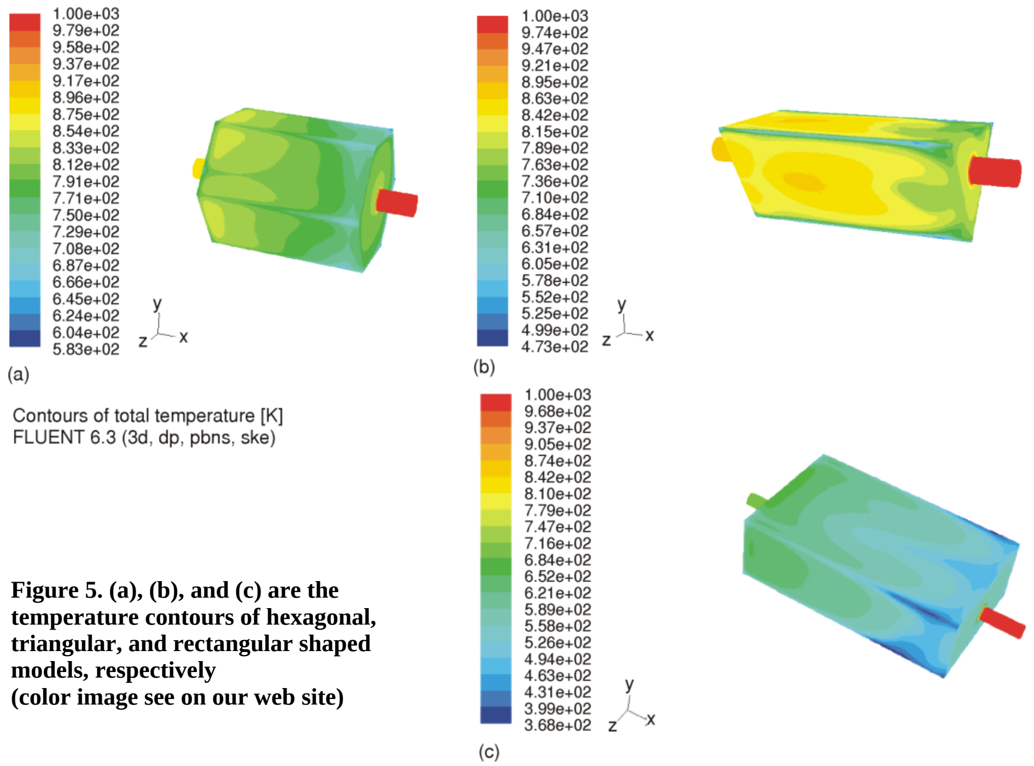


**Figure 5. (a), (b), and (c) are the temperature contours of hexagonal, triangular, and rectangular shaped models, respectively (color image see on our web site)**

## Design of the thermoelectric generator

The TEG consists of an exhaust gas heat exchanger, counter flow coolant cooling chamber and 18 TEM connected in series. The amount of heat transferred from the exhaust gas to the TEM depends on the design of the TEG and the critical parameter is the heat flux which crosses the TEM. In order to achieve this, the TEM should work close to its best conditions of power, and it is also necessary to reduce the thermal resistance which includes thermal resistance from the exhaust gases to the inner wall of heat exchanger, and the thermal resistance from the inner wall of the heat exchanger to the hot surface of the module.

The heat transmission from the inner wall to the hot surface of the TEM is basically a heat conduction problem. Thermal resistance exists between the surfaces of the hot plate and TEM because of the surface roughness. Hence, care was taken to ensure high degree of smoothness between the surfaces by polishing it. The most common materials used in the construction of the support structure of the TEG are steel, stainless steel, and in one case haste alloy, and aluminum [1]. Table 1 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 steel and stainless steel, respectively, while the maximum gain in weight compared to the lightest steel is only 14.3%.

**Table 1. Properties of different materials**

| Properties | | Hastelloy | Steel | Stainless steel | Copper | Duralumin |
|---|---|---|---|---|---|---|
| Type | | – | AISI 1010 | AISI 302 | 99.9 Cu + Ag | – |
| Melt point [K] | | 1533 | 1670 | 1670 | 1293 | 923 |
| Density [kgm$^{-3}$] | | 8300 | 7830 | 8055 | 8950 | 2770 |
| $k$ [Wm$^{-1}$K$^{-1}$] | $T$ = 294 K | 9.1 | – | – | – | – |
| | $T$ = 300 K | - | 64 | 15 | 386 | 174 |
| | $T$ = 473 K | 14.1 | – | – | – | – |
| | $T$ = 500 K | – | 54 | 19 | – | 188 |
| $k_p$ [Jkg$^{-1}$K$^{-1}$) | $T$ = 294 K | 486 | – | – | – | – |
| | $T$ = 300 K | – | 434 | 480 | 385 | 875 |

Another possibility, could be an aluminum 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 500 ºC, and in some cases is surpassed by the exhaust gas temperatures. As the TEG has to be fabricated for a small car, aluminum was the only choice for the use of hot plate due to its high conductivity and light weight.

Cast iron of 5 mm thickness was used to make the frame of the heat exchanger. Figure 6 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 7 shows the aluminum plate with

**Figure 6. Cast iron frame**

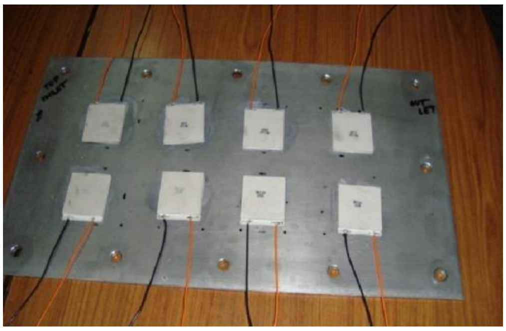

**Figure 7. Aluminum plate with modules**

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.

Figure 8 shows the complete assembly of TEG.

The coolant used in engine cooling system is circulated into the TEG by using a small split joint. Figure 9 shows the schematic of the TEM sandwitched between hot and cold plate and the flow direction of the hot and cold fluids. This avoids the requirement of a separate cooling system for modules. The power required to pump the coolant to the TEG is one of the losses as compared to the power produced by the TEG. As the coolant chamber has to be designed to accommodate maximum flow of coolant at higher speeds and loads, the maximum flow of coolant was estimated by taking exhaust gas properties at higher speeds and loads. The specific heat capacity of the exhaust gas was calculated using an exhuast gas calorimeter.

**Figure 8. TEG with the stand**

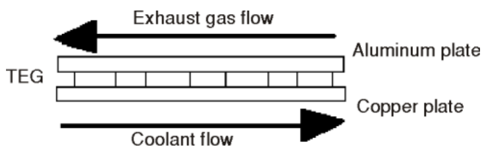


**Figure 9. Schematic diagram of the TEM sandwitched between the hot plate and cold plate**

$$Q_{\text{lost}} = Q_{\text{gained}} \tag{6}$$

$$Q_{\text{lost}} = m_{\text{ex}} c_{\text{pg}} (T_{\text{g1}} - T_{\text{g2}}) \tag{7}$$

$$Q_{\text{gained}} = m_{\text{w}} c_{\text{pw}} (T_{\text{wo}} - T_{\text{wi}}) \tag{8}$$

$$m_{\text{ex}} = m_{\text{f}} + m_{\text{a}} \tag{9}$$

The total heat flow from the exhaust gas side to the coolant side [10]:

$$Q = \frac{1}{\dfrac{1}{h_1 A_1} + \dfrac{L_1}{k_1 A_1} + \dfrac{L_2}{8k_2 A_2} + \dfrac{L_3}{k_3 A_3} + \dfrac{1}{h_2 A_4}} \frac{(T_{\text{h2}} - T_{\text{c1}}) - (T_{\text{h1}} - T_{\text{c2}})}{\ln \dfrac{T_{\text{h2}} - T_{\text{c1}}}{T_{\text{h1}} - T_{\text{c2}}}} \tag{10}$$

Mass flow rate of water is calculated by

$$Q = m_{\text{w}} c_{\text{pw}} (T_{\text{c2}} - T_{\text{c1}}) \tag{11}$$

## Experimental set-up

The test was carried out on an engine dynamometer, details of which are given in tab. 2. No modifications were made on the engine. The exhaust pipe was insulated on the upstream side of the exhaust chamber up to the catalytic converter to minimize heat loss. 0-1200 °C K-type thermocouples with digital measuring unit were used to measure exhaust gas temperature, hot and cold side temperatures of TEM. Backpressure of the exhaust gas was measured using a U--tube mercury manometer. DC voltmeter and ampermeter were used to measure the voltage and current produced by the TEG. A rotameter was used to find the flow rate of the engine coolant flowing through the cooling chamber. An additional coolant circuit (by-pass) was provided for TEG using solenoid valve in order to overcome the burn out of the TEM during the engine warm up period. Once the engine thermostat valve opens, the by-pass valve closes and coolant circuit resumes with engine coolant circuit. Three bulbs of 25 W each and one bulb of 15 W were used as load for the TEM. Dynamometer torque, engine speed, TEG output, TEG coolant inlet and exit and surface temperatures were measured. The engine was operated at various loads using eddy current dynamometer. Engine load was varied by changing the engine speed keeping the torque constant. Horiba exhaust gas analyzer was used to measure the exhaust gas toxicity. Table 3 shows the range, accurary, and uncertainties of the instruments used in this study. To achieve higher exhaust gas temperature the thermoelectric generator was located just down-

**Table 2. Specification of the test setup**

| Make | Maruti 800 |
|---|---|
| Type | Three cylinder, 4-stroke SI engine, water cooled SOHC |
| Displacement | 796 $cm^3$ |
| 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 3. Range, Accuracy and Uncertainties of the instruments**

| Instruments | Range | Accuracy | % Uncertainties |
|---|---|---|---|
| Gas analyzer make Horiba | HC 0-9999 ppm | ±10 ppm | ±0.1% |
| | CO 0-10% | ±0.01% | ±0.1% |
| | $CO_2$ 0-20% | ±0.03% | ±0.15% |
| TFC high precision physical balance | 0-2000 g | ±0.01g | ±0.0005% |
| MAF sensor | 0-170 kg/h | ±0.024 kg/h | ±0.014% |
| Engine speed | 0-10 000 rpm | ±10 | ±0.1% |
| Dynamometer load cell | 0-30 kg | ±10 g | ±0.03% |
| EGT thermocouple | 0-1200 °C | ±1 °C | ±0.1 °C% |

stream of the exhaust headers next to catalytic converter. The only concern is that the generator, if located upstream of the catalytic converter, would decrease the efficiency and increase the warming time of the catalytic converters. Schematic diagram of the experimental setup is shown in fig. 10.

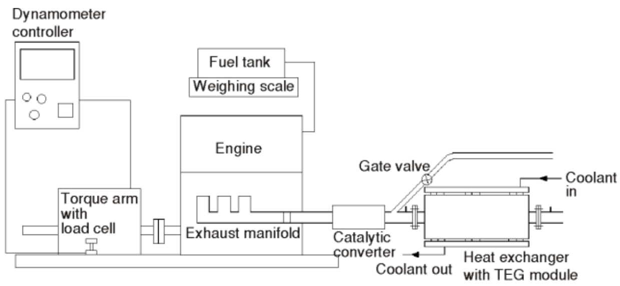


**Figure 10. Schematic diagram of experimental set-up**

## Result and discussion

In order to observe the differential change in exhaust back pressure and exhaust emissions due to the addition of TEG to the exhaust system, experiments were conducted on the test engine with and without TEG and results were compared. Figures 11 to 14 shows the variation of exhaust back pressure, engine coolant flow, HC, and CO emission with respect to engine

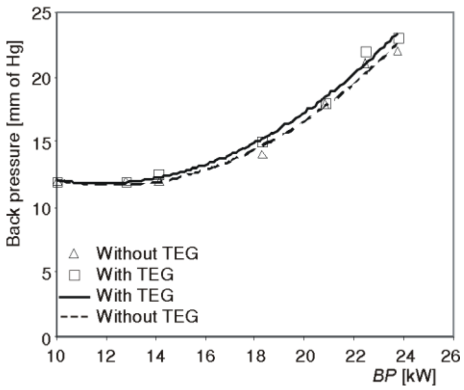


**Figure11. Variation of back pressure with brake power**

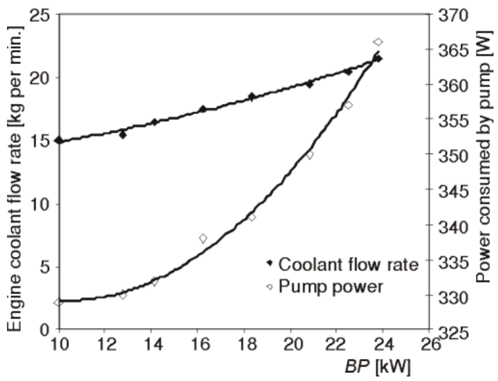


**Figure 12. Variation of engine coolant flow rate with brake power**

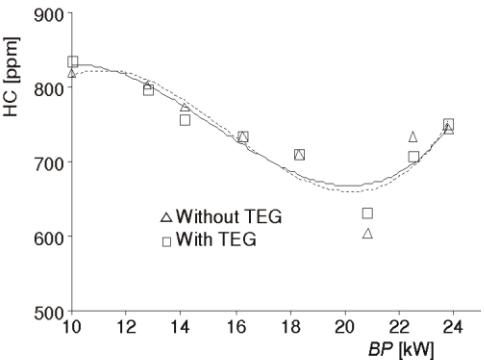


**Figure13. Variation of hydrocarbon emission with brake power**

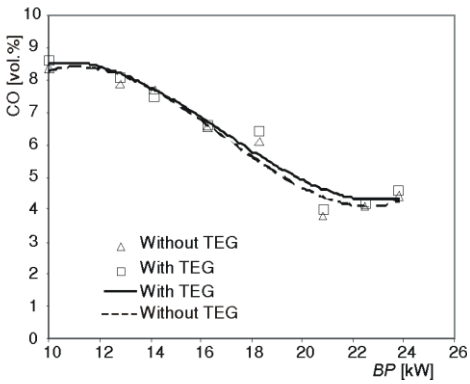


**Figure14. Variation of carbon monoxide emission with brake power**

brake power (BP). It was very clear that the addition of TEG to the engine exhaust has very little effect on exhaust back pressure and exhaust emissions. Moreover at maximum load the amount of coolant circulated in TEG is 0.45 kg/min. which is around 2.1% of the coolant circulated in the engine cooling system at the same load. Figure 15 shows the power generated by TEG during the tests. The power output of TEG increased with increase in the temperature difference ($\Delta T$), this is due to increase in the exhaust gas temperature with increase in engine power output. The increase in exhaust mass flow rate also plays an important role in the power produced by TEG. A thermoelectric generator's power increases with the square of the temperature difference applied across it [11]. Figure 16 shows the variation of exhaust gas temperature (EGT) with the power produced by the engine. To

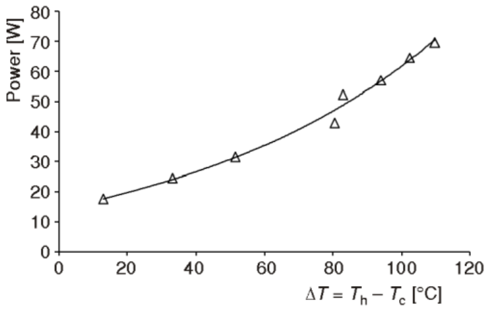


**Figure15. Variation of power with temperature difference**

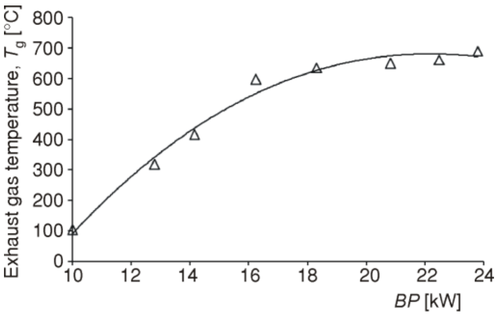


**Figure 16. Variation of EGT with brake power**

extract more power, the length of TEG can be increased and more modules can be added. Due to constraints like space availaibility and weight it becomes cumbersome in this study. The specific power of the present TEG was 0.0048 kW/kg (power out of the TEG/total weight of the TEG). The temperature drop across the exhaust in TEG is mainly due to convective heat transfer to the walls. At higher engine power the effectiveness of the heat exchanger decreases due to higher exhaust gas velocity and this results in the offset of $\Delta T$ *vs.* power curve from linear trend. Figure 17 shows the variation of temperature difference between the hot plate and the cold plate with respect to power developed by the engine. If internal fins were used in the TEG, the heat transfer would have been augmented. Since the maximum hot side temperature of the module limits to 220 $^{o}$C and the possible increase in exhaust back pressure it is not possible to implement fins in our study. Small change in exhaust back pressure was regulated by means of a by-pass line fitted with the gate valve. This same arrangement will not be effective for larger back pressure variations. Since, opening of the gate valve will affect the effectiveness of the heat exchanger. The conversion efficiency of the TEG was calculated using eqs. (1)-(4). The range of the efficiency is between 1.5 at 10 kW to 3% at 25 kW. The conversion efficiency of the TEG can improved if the operating region of the same is situated in the parts of power and efficiency curve with negative slope as given in [12].Variations in both the bulk and surface temperature on the coolant side were

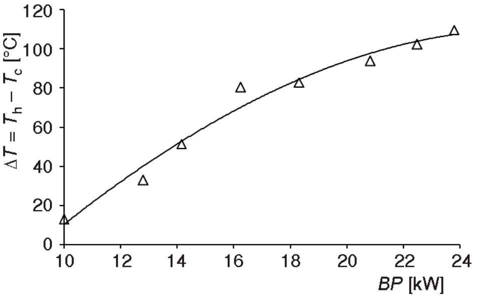


**Figure 17. Variation of temperature difference with brake power**

much smaller than in the exhaust side and thus decreasing the coolant side temperatures would be beneficial.

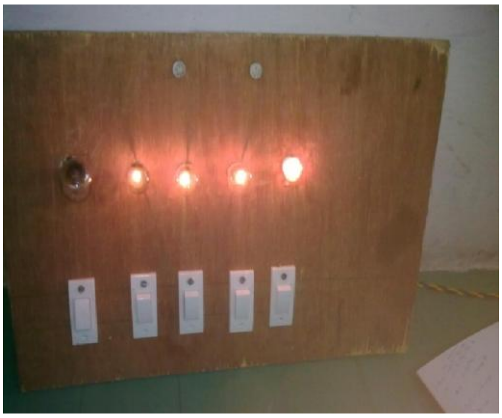

**Figure 18. Electric bulb load pannel**

## Conclusions

Though energy can be recovered from a cheaper source using thermoelectric generator, the relative fuel saving may not be in proportion. To maximize power-generation efficiency of TEG large temperature difference must be provided between hot and cold side. Moreover cost, space, weight, additional cooling circuit provision, module interface, electronic control, and unsteady exhaust flow are practically difficult issues in implementing TEM. With better high temperature module and heat exchanger design the module size can be reduced. With respect to the investigation carried out, the results are summarized as follows.

Three different models of heat exchanger were modeled using CAD and their CFD analysis was done using FLUENT software. It was found that rectangular shaped TEG gave better results as compared to other two models. Rectangular model was then fabricated and tested on an engine dynamometer. The power produced by the TEG increased with the increase in power output of the engine. The temperature drop between the hot plate and the cold plate plays a major role in the working of the TEM. The maximum temperature on the exhaust side is limited due to maximum operating temperature of TEM. To increase the efficiency of the modules, the coolant side temperature can be reduced. The total power that could be extracted from the exhaust gases was limited due to space and cost constraints and due to which the output of the present design is small, a much larger unit with improved heat exchanger design would be required to fully utilize the exhaust energy. However, with the current design maximum allowable hot junction temperature for the module was readily reached during testing. Higher temperature resistant thermoelectric module along with better heat exchanger can improve the exhaust energy recovery.

## Acknowledgments

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## Nomenclature

$A_1$ – surface area of aluminum plate, [m$^2$]
$A_2$ – surface area of TEG, [m$^2$]
$A_3$ – surface area of copper plate in contact with TEG, [m$^2$]
$A_4$ – surface area of copper plate in contact with coolant, [m$^2$]
$c_p$ – specific heat, [Jkg$^{-1}$K$^{-1}$]
$c_{pg}$ – specific heat of exhaust gas, [Jkg$^{-1}$K$^{-1}$]
$c_{pw}$ – specific heat of water, [Jkg$^{-1}$K$^{-1}$]
$h_1$ – convective heat transfer coefficient of exhaust gas, [Wm$^{-2}$K$^{-1}$]
$h_2$ – convective heat transfer coefficient of coolant, [Wm$^{-2}$K$^{-1}$]
$k_1$ – thermal conductivity of aluminum plate, [Wm$^{-1}$K$^{-1}$]
$k_2$ – thermal conductivity of TEG, [Wm$^{-1}$K$^{-1}$]
$k_3$ – thermal conductivity of copper plate, [Wm$^{-1}$K$^{-1}$]

$L_1$, $L_2$, $L_3$ – thickness of aluminum, TEG, and copper plate, respectively, [m]
$m$ – mass flow rate of water through calorimeter, [kgs$^{-1}$]
$m_a$ – mass flow rate of air, [kgs$^{-1}$]
$m_{ex}$ – mass flow rate of exhaust gas, [kgs$^{-1}$]
$m_f$ – mass flow rate of fuel, [kgs$^{-1}$]
$m_w$ – mass flow rate of water, [kgs$^{-1}$]
$Q_{gained}$ – heat gained by the water, [W]
$Q_{lost}$ – heat lost by exhaust gas, [W]
$T_{c1}$ – coolant water inlet temperature, [K]
$T_{c2}$ – coolant water outlet temperature, [K]
$T_{g1}$ – exhaust gas temperature at the inlet of calorimeter, [K]
$T_{g2}$ – exhaust gas temperature at the outlet of calorimeter, [K]
$T_{h1}$ – exhaust gas inlet temperature, [K]
$T_{h2}$ – exhaust gas outlet temperature, [K]
$T_{wi}$ – water temperature at the inlet of calorimeter, [K]
$T_{wo}$ – water temperature at the outlet of calorimeter, [K]

*Acronyms*

TEG – thermoelectric generator
TEM – thermoelectric module

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