Waste Heat Utilization of I.C. Engine by Thermoelectric Power Generation Method

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Abstract- The efficiency in an internal combustion engine ranges from 25% to 35%. About 40% of the overall fuel energy losses in a combustion engine are waste heat which is blown out with the exhaust gases and 30% is cooled away by the vehicle’s radiator. Even if a small fraction of the waste heat could be turned into useful energy again it would be a step in the right direction of improving fuel economy. In order to achieve uniform temperature distribution and higher interface temperature, the thermal characteristics of heat exchangers with various heat transfer enhancement features such as internal structure, material and surface area is to be considered. After designing suitable heat exchanger the thermo electric modules will be incorporated on the heat exchanger for performance analysis. In order to observe the differential change in exhaust conditions due to the addition of thermoelectric generator to the exhaust system, experiments to be conducted on the test engine. Thus this work aims to analyze the performance of thermoelectric generator under various engine operating conditions like engine speed. It would be useful to update the potential of thermoelectric generation in the automobile industry nowadays.

Keywords- Figure of merit, Seebeck Effect, Thermoelectric Module, Thermoelectric Generator, Waste Heat Recovery.

I. INTRODUCTION

Most engines operate with an efficiency rate of about 30%, with most of the wasted energy lost as heat. There is an increased need to identify alternative energy sources and enhance the efficiency of engines in order to reduce the consumption of fuel. The purpose of this project is to examine whether lost energy can be recovered in the form of electricity to power the electrical components of a vehicle. Thermoelectric Power generator will be analyzed as possible solutions to recover this lost energy in order to improve the overall engine efficiency. Study on automobiles gasoline powered internal combustion engine shows that only approximate 25% of the fuel energy is used to drive the engine, whereas 40% of the fuel energy is wasted in exhaust gas, 30% in engine coolant and 5% in friction and parasitic losses. For example, a full tank of vehicle capacity is 100 liter fuels, but only 25 liter of fuel is turn into useful mechanical energy to power vehicle, the remaining of 75 liter of fuel is dissipate as heat energy. This is not logic and non economical but this is what vehicle does every day. Therefore many studies had carried out to recover the waste heat dissipated by vehicle.

1.1 Problem statement:
If the waste heat can recover, not only the every Ringgit spends for fuel is become more valuable, but also can reduce the fuel consumption due to less fuel require to generate electric for vehicle. As a conclusion, the increasing of oil prices in the world market and low utilization of gasoline powered engine makes it necessary to generate new sustainable sources of electric power in modern automobiles. Furthermore, vehicle nowadays requires more and more electricity energy in order to maintain the communication, navigation, engine control, and safety systems of the vehicle. Therefore TEG is the best solution to recover waste heat through converts the heat energy into electricity. The focus of this project is to design a TEG system which can integrate into the automobile vehicle to generate electricity.
II. METHODOLOGY

2.1 Thermoelectric Power Generator:

The basic theory and operation of thermoelectric based systems have been developed for many years. Thermoelectric power generation is based on a phenomenon called “Seebeck effect” discovered by Thomas Seebeck in 1821. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators.

A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Fig. 1. As shown in fig. heat is transferred at a rate of $Q_H$ from a high-temperature heat source maintained at $T_H$ to the hot junction, and it is rejected at a rate of $Q_L$ to a low-temperature sink maintained at $T_L$ from the cold junction. Based on Seebeck effect, the heat supplied at the hot junction causes an electric current to flow in the circuit and electrical power is produced. Using the first-law of thermodynamics (energy conservation principle) the difference between $Q_H$ and $Q_L$ is the electrical power output $W_e$.

![Fig. 1 Basic concept of a simple thermoelectric power generator operating based on Seebeck effect. [2]](image-url)

Fig. 1 shows a schematic diagram illustrating components and arrangement of a conventional thermoelectric power generator. As shown in figure, it is composed of two ceramic plates (substrates) that serve as a foundation, providing mechanical integrity, and electrical insulation for n-type (heavily doped to create excess electrons) and p-type (heavily doped to create excess holes) semiconductor thermo elements. In thermoelectric materials, electrons and holes operate as both charge carriers and energy carriers. The ceramic plates are commonly made from alumina ($\text{Al}_2\text{O}_3$), but when large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllium and aluminum nitride) are desired. The semiconductor thermo elements (e.g. silicon-germanium, lead-telluride Pb-Te based alloys) that are sandwiched between the ceramic plates are connected thermally in parallel and electrically in series to form a thermoelectric device (module). More than one pair of semiconductors are normally assembled together to form a thermoelectric module and within the module a pair of thermo elements is called a thermocouple. The junctions connecting the thermo elements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips as shown in figure.
The potential of a material for thermoelectric applications is determined in large part to a measure of the material’s dimensionless figure of merit (ZT). Semiconductors have been primarily the materials of choice for thermoelectric applications. There are challenges in choosing suitable materials with sufficiently higher ZT for the applications.

2.2 Figure of merit:

The performance of thermoelectric materials can be expressed as

\[ Z = \alpha^2 k R \] ........................................ (1)

Where, \( Z \) is the thermoelectric material figure-of-merit,
\( \alpha \) is the Seebeck coefficient given by,
\[ \alpha = \frac{\Delta V}{\Delta T} \] ........................................ (2)

\( R \) is the electric resistivity (inverse of electric conductivity) and \( k \) is the total thermal conductivity.

The figure of merit depends on the properties of thermoelectric material used. A high value of \( Z \) is obtained by using materials of large seebeck coefficient, small thermal conductivity and small electrical resistivity. This figure-of-merit may be made dimensionless by multiplying by \( T \) (average absolute temperature of hot and cold plates of the thermoelectric module, K), i.e,

\[ ZT = \alpha^2 k R T \] ........................................ (3)

\[ T = \frac{TH+TL}{2} \] ........................................ (4)

The term \( \alpha^2 k R \) is referred to as the electrical power factor. In general, a thermoelectric power generator exhibits low efficiency due to the relatively small dimensionless figure-of-merit (\( ZT \leq 1 \)) of currently available thermoelectric materials. The conversion efficiency of a thermoelectric power generator defined as the ratio of power delivered to the heat input at the hot junction of the thermoelectric device, is given by,

\[ n = \frac{W}{E} \] ........................................ (5)

The maximum conversion efficiency of an irreversible thermoelectric power generator can be estimated using,

\[ n_{\text{ideal}} = (1-TLTH)[M-1M+TLTH] \] ........ (6)

Where,

\[ M = \left[ 1 + Z^2 (TH+TL) \right]^{1/2} \] ........ (7)

The value of the figure-of-merit is usually proportional to the conversion efficiency. The dimensionless term \( ZT \) is therefore a very convenient figure for comparing the potential conversion efficiency of modules using different thermoelectric materials.

III. LITERATURE REVIEW

Crane D. et al. [1] described a design concept that maximizes the performance for thermoelectric power generation systems in which the thermal power to be recovered is from a fluid stream (e.g., exhaust gas) subject to varying temperatures and a broad range of exhaust flow rates. The device is...
constructed in several parts, with each part optimized for a specific range of operating conditions. The thermoelectric system characteristics, inlet mass flow rates and fluid temperatures, and load and internal electrical resistances are monitored and generator operation is controlled to maximize performance. With this design, the system operates near optimal efficiency for a much wider range of operating conditions. Application of the design concept to an automobile is used to show the benefits to overall system performance.

Basel I.I. et al. [2] presented a background on the basic concepts of thermoelectric power generation and recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed.

Liang G. et al. [3] studied the performances of parallel thermoelectric generator (TEG) by theoretical analysis and experimental test. An analytical model of parallel TEG was developed by theoretical analysis and calculation, based on thermodynamics theory, semiconductor thermoelectric theory and law of conservation of energy. Approximate expressions of output power and current of parallel TEG were deduced by the analytical model.

C.Ramesh Kumar et al. [4] experimentally studied 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. Various designs of the heat exchangers were modelled using computer aided design and analysis was done using a computational fluid dynamics code. From the simulated results it was found that rectangular shaped heat exchanger met our requirements and also satisfied the space and weight constraint.

Hsu C. et al. [5] constructed a system to recover waste heat comprised 24 thermoelectric generators. Simulations and experiments for the thermoelectric module in this system are undertaken to assess the feasibility of these applications. A slopping block is designed on the basis of simulation results to uniform the interior thermal field that improves the performance of TEG modules. Besides simulations, the system is designed and assembled. Through simulations and experiments, the power generated with a commercial TEG module is presented.

Dai D. et al.[6] proposed a new type of thermoelectric generator (TEG) system based on liquid metal which serves to harvest and transport waste heat. To demonstrate the experimental prototype which combined commercially available thermoelectric (TE) modules with the electromagnetic pump was set up. Output voltage from TE modules and temperature changes of the main parts of the liquid based TEG system were experimentally measured, as well as the flow rate of cooling water and the load resistance. It was shown that the maximum open-circuit voltage of 34.7 V was obtained when the temperature of the waste heat source was 195.9°C and the temperature gap between liquid metal heating plate and cooling-water plates was nearly 100°C.

Love N.D. et al. [7] experimentally investigated a thermoelectric which is in the contact with clean and fouled heat exchangers of different materials. The thermoelectric devices are tested on a bench-scale thermoelectric heat recovery apparatus that simulates automotive exhaust. It is observed that for higher exhaust gas flow rate, thermoelectric power output increases from 2 to 3.8W while overall system efficiency decreases from 0.95% to 0.6%. Degradation of the effectiveness of the EGR-type heat exchangers over a period of driving is also simulated by exposing the heat exchangers to diesel engine exhaust under thermophoretic conditions to form a deposit layer.

S. R. Jumade et al. [8] demonstrated the potential of thermoelectric generation. The use and evolution of different kinds of thermoelectric materials presented. Also, several main characteristics
of the different structures proposed for the thermoelectric generators (TEGs) compared. The results presented can be considered as references of the minimum goals to be reached.

Weng C.et al. [9] explored influences of the number and the coverage rate on the heat-exchanger of the TEGs via simulations. It was found that implementing more TE couples does not necessarily generate more power in total, and most of all the average power per TE couple decreases rapidly. Furthermore, it was also found that for a given total number of TE couples, it is better to retain a portion of the heat exchanger uncovered with TE couples at the downstream side so that the downstream wall of the exhaust pipe uncovered with TE couples becomes even hotter than the upstream wall covered with TE couples. Heat is consequently conducted from the downstream wall to the upstream wall and successively to the attached TEGs; a larger total power can be thus obtained.

IV. PROPOSED WORK

As shown in the Fig.3, the proposed system consists of one hot side heat exchanger and one cold side heat exchanger. Between the two heat exchangers the thermoelectric modules (TEG) are placed. The exhaust gas from engine passes through hot side heat exchanger and cooling water from radiator passes through cold side heat sink. According to the principle of Seebeck effect, thermoelectric modules convert the heat into useful electricity.

4.1. Experimental set-up:
1. Thermoelectric material for module:
Thermoelectric modules are selected according to the temperature difference between exhaust gases side and the engine coolant side. Thermoelectric materials are evaluated by figure of merit which is determined by three physical values - Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ). The larger the value of Z, the better is the thermoelectric material. The main focus is to investigate the possibility of a low-cost thermoelectric generator (TEG) to harvest the wasted heat of vehicles.

2. Hot-side Heat Exchanger:
The function of hot-side heat exchanger is to extracting waste heat and delivering this heat to the surface of TEM. Sizing up the heat exchanger will be based on the size, orientation, and number of modules. Because the modules are assumed to be square as they often are, length and width differ by the number of modules defined by flow orientation. So that design of hot side heat exchanger will be done analytically.

3. Cold-side Heat Exchanger:
The cold-side heat exchanger is responsible for dissipating heat from TEM to prevent damage on TEM due to high temperature. The basic requirement of cold side heat sink are heat sink should flow with full of water i.e. no air gap should get created and length of cold side heat sink should be larger than hot side heat exchanger as cooling should be effective. So that design of cold side heat sink will be done analytically.

4. Manufacturing and assembly:
The heat exchangers will be assembled with the sandwich arrangement of TEG modules between them as shown in fig.3. Before assembly thermal insulation will be applied on both the surfaces of TEG modules to enhance the heat transfer. Thermocouples will be connected along with the display for temperature measurement.

5. Performance analysis of TEG:
After successful assembly, sets of trials will be taken on the TEG System retrofitted on an I. C. engine at different RPMs. Using the thermocouples; temperatures at different sections will be
measured on Digital temperature indicator. Then voltage & current at various engine speeds will be measured on Digital multimeter. Performance analysis will be done through the output power of TEG system.

V. EXPERIMENTAL WORK

The heat exchangers are assembled with the sandwich arrangement of thermoelectric modules between them. Before assembly the thermal grease is applied on both the surfaces of TEG modules to enhance the heat transfer. Ceramic pads are inserted between the exchangers for insulation for the area not covered by modules. Thermocouples (K-Type) are connected along with the display for temperature measurement.

After successful assembly of heat exchangers, TEG System is attached on a 3 cylinder, 4 stroke, and Petrol Engine test rig. Experimental Setup is ready to take sets of trials at different engine speed. As a load on system, LED load bank is used. Using the thermocouples; temperatures at 6 sections are measured on Digital temperature indicator. Then voltage & current at various engine speeds are measured on Digital multimeter.

Fig.5 Three cylinder, four stroke, Petrol Engine test Rig with TEG System

Fig.6 Thermoelectric module
Calculations:

\( T_1 = \) Hot side inlet temperature
\( T_2 = \) Hot side outlet temperature
\( T_3 = \) Cold side inlet temperature
\( T_4 = \) Cold side outlet temperature
\( T_{in} = \) Exhaust gas temperature at TEG system inlet
\( T_{ex} = \) Exhaust gas temperature at TEG system exit

Sample Calculation:
Engine Speed \((N) = 2122\, \text{rpm}\)
Inlet Temperature of exhaust gas = \(278^0\, \text{C}\)
Monomeric deflection = 38 mm
Fuel flow in sec/100ml = 70 secs
Coefficient of discharge \(C_d = 0.6\)
Orifice diameter = 35mm
Density of air = 1.16 kg/m\(^3\)

1. Fuel intake \((m_f)\):

\[
m_f = \frac{\text{fuel consumed in } m^3 \times \text{density of fuel}}{\text{time required (t)}}
\]
\[
m_f = \frac{100 \times 10^{-6} \times 740}{70} = 1.065 \times 10^{-3} \, \text{kg/s}
\]

2. Mass flow rate of air \((m_a)\):

\[
m_a = C_d \times A \times \sqrt{\frac{2g \times H_w \times \left(\frac{\rho_w}{\rho_a}\right)}{\pi}}
\]
\[
m_a = 0.6 \times \frac{\pi}{4} \times (0.035^2) \times \sqrt{2 \times 9.81 \times 0.038 \times \left(\frac{1000}{1.16}\right)}
\]

3. Exhaust mass flow rate \((m_{ex})\):

\[
m_{ex} = m_a + m_f
\]
\[
m_{ex} = 15.329 \times 10^{-3} + 1.065 \times 10^{-3}
\]
\[
m_{ex} = 16.394 \times 10^{-3} \, \text{kg/s}
\]

4. Temperature drop:

\[
\Delta T = (T_{in} - T_{ex})
\]
\[
T_{in} = 278^0\, \text{C} \quad T_{in} = 278^0\, \text{C}
\]
\[
T_{ex} = 273^0\, \text{C}
\]
\[
\Delta T = (278 - 273)
\]
\[
\Delta T = 5^0\, \text{C}
\]

5. Input power of exhaust gas:

\[
P_{in} = m_{ex} \times C_p \times \Delta T
\]
Where,
Specific heat of exhaust gas = 1.02KJ/kg-k
\[
P_{in} = 16.394 \times 10^{-3} \times 1.02 \times 5
\]
\[
P_{in} = 91.31 \, \text{W}
\]

6. TEG output power:

\[
P_{out} = V \times I
\]
Where,
Voltage generated, \[ V = 5.22 \text{ Volts} \]
Current generated, \[ I = 0.55 \text{ Amp} \]
So,
\[
\begin{align*}
\text{Power generated} &= V \times I \\
&= 5.22 \times 0.55 \\
&= 2.866 \text{ W}
\end{align*}
\]

7. **TEG Overall efficiency:**

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100
\]

So, at the engine speed of 2122 rpm, input power of engine exhaust gas is 91.31 W & the TEG output power is 2.71 W, hence the overall efficiency obtained is 2.97%.

### Table 1. Mass Flow Rates of Engine Exhaust Gas at Various Engine Speed

| Sr. No. | Engine Speed (rpm) | Air Intake \( m_a \times 10^{-3} \) (kg/sec) | Fuel Intake \( m_f \times 10^{-3} \) (kg/sec) | Mass Flow Rate of Exhaust Gas \( m_{\text{ex}} \times 10^{-3} \) (kg/sec) |
|---------|---------------------|---------------------------------------------|---------------------------------------------|------------------------------------------------|
| 1       | 2122                | 15.329                                      | 1.065                                       | 16.394                                        |
| 2       | 2475                | 16.168                                      | 1.158                                       | 17.326                                        |
| 3       | 2845                | 18.552                                      | 1.342                                       | 19.894                                        |
| 4       | 3096                | 20.596                                      | 1.391                                       | 21.987                                        |
| 5       | 3186                | 20.983                                      | 1.434                                       | 22.417                                        |
| 6       | 3398                | 22.336                                      | 1.576                                       | 23.912                                        |
| 7       | 3566                | 22.389                                      | 1.598                                       | 23.987                                        |
| 8       | 3603                | 22.390                                      | 1.607                                       | 24.007                                        |
| 9       | 3708                | 22.396                                      | 1.617                                       | 24.013                                        |
| 10      | 3736                | 22.671                                      | 1.645                                       | 24.317                                        |

### VI. RESULT AND DISCUSSION

The results obtained from experimentation, result table 2 has prepared which give information about:
1. Engine speed
2. Mass flow rate of exhaust gas
3. Temperature drop
4. Input power of exhaust gas
5. Output power of TEG
6. TEG overall efficiency

#### 5.1 Voltage Vs Engine Speed:

![Fig.7 Voltage Vs Engine Speed](image-url)
The graph shows that as the engine speed increases voltage generated also increases. Hence voltage is proportional to engine speed. With the engine speed of 3736 rpm, voltage generated is 9.56 Volts.

5.2 Voltage Vs Mass flow rate of engine exhaust gas:

![Voltage Vs Mass Flow Rate of Exhaust Gas](image1)

Fig. 8 Voltage Vs Mass flow rate of engine exhaust gas

Fig. 8 shows variation of voltage generated with respect to mass flow rate of engine exhaust. When mass flow rate of engine exhaust is $24.317 \times 10^{-3} \text{ kg/s} = 10^{-3} \text{ kg/s}$, voltage generated is 9.56 Volts.

5.3 Current Vs Engine Speed:

![Current Vs Engine Speed](image2)

Fig.9 Current Vs Engine Speed

The fig. 9 explains that the current increases with the engine speed. It first increases gradually up to 2845 rpm then rapidly beyond that speed. At the speed of 3736 rpm the current is 1.37 Amperes.

4 Current Vs Mass flow rate of engine exhaust gas
Fig. 10 Current Vs Mass flow rate of engine exhaust gas

Fig. 10 shows variation of current generated with respect to mass flow rate of engine exhaust. When mass flow rate of engine exhaust is $24.317 \times 10^{-3} \text{ kg/s} \times 10^{-3} \text{ kg/s}$, current generated is 1.37 Amperes.

5.4 Mass Flow Rate of Exhaust Gas Vs Engine Speed:

Fig. 11 Mass Flow Rate of Exhaust Gas Vs Engine Speed

Fig. 11 shows variation of mass flow rate of engine exhaust gas with respect to engine speed. With engine speed is 3736 rpm; mass flow rate of engine exhaust is $24.317 \times 10^{-3} \text{ kg/s} \times 10^{-3} \text{ kg/s}$. So that the mass flow rate of exhaust gas is function of engine speed.
5.6 TEG Overall Efficiency Vs Engine Speed:

![TEG Overall Efficiency Vs Engine Speed](image)

**Fig. 12 Efficiency Vs Engine Speed**

The graph explains the relation between the overall efficiency of the system and engine speed. At 3736 rpm the efficiency obtained is 5.28%.

5.7 TEG Output Power Vs Input Power of Exhaust Gas:

![TEG Output Power Vs Input Power of Engine Exhaust Gas](image)

**Fig. 13 TEG Output Power Vs Input Power**

The graph shows that at the engine speed of 3736 rpm, input power of engine exhaust gas is 248.03 W & the TEG output power is 13.106 W, hence the overall efficiency obtained is 5.28%.
5.8 Power Output Vs Mass Flow Rate of Exhaust Gas:

![Power Output Vs Mass Flow Rate of Exhaust Gas](image)

Fig.14 Power Output Vs Mass Flow Rate of Exhaust Gas

The graph shows that the power output is a function of mass flow rate of exhaust gas. At the mass flow rate of exhaust gas of $24.317 \times 10^{-3} \times 10^{-3}$ Kg/sec, the power developed by TEG system is 13.106 W.

VII. CONCLUSIONS

1. At high vehicle speeds, the total power that could be extracted is increased.
2. More power could also be extracted by improving the exhaust gas heat exchanger.
3. Results show that voltage, current, power developed and efficiency of the system increase with the increase in engine speed & mass flow rate of exhaust gas.
4. At the engine speed of 3736 rpm, the power generated is 13.106W and efficiency of the system is 5.28%.
5. Hence the TEG system traps the waste heat of exhaust gases from engine & generates useful power which can be used to charge the automobile batteries, to power auxiliary systems and minor automobile electronics system.
6. As this system recovers the lost energy in exhaust of the engine therefore the overall efficiency increases.

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