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Experimental analysis of Waste heat recovery using TEG for an internal combustion Engine

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ABSTRACT

With the rapid development of population and vehicle industry in the world during the past 20th century, the demand on passenger vehicles has increased sharply. Only 41% of a diesel engine's fuel combustion energy is converted into useful work to drive a vehicle and its accessory loads. The remainder is waste heat dissipated by engine exhaust system and also the convection as well as radiation heat loss from engine block. This increases fuel consumption which brings serious energy crisis and has environmental effects. As 30% to 40% of exhaust gases containing heat energy liberated from the internal combustion engine, and having temperature up to 200^{o}C to 250^{o}C are wasted directly to the atmosphere. So the objective of the work is to utilize that heat energy of internal combustion engine. By utilizing that heat energy of fuel which is consumed in the internal combustion engine can be reduced which increases efficiency of internal combustion engine. The work is to design a duct that can be modified in order to increase the heat transfer so that maximum heat can be dissipated to hot side of TEG module. Further fins can be used in the design of the duct, which will increase heat transfer also.

Keywords: TEG module, Seebeck coefficient effect, ICE, N-P type element Thermocouple.

1. INTRODUCTION

Recent studies indicate that, if this waste heat of IC engines could be recaptured efficiently, engine output power will be significantly enhanced without additional fuel consumption. Thus, large amount of fossil fuel can be saved and much less harmful exhaust gases are dissipated to environment when the same output power is generated. Furthermore, global warming will be relieved. However, it should be noticed that the potential energy savings from improved energy efficiency are estimated using basic physics principles and engineering models. The actual energy savings from such improvements generally falls short of such estimates due to the rebound effect. A possible explanation for this phenomenon could be that such improvements encourage the consumption of energy services where part or all of the gain would be offset by the increase in consumption. Since the price of fossil fuel rises greatly due to serious energy crisis, renewable clean energy will play an important role in the future. In other words, it is a considerable solution to improve engine efficiency via waste heat recovery system. In particular, it has considerable potential environmental and economic benefits. New opportunities for efficiently recovering waste heat have been created because of advances in micro- and nano-technologies. The key to identifying TEG waste heat recovery applications is to determine when thermal exchange between existing process fluids is not an available option or provides no useful technical or economic benefit. The quality of waste heat (i.e., temperature, composition, energy content, and accessibility) varies significantly and depends on the industrial process emanating it.

Thus, many researches and projects focus on enhancing engine performance and thermal efficiency, aiming at lowering fuel requirement and exhaust that are harmful to human body. Converting exhaust heat to electricity by “Thermoelectric generator module” is an interesting and actual avenue among many methods of recovering the waste heat.

2. INTRODUCTION TO TEG & THERMOELECTRIC THEORY

Thermoelectric generator modules are solid device which can convert heat or temperature difference into electrical energy. Thermoelectric elements are made of P type and N type semiconductor. Thermoelectric modules are based on Seebeck effect. When there is a temperature difference between two sides of semi conductor, a voltage is created. Current flows from N type element and passes into P type element. Thermoelectric modules are devices that either convert thermal energy from a temperature gradient into electric energy or vice versa, convert applied electric energy into a temperature gradient. [1]

2.1 *Thermoelectric Power Generation*: The thermoelectric power generation is based on the Seebeck effect – If heat is applied to a circuit at the junction of two different conductors, a current will be generated. Seebeck tested a wide range of materials, including the naturally found semiconductors ZnSb and PbS. [2] The Seebeck coefficient measured in micro volts/K is defined as the open circuit voltage produced between two points on a conductor when a uniform temperature difference of 1 K is applied between those points.

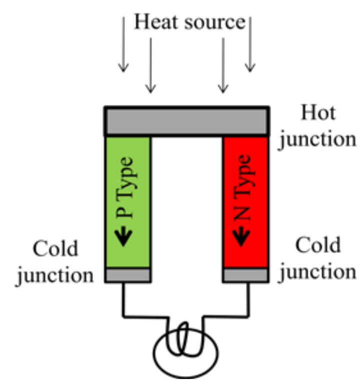

Figure 1: Electric power generation

2.2 *Thermoelectric Heating and Cooling*: Thermoelectric heating and cooling devices are based on the Peltier effect – If a current is passed through a circuit of two dissimilar conductors, there will be a rise or fall in temperature at the junction depending on the direction of the current flow. When electric input is applied to a thermocouple, as shown in figure 4. Electrons move from p- type material to n-type material absorbing thermal energy at the cold junction. The electrons dump their extra energy at the hot junction as they flow from n-type back to the p-type material through the electrical connector. Removing heat from the hot side will drop the temperature on the cold side rapidly.

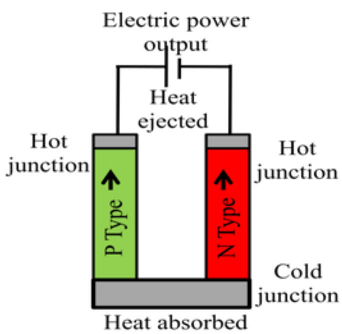

Figure 2: Thermoelectric cooling

2.3 Material used for TEG

Among the vast number of materials known to date, only a relatively few are identified as thermoelectric materials. Thermoelectric materials can be categorized into established (conventional) and new (novel) materials. Today's most thermoelectric materials, such as Bismuth Telluride (Bi2Te3)-based alloys and Pb-Te-based alloys, have a *ZT* value of around unity (at room temperature). However, at a *ZT* of 2-3 range, thermoelectric power generators would become competitive with other power generation systems. Effective thermoelectric materials should have a low thermal conductivity but a high electrical conductivity. A large amount of research in thermoelectric materials has focused on increasing the Seebeck coefficient and reducing the thermal conductivity, especially by manipulating the nanostructure of the thermoelectric materials. Different thermoelectric material can be used depending upon temperature difference which we are getting between hot side and cold side of the TEG module. Material with range of temperature for which TEG is made is given in the table below.

Table-1.1: Material used in TEG with range of temperatures

Sno	TEG Material	Temperature Range
1	Alloys based on Bismuth (Bi) in combinations with Antimony(An), Tellurium (Te) or Selenium (Se)	Low temperature up to 450K
2	Materials based on alloys of Lead (Pb)	Intermediate temperature up to 850K
3	Material based on Si-Ge alloys	Higher temperature upto1300K

Although the above mentioned materials still remain the corner stone for commercial and practical application in thermoelectric power generation, significant advances have been made in synthesizing new materials and fabricating material structures with improve thermoelectric performance and by reducing the thermal conductivity [2].

3. Related Work

The waste gases are obtained from different sources like automobile, industries, heat generated from solid waste etc. The main aim is to convert these heats into useful energy. To do these we require a system by which it is possible to convert heat into useful work. The properties of material also play main role while selecting the TEG for calculation of energy and exergy of exhaust gases. *G. shu, J. Zhao, H. Tian, X. Liang, H. Wei* [1]-The paper analyzes the combined TEG-ORC (thermoelectric generator and organic Rankine cycle) used in exhaust heat recovery of ICE. They calculated the optimal parameters of the bottoming cycle based on thermodynamic theory when net output power and volumetric expansion ratio are selected as objective functions, which affect system performance and size. The effects of relative TEG flow direction, TEG scale, highest temperature, condensation temperature, evaporator pressure and efficiency of IHE (internal heat exchanger) on system performance. R123 is chosen among the fluids whose decomposition temperature exceeds 600 K to avoid fluid resolving and resulting in wet stroke when expansion process ends.*B. I. Ismail, W. H. Ahmed*. [2] Worked on use of thermoelectric module, performance parameter. "Figure of merit" which plays an important role in behavior of thermoelectric generator module. Efficiency of thermoelectric modules basically depends on "Figure of merit" Z and operating temperature difference. This paper mainly pays attention toward the applications of this conversion system in wide area like micro-scale waste heat application as in electronic chip in domestic gas-monitoring system etc.

M. He, X. Zhang, K. Zeng, K. Gao, worked on waste heat of combined cycle (i) Organic rankine cycle, for recovering waste heat of oil lubricant (ii) Internal combustion engine, for recovering waste heat of high temperature exhaust gases. For studying the energy balance of ICE an experiment was conducted on a TOYOTA 8A gasoline engine. In their work energy and exergy analysis of waste heat from exhaust gases is done [5]. *X. Gao, S. Juhl, Andreasen, M. Chen, S. Knudsen Koer*. They presented a numerical model of an exhaust heat recovery system for a high temperature polymer electrolyte membrane fuel cell (HTPEMFC) stack. They designed a system in which thermoelectric generators are sandwiched in the walls of a compact plate fin heat exchanger. Their model is based on finite element approach. In this approach they calculated fluid properties, heat transfer process and TEG performance.[6] *M. strasser, R. Aigner, M. Franosch, G. Wachutk* worked on miniaturized thermoelectric generators, which are being developed to convert waste heat into a few microwatt of electrical energy. In order to optimize the device, they suggested that material should have low thermal conductivity which increases output power. Materials which they have used are poly-Si and poly-si-Ge. [8]

4. EXPERIMENTAL SETUP FOR WASTE HEAT RECOVERY

A description of experimental setup is explained including description of ICE, rectangular duct, connection of thermoelectric generator and devices for measuring different temperatures and voltages etc. The test rig is made which consists of a vertical single cylinder water cooled compression ignition type diesel engine. It is coupled to a loading dynamometer; all the components are mounted on heavy duty MSchannel.

Figure: 3 Test Rig setup

A desk type control panel consists of following instrumentations. A Digital RPM indicator to measure speed of the engine. A Digital temperature indicator to measure various temperatures and a Burette with manifold to measure the rate of fuel consumption during test.

4.1 Description of Rectangular duct

A duct made up of stainless steel is used in the experimental setup to flow hot exhaust gases which is exhausted from the exhaust manifold of the internal combustion engine. A device known as thermoelectric generator is placed at the top of the duct. It is a solid device which converts heat taken into electricity directly. In setup two TEG modules are used and they are connected in series. When they are connected in series performance increases. To ensure that maximum heat flow toward top of duct, insulation is required, that is a combination of insulation paper and cotton, so that maximum heat can be utilized by TEG modules. The specification of duct considered is Rectangular shape with Size of 13 cm× 4 cm× 3 cm *and* Material used is Stainless steel. Figure below shows combination of both duct with TEG sandwiched in between.

Figure 4 : TEGs sandwiched in between two ducts

To measure the voltage generated between two terminals of TEG, multi-meter is used. And for measuring temperature at the hot side and cold side of the duct a thermocouple is used. During measurement of temperature one point of the thermocouple is set to zero value hence difference in temperature itself gives value of temperature of hot and cold side respectively. Figure below shows the image of multi-meter and thermocouple which is used to measure voltage and temperature respectively

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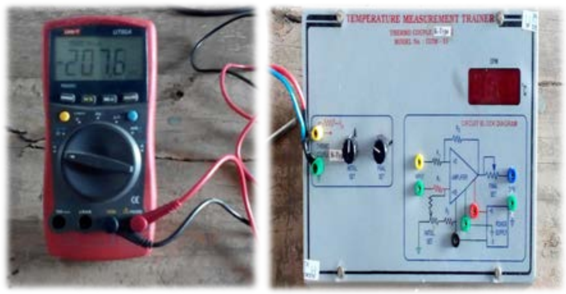

(a) (b)

Figure 5 : (a) Multi-meter (b) Thermocouple

4.2 Working procedure of the setup

In this experimental setup, experiment is done for finding the different parameters like "mass of fuel consumed, amount of heat added, brake power obtained from rope brake dynamometer, amount of heat carried by exhaust gases" at different load and speed of the engine. Test is performed for three different speeds and ten different loading conditions. The procedure for finding the above parameters are described below:

(i) Fill up the diesel into the fuel tank mounted on the panel frame.

(ii) Check the lubricating oil in the oil sump

(iii) Connect the instrumentation power input plug to a 230 volt, single phase power source. Now a digital meter RPM and temperature indicators display the respective readings.

To conduct the performance test on the engine

(i) Open the fuel valve and ensure no air trapped in the fuel line

(ii) Start the engine and allow it to settle at rated speed. At first speed of the engine is set to the 1300 RPM. Apply the load by rotating the hand wheel on the dynamometer gradually to the desired load. Load for constant speed varies from 2 kg to 20kg.

(iii) Mass of fuel consumed in the burette in cc is measured at speed of 1300 RPM and by varying load from 2 kg to 20 kg respectively

(iv) Different temperatures like temperature of hot exhaust gases, temperature of hot exhaust gases , temperature of water inlet and outlet to & fro from is measured by the indicator.

(v) Repeat the same procedure for speed of 1400 RPM and 1500 RPM as above.

Now test is performed for calculation of power obtained from TEG modules, which are connected in series at the top of duct. The procedures for finding are as follows:

(i) Connect the duct to the exhaust manifold of the internal combustion engine.

(ii) There should be proper connection of the duct to the exhaust manifold so that there should not be any leakages at the junction of the exhaust manifold and the duct pipe.

(iii) Connect the two terminals of the TEG modules with multimeter and place the thermocouple rod at the top of duct at different load and speed conduction.

(iv) Start the engine and set speed & load of the engine to a desired value. Here at starting calculation is made for 1300 RPM with load from 2 kg to 20 kg

(v) Note down the temperature at the top of duct and voltage generated at each and every set of speed.

(vi) At first the reading was taken by the cold side of TEG when opened to atmosphere and then the cold fluid is made to flow in the upper duct which is kept at the top of the TEG.

(vii) Repeat the same procedure for speed of 1400 RPM, 1500 RPM with different loads.

5 METHODOLOGY

5.1 *Energy analysis of fuel in ICE*

The amount of heat given to the heat engine is *ENERGY* and maximum useful work which we can obtain by converting this heat into work is known as available energy or *EXERGY* of the system. Some amount of heat which goes on waste is known as unavailable energy. The whole process of heat engine is shown in figure below:-

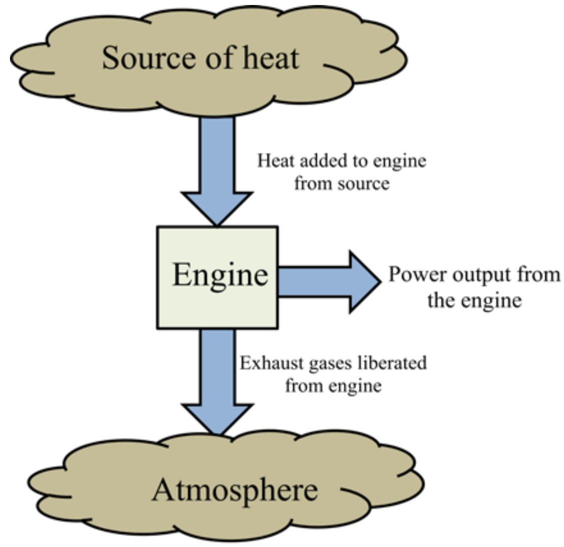

Figure 6: Flow diagram of engine

For calculating the brake power, mass of fuel consumed and amount of heat contained in exhaust gases can be calculated by following relationship.

5.1.1Calculation of brake power of engine

$$BP = T \times \omega$$

Where ω is angular velocity (in rad/sec) of engine, which can be calculated by

$$\omega = 2\pi N/60$$

N is speed in revolution per minute (RPM)

T Torque generated which can be calculated as

T = spring balance difference × g × effective brake drum radius

P = brake power produced. Brake power (BP) produced (in kJ/s) can be find out by

5.1.2 Calculation of mass of fuel consumed and heat added to engine

Mass of fuel consumed (in kg/hr) in the combustion chamber can be calculated by:-

$$mfc = (X \times `10\text{^} - 6 \times 820)/(300)$$

Where X is burette reading in cc, 820 is density of diesel in Kg/m^3, t is time taken in sec.

If mass of fuel consumed is known, by conidering calorific value of fuel (C_f), amount of heat added to engine can be calculated by

Amount of heat added $Q_a = mfc \times C_f$

5.1.3 Calculation of amount of heat contained in exhaust gases

Heat carried away by exhaust gases (Q_{eg}) can be worked out by applying "First law of thermodynamics". While calculating the heat carried by exhaust gases it is assumed that no heat is transferred to atmosphere and taking that heat of exhaust gases is completely used for cooling of engine by flow of water. So from heat balance:- Heat gained by exhaust gases = heat carried by the cold water that is

$$m_{eg} \times C_{peg} \times (T_{gi} - T_{go}) = m_w \times C_{pw} \times (T_{wo} - T_{wi})$$

Where m_{eg} = mass flow of exhaust gases (kg/s)

C_{peg} = Specific heat of exhaust gases (kJ/kg K)

m_w = Water flow rate (in kg/s by 1 litre jar)

C_{pw} = Specific heat of water (4.187 kJ/kgK)

T_{gi} = Exhaust gas inlet temperature (in ^{o}C)

T_{go} = Exhaust gas outlet temperature (in ^{o}C)

T_{wi} = Water inlet temperature (in ^{o}C)

T_{wo} = Water outlet temperature (in ^{o}C)

By using above relationship, heat capacity ($m_{eg} \times C_{peg}$) can be calculated and heat carried by hot exhaust gases (in kJ/sec) is given by

$$Q_{eg} = m_{eg} \times C_{peg} \times (T_{gi} - T_{go})$$

6 RESULT & CONCLUSION

This chapter deals with results obtained while performing experiment on the test rig for analysis of waste heat recovery from waste exhaust gases of ICE. In the experimental setup test is performed for calculation of mass of fuel consumed, amount of heat added, brake power and heat carried away be exhaust gases, heat transferred to hot side and cold side of TEG and power obtained from TEG.

At first calculation is made for speed of the engine of 1300 RPM and load variation of 2 kg to 20 kg and values like mass of fuel consumption, amount of heat added to the engine, amount of heat rejected from the engine and amount of heat carried away by exhaust gases is calculated. It was found that maximum amount of heat carried away by hot exhaust gases are obtained at speed of 1300 RPM and load of 20 Kg and the value is 2597.61 J/s. When TEG is sandwiched between hot junction and cold junction and speed of engine is maintained at 1300 RPM with load of 20 kg and cold water flows at a temperature of 16^{o}C, maximum power obtained from TEG module is 29.94 J/s. Similarly by taking 1400 RPM and 1500 RPM with load variation 2 kg to 20 kg, maximum amount of heat carried by hot exhaust gases obtained is 2625.25 J/s for speed of 1400 RPM with load 20 kg , 7174.84 J/s and power obtained for 1400 RPM and 1500 RPM with load 20 kg and water temperature at 16^{o}C are 31.86 J/s and 33.16 J/s respectively.

parameters with respect to loads and speed.

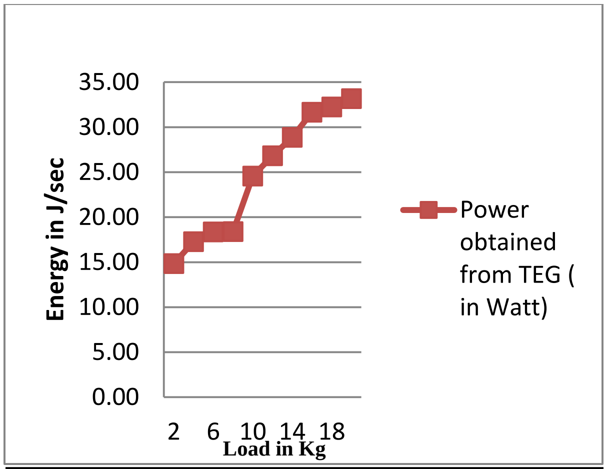

Figure 7: Graphical representations of variation of power obtained from TEG at speed of 1500 RPM and load variation of 2 kg to 20 kg, when cold fluid at 16 degree Celsius is flowing

Finally validation of experimental data is done by comparing the results obtained by previous work for different temperature difference and types of cooling used and it is found that data obtained by experimental setup is comparable and reliable.

Sill there is opportunity to search for semiconductor material which provides high temperature difference so that maximum heat can be utilized from system. In future the design of duct can be modified in order to increase the heat transfer so that maximum heat can be dissipated to hot side of TEG module. Further fins can be used in the design of the duct, which will increase heat transfer as well.

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Table 2: Data obtained from experiment for amount of heat absorbed to hot side of TEG, heat transferred to cold side of TEG and power obtained from TEG at constant speed of

Sn.	Load Kg	Temp. at hot side of duct degree Celsius	Temp. at cold side of duct degree Celsius	Heat absorbed by hot side of TEG Qh in Watt	Heat received by cold side of TEG Qc in Watt	Power obtained from TEG in Watt
1	2	135	16	371.66	360.79	14.85
2	4	140	16	391.78	378.90	17.28
3	6	146	16	411.28	397.54	18.36
4	8	152	16	427.58	413.59	18.40
5	10	164	16	476.53	457.45	24.56
6	12	172	16	503.42	482.03	26.83
7	14	181	16	531.81	508.09	28.86
8	16	189	16	559.48	532.90	31.65
9	18	197	16	581.93	554.46	32.25
10	20	210	16	619.05	590.44	33.16

When cold fluid at 16 degree Celsius is flowing through duct

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