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Combined Efficiency Calculation of Bismuth Telluride and Lead Telluride in Thermoelectric Module

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Abstract:- The heat rejected from an internal combustion engine is 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 is approximately 30-40%.The thermoelectric generators are used for power generation . Thermoelectric modules which are used in 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. The objective of this project is to include fin effect to increase cooling rate , to reduce the temperature by increasing the temperature difference and to use long fin and avoid accumulation of heat in between fins . The TEG system is directly connected to the exhaust pipe and the amount of electricity generated by the thermoelectric material is directly proportional to their heated area . The materials used in TEG are Bi_2Te_3 - Bismuth Telluride and PbTe - Lead Telluride . Bi_2Te_3 module TEG is highly efficient in room temperature , but heat withstanding capacity of Bi_2Te_3 is less than PbTe.The combination of these thermoelectric materials are used for better efficiency . The testing is done for above conditions and experimental results with this setup are performed and presented.

Keywords:- Thermoelectric generator, lead telluride, bismuth telluride, boost up circuit, seebeck effect.

I. INTRODUCTION

A highly efficient combustion engine converts only about one third of the energy in the fuel into mechanical power serving to actually drive the car. The rest is lost through heat discharged into the surroundings or, quite simply, leaves the vehicle as “waste heat”.

The generation of electric power in the motor vehicle is a process chain subject to significant losses. Quite simply because the chemical energy contained in the fuel is first converted into mechanical energy and then, via an generator, into electric power. Now the BMW Group’s engineers are working on a technology able to convert the thermal energy contained in the exhaust gas directly into electric power. This thermoelectric process of recovering energy and generating power by means of semi-conductor elements has already been used for decades by NASA, the US Space Agency, in space probes flying into outer space. Until just a few years ago, however, such thermoelectric generators (TEGs) were unsuitable for use in the automobile due to their low level of efficiency. But since significant progress has been made in materials research in recent times, the performance and output of such modules has increased significantly. To generate electric power in the vehicle a thermoelectric generator is integrated in the exhaust gas manifold.

II. MOTIVATION

Systems based on petroleum account for a significant fraction of the waste heat utilization sector and fuels based on petroleum have assumed a position of leadership in the transportation and energy sector.

However, due to factors such as our dependence on depleting oil reserves and environmental issues, alternative fuels and propulsion systems are being sought that can provide an increase in efficiency and reduction in emissions.

The energy budget for various gasoline, diesel, and natural gas engines at engine loadings of 30, 60, and 90% of their maximum rated power. The listed engines are employed for various stationary and mobile applications. From the results shown in Table 1.1, approximately 20 to 30% of the available energy in the fuel converter is rejected as heat to the exhaust and 30 to 55% to the coolant and ambient through conduction, convection, and radiation. As a result only 15 to 45% of the original energy contained in the fuel is converted into shaft power of the engine. Depending on the application, a limited or complete portion of the shaft power is converted into electrical power. Therefore a means to improve the fuel economy is to increase the overall efficiency of the power train by recovering waste heat from the exhaust and converting it into electrical energy. A thermoelectric generator (TEG) system can be used to convert this heat energy into electrical power.

The TEG works on the principle of the Seebeck effect, when the junctions formed by joining two dissimilar current carrying conductors are maintained at different temperatures, an electromotive force (emf) is generated in the circuit. The current carrying conductors are known as thermoelectric elements and the couple formed out of the two current carrying conductors is known as a thermoelectric couple. In a typical generator, heat exchangers are used to transfer heat from the heat source and to the heat sink through the junctions of the thermocouple. The heat exchangers and the thermoelectric couple unit is known as a TEG. The two dissimilar current carrying conductors are formed out of n and p-type semiconductor materials and referred to as n and p-type thermoelectric materials.

III. THERMOELECTRIC MODULE

In this section a description and functionality of the constituents of the thermo-electric modules are discussed. The modules are the basic building blocks within thermoelectric power generators or coolers. Modules are a matrix of semiconductor thermoelectric couples that are connected electrically in series and thermally in parallel. The thermoelectric couples and their electrical interconnects are sandwiched between two ceramic substrates. Figure 1.5 shows the arrangement of the different constituents of a thermoelectric module. The main constituents of a thermoelectric module are (1) thermoelectric elements (or legs), (2) ceramic substrates, (3) metal interconnects, and (4) external electrical connections.The thermoelectric elements (or legs) are the couples used for generating electricity in thermoelectric modules. They are formed out of materials such as bismuth-telluride, lead-telluride, antimony telluride, silicon-germanium semiconductor alloys. The selection of material depends on the field of application and operating temper-ature range. The thermoelectric legs are arranged in a regular matrix within the module.Ceramic substrates are used to electrically insulate the thermoelectric module from external mounting surfaces. The substrates must also have good thermal conductance to provide heat transfer with minimal thermal resistance. A common ceramic substrate is aluminium oxide (Al_2O_3).The metal interconnects serves as electrical contacts between thermoelectric legs. The contacts are arranged in such a way that all the legs are connected electrically in series.External electrical connections are used to connect the module to an electrical load in case of power generation or to an electrical source in case of the module being used for thermoelectric cooling.

IV. PRINCIPLE OF THERMOELECTRIC GENERATOR

The typical thermoelectric module is manufactured using two thin ceramic wafers with a series of P and N doped bismuth telluride and lead telluride semiconductors material sandwiched between them. The ceramic material on both sides of the thermoelectric adds rigidity and the necessary electrical insulation. The N type material has an excess of electrons, while the P type material has a deficit of electrons. One P and one N make up a couple. The thermoelectric couples are electrically in series and thermally in parallel. A thermoelectric module can contain one to several hundred couples.

V. THERMOELECTRIC MATERIALS

Thermoelectric materials (those which are employed in commercial applications) can be conveniently divided into three groupings based on the temperature range of operation. Alloys based on Bismuth (Bi) in combinations with Antimony (An), Tellurium (Te) or Selenium (Se) are referred to as low temperature materials and can be used at temperatures up to around 450K. The intermediate temperature range - up to around 850K is the regime of materials based on alloys of Lead (Pb) while thermo-elements employed at the highest temperatures are fabricated from SiGe alloys and operate up to 1300K. Although the above mentioned materials still remain the cornerstone for commercial and practical applications in thermoelectric power generation, significant advances have been made in synthesizing new materials and fabricating material structures with improved thermoelectric performance. Efforts have focused primarily on improving the material's figure-of-merit, and hence the conversion efficiency, by reducing the lattice thermal conductivity.

In all of the above mentioned TE materials, performance of the Bismuth-Telluride peaks within a temperature range that is best suited for most cooling and heating applications.

VI. PERFORMANCE OF THERMOELECTRIC POWER GENERATORS

The performance of thermoelectric materials can be expressed as

$$Z = \alpha^2 / kR ,$$

where Z is the thermoelectric material figure-of-merit, α is the Seebeck coefficient given by

$$\alpha = -\frac{\Delta V}{\Delta T},$$

This figure-of-merit may be made dimensionless by multiplying by □ (average absolute temperature of hot and cold plates of the thermoelectric module, *K*), i.e.

$$Z\overline{T} = \alpha^2 \overline{T} / kR$$

$$\overline{T} = \frac{T_H + T_L}{2}.$$

In general, a thermoelectric power generator exhibits low efficiency due to the relatively small dimensionless figure-of-merit Z□<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

$$\eta = \frac{\dot{W}_e}{\dot{Q}_H}$$

Limited by the second-law of thermodynamics, the ideal (absolute maximum) efficiency of a thermoelectric power generator operating as a reversible heat engine is Carnot efficiency, given by

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

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

$$\eta = \eta_{Carnot} \left[\frac{\sqrt{1 + Z\overline{T}} - 1}{\sqrt{1 + Z\overline{T}} + T_L / T_H} \right]$$

VII. DESIGN OF THERMOELECTRIC GENERATOR

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.

As shown in Figure 6.4 , 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.

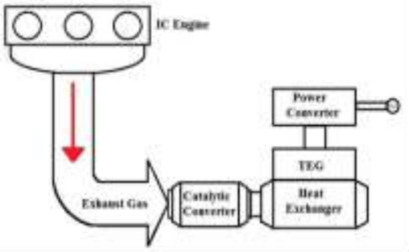
Using the first-law of thermodynamics (energy conservation principle) the difference between Q_h and Q_l is the electrical power output *we*. It should be noted that this power cycle intimately resembles the power cycle of a heat engine (Carnot engine), thus in this respect a thermoelectric power generator can be considered as a unique heat engine.

VIII. EXPERIMENTAL SETUP

The exhaust pipe contains a block with thermo electric materials that generates a direct current, thus providing for at least some of the electric power requirements. In which two different semiconductors are subjected to a heat source and heat sink. A voltage is created between two conductors. It is based on the seeback effect. The Cooling and Heating is done by applying electricity. It is low efficiency approximately (2 to 5%) and high cost. Thermoelectric devices may potentially produce twice the efficiency as compared to other technologies in the current market . Thermo Electric Generator is used to convert thermal energy from different temperature gradients existing between hot and cold ends of a semiconductor into electric energy . This phenomenon was discovered by Thomas Johann Seebeck in1821and called the **"Seebeck effect "**. The device offers the conversion of thermal energy into electric current in a simple and reliable way.

Thermal power technology such as the Thermoelectric Generator arises, therefore, significant attention worldwide. Thermoelectric Generator is a technology for directly converting thermal energy into electrical energy.

Pilot program is made to investigate the applicability of thermoelectric generators to the recovery of medium-temperature waste heat from a low-power stationary diesel engine. Experimental investigation to the optimum operating conditions to achieve maximum power outputs from the waste heat recovery system . Study on waste heat recovery system by using thermoelectric generator from internal combustion engine reviews the main aspects of thermal design of exhaust-based thermoelectric generators (ETEG) systems . Analysis of thermoelectric generator for power generation from internal combustion engine shows results as 20% of energy releasing for the waste heat from engine. It is able to 30-40% of the energy supplied by fuel depending on engine load .



IX. ENGINE SPECIFICATIONS

Type : 4 Stroke Diesel Engine
Make : Kirloskar
Speed : 1500 Rpm
Compression ratio : 17:5:1
Stroke : 80 mm
Load : Rope Brake
Maximum Load : 15 Kg
Power : 6HP
Fuel : Diesel
Bore : 87.5 mm
Cooling : Air cooled
Radius of brake drum : 0.15 m
Volumetric Efficiency = η_v = 0.8 to 0.9
Density Diesel fuel is 0.84 to 0.85 gm/cc
Calorific value of diesel is 42 to 45 MJ/Kg
Density air fuel is 1.167 Kg/m3
Specific heat of exhaust gas is 1.1 to 1.25 KJ/KgK
Heat loss in exhaust gas (QE):

$$QE = \dot{m}E \times Cp \times \Delta T$$
$$= 8.911 \times 10^{-3} \times 1.25 \times (450 - 156)$$
$$= 3.2747 \text{ KW}$$

Therefore, the Total Energy lost by Kirloskar 4 - stroke Diesel Engine is 26.74 %.

10 CALCULATION OF EFFICIENCY OF Bi2Te3 OF TEM 1

Net Heat Input = 520.94 W,
Output = 9.23 W.
η = 9.23/520.94
= 1.785 %.

Geometrical Dimensions of Thermoelectric module: 40 mm x 40 mm

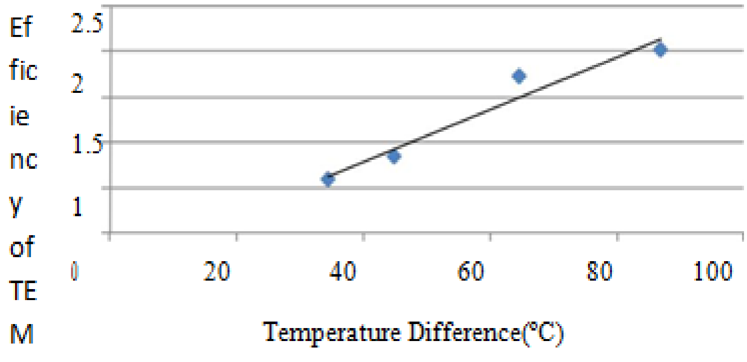
TEG Specifications:
Internal Resistance = 3.840 ohm
Heat Resistance = 2.23 K/W
Voltage = 2.50 V
Current = 0.65 A
Power = 1.63 W
Material = Alloy of Bi2Te3 & PbTe

Efficiency of TEG $= \Delta T/ h \times(\sqrt{1+ZT} - 1) /(\sqrt{1+ZT} + Tc / Th):$

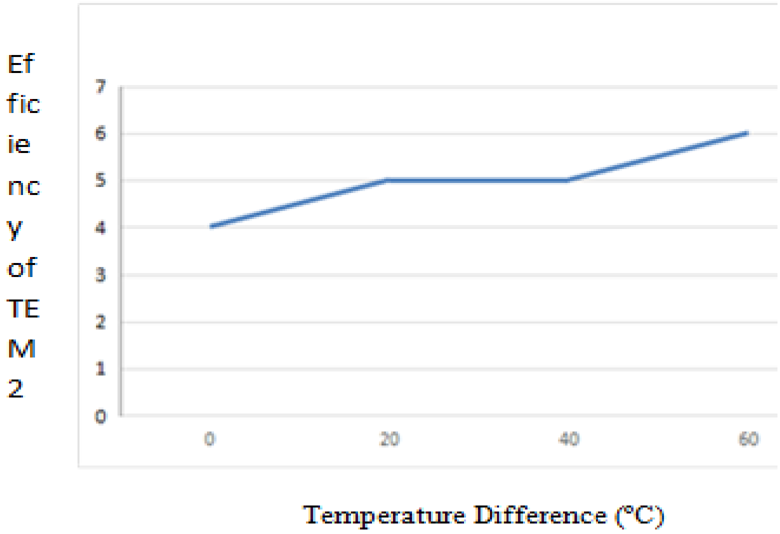
η = 6.847 %

X. RESULTS AND DISCUSSIONS

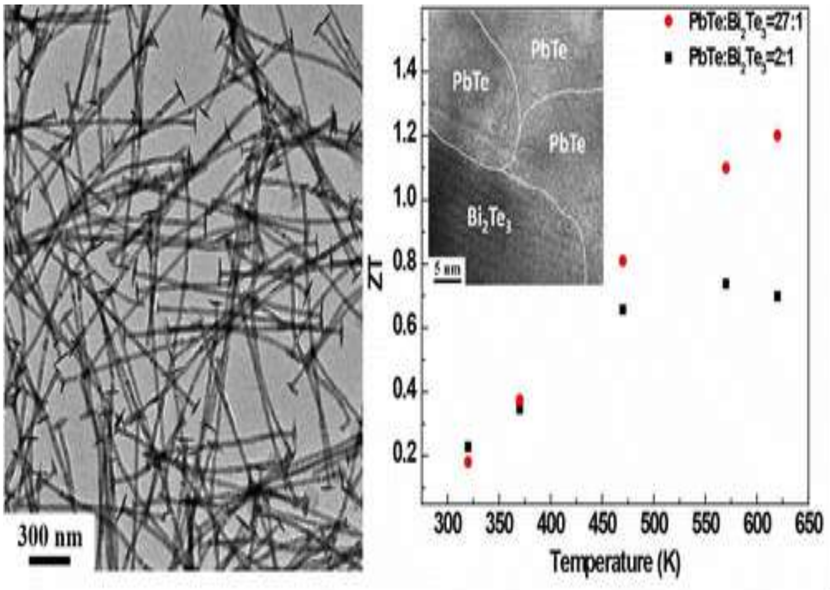
The calculations show the comparison between the thermoelectric module that contains Bi2Te3 and combination of both Bi2Te3 and PbTe alloy semiconductors. The TEM 2 efficiency is 6.847 % and TEM 1 efficiency is 1.785 %. So the calculated efficiency of TEM 2 is more than TEM 1 which shows that the thermoelectric module used in this project is efficient. The following are the results.



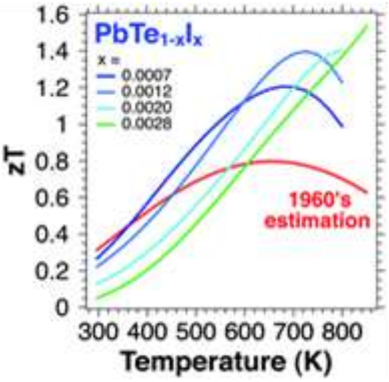
Temperature and Efficiency relation of TEM 1



Temperature and Efficiency relation of TEM 2



Material distribution



Lead Telluride - Figure of merit

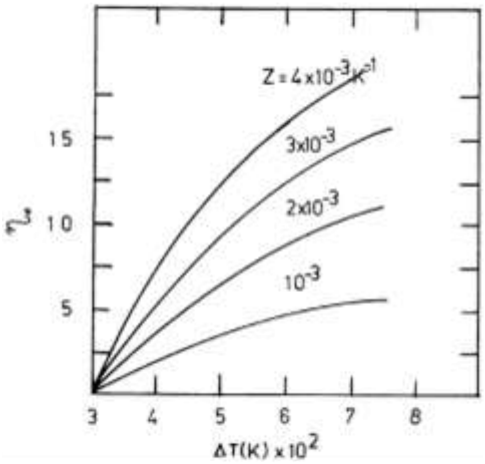


Figure of merit and Efficiency relation

It is found that from the experiment about 73.26% harmful emission is getting reduced and also the fuel consumption is decreased. About 6.487 % of fuel is saved by using thermoelectric generator. From experiment we have got about 20ml of fuel decrement in fuel consumption. From the experiment, it has also been identified that there are large potentials of energy savings through the use of waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat from internal combustion engine and using it for heating or generating mechanical or electrical work. It would also help to recognize the improvement in performance and emissions of the engine if these technologies were adopted by the automotive manufacturers. The study also identified the potentials of the technologies when incorporated with other devices to maximize potential energy efficiency of the vehicles. PbTe based module and segmented Bi_2Te_3 module reaches 6.87% for a ΔT of 50 K and 12.2 % for a ΔT of 90 K respectively, which could be achieved if the electrical and thermal contact between the nanostructured PbTe legs and Cu interconnecting electrodes is further improved.

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