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Enhancement of Efficiency of the Diesel Locomotive using Exhaust Thermal Heat

Sumit Saroha[1], Vineet Singh Bist[2], Pushan Mohanta[3]
[1]Electrical and Electronics Engineering, SRM University, Ghaziabad, India
[2,3]Mechanical Engineering, SRM University, Ghaziabad, India
[1]saroha_sumit0178@yahoo.com, [2]vineetbist1104@gmail.com, [3]pushan12345@gmail.com

***Abstract*—The locomotive industry has been reached in advance stage of research with precise technological development and enhancement. The main aim is to minimize the error in existing technological design in an efficient manner. Therefore, the focus of this paper is to present a modified Thermoelectric Module (TEM) exhaust system for the utilization of the exhaust heat (energy) into electricity of the engine of Locomotive. In the propose approach, Silicon Germanium (SiGe) based TEM has been analyzed on different performance indices such as: generated output voltage and the thermal stability at very high temperature in the range of 500-600^{o}C. It has been observed that the performance of Silicon Germanium (SiGe) have been found satisfactory for the generation of electricity.**

***Index Terms*— Thermoelectric Module, See Back Effect, Locomotive**

I. INTRODUCTION

Earlier, The Diesel Locomotive, which is widely used in the Indian Railways as well as various railways of the world, has been used for many significant decades with many modifications with an aim to improve the efficiency. But, the persistent problem is remains the same that the energy has been wasted in different forms such as: heat energy, sound energy, etc. The exhaust of the V-12 and V-16 engine of the Diesel Locomotive has a range of temperature of about 500-600^{o} C. This thermal heat loss is the one of the prime losses, which decreases the efficiency of the Diesel Locomotive. In order to enhance the efficiency, there is need to minimize the heat wasted in the form of exhaust and utilize that heat in another form of energy like electricity. Many contributions have been made aiming at harnessing the thermal energy of the exhaust.

The utilization of the thermal energy of the locomotive exhaust is use to provide the heat to the boiler of the thermal power cycle for the generation of electricity. The working principle is same as that of a thermal power cycle; only the external heat source is taken as the exhaust to heat the working fluid of the cycle. The mechanism proposed can generate sufficient electricity but the main problem of the system lies in the bulky mechanism of installing boiler and turbine. The system proposed was not feasible for installation point of view because of its cost, heavy equipments and bulky size [1]. Kumar *et.al* [2] has analyzed the performance of thermoelectric generators under different engine operating conditions in which heat exchanger of 18 thermoelectric generator modules has been designed and tested in the engine test rig. The location of TEM has been selected according to the difference of temperature between exhaust side and the engine coolant side.

In order to access the waste heat recovery, the performance of different technological based models has been which combines the waste heat recovery technologies and optimized heat recovery utilization scheme. The scheme not only conserves fuel (fossil fuel) but also has been reduced the amount of heat and greenhouse gases dumped to environment [3]. Filippone *et.al* [4] has presented the use of the high temperature of exhaust gas, which can be used in the thermal power cycle to increase the temperature of the water to change its state to steam, which rotate the turbine and thus electricity has been produced. Therefore, on the behalf of existing literature, in order to utilize the heat of exhaust, Thermoelectric Module (TEM) has been proposed on the basis of Seebeck thermal effect instead of bulky components of the thermal power cycle. The TEM consists of two dissimilar thermoelectric materials joining in their ends: an n-type (negatively charged); and a p-type (positively charged) semiconductors. A direct electric current flow in the circuit takes place when there is a temperature difference between the two materials. The use of thermoelectric module makes the system vital; because it directly converts heat energy into electric potential with reduction of significant conversion losses.

A detailed calculative analysis has been done to measure the electric potential developed due to a range of temperature difference that results in sufficient electricity generation. This electricity generated can be used for the auxiliary electric supply of the coaches or for the batteries of electric starters of the Diesel Locomotive.

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II. EXHAUST TEMPERATURE OF THE DIESEL LOCOMOTIVE

Diesel engine exhaust consists of combustible and non-combustible gases with sufficient heat energy. Its composition may vary with type of fuel utilized or the rate at which consumption take place, or speed of operation of engine. A major part of the heat supplied in an internal combustion engine is not realized as work output; but, dumped into the atmosphere as exhaust heat. If this heat energy is tapped and converted into usable form then, 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 [2]. The detail of a diesel locomotive has been given in Table 1.

Table 1: Exhaust gas temperature of diesel locomotive at various stages

Engine Operating Parameters	Stage-1 (2600FE)	Stage-2 (3100H)	Stage-3	
			3300HP	3600HP
Peak firing Pressure (psi)	1650	1900	1850	1870
Exhaust Gas Temp. (^{0}C)	600	500	509	525
Boost Pressure (bar)	1.2	1.6	2.0	2.2
BMEP (bar)	13.5	14.7	15.7	17.5
Fuel Injection Pressure (bar)	850	950	1010	1040
Engine speed	1000	1050	1050	1050
SFC 8th Notch (gm/bhp-hr)	166	156	154	152

From the above data, it is clear that the exhaust gas temperature of a locomotive falls in the range of 500^o-600^o C. This high temperature exhaust can be used to convert the heat energy lost from the system to generate electricity with the help of TEM.

III. SEEBECK EFFECT AND THERMO EMF

In 1821 Thomas Seebeck, a German physicist discovered that when two dissimilar metal (Seebeck used copper and bismuth) wires are joined at two ends to form a loop; a voltage is developed in the circuit if the two junctions are kept at different temperatures. The pair of metals forming the circuit is called a thermocouple. The effect is due to conversion of thermal energy to electrical energy.

The existence of current in the closed circuit may be confirmed by the deflection of a magnetic needle caused by the magnetic field of the current Joule heating produced in the wires closing the circuit with a capacitor to accumulate measurable charge placing a sensitive ammeter or a galvanometer in the circuit measuring the amount of chemical deposit at the electrodes of an electrochemical cell.

$$\Delta V = S_{AB}\,(T_h - T_c) \qquad (1)$$

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$$\Delta V = S_{AB}\,(T_h - T_c) \qquad (1)$$

Where, S_{AB} is the coefficient of proportionality known as the thermoelectric power or the Seebeck Coefficient. The term thermoelectric power is a misnomer because it does not measure any power and is measured in volt/ K. By convention, Seebeck coefficient's sign is the sign of the potential of the cold end with respect to the hot end. Thus it is positive, conventional current flows from A to B at the hot junction. Seebeck coefficient is not a constant but is dependent on temperature. The temperature dependence of a commercial thermocouple is usually expressed as a polynomial expansion in powers of temperature. For instance, for a thermocouple with Platinum as one of the metals and an alloy of Pt-Rh (90:10), the open circuit voltage is given approximately by the given quadratic equation (2) and the output power of TEM is calculated by (3).

$$V = c + aT + BT^2 \qquad (2)$$

$$dV/dT = a + 2bT \qquad (3)$$

A complete understanding of Seebeck effect requires knowledge of behavior of electron in a metal which is rather complicated. The Seebeck coefficient depends on factors like work functions of the two metals, electron densities of the two components, scattering mechanism within each solid etc. Seebeck effect is a manifestation of the fact that if two points in a conductor (or a semiconductor) are maintained at different temperatures, the charged carriers (electrons or holes) in the hotter region, being more energetic (and, therefore, having higher velocities) will diffuse towards region of lower temperature. The diffusion stops when the electric field generated because of movement of charges has established a strong enough field to stop further movement of charges. For a metal, carriers being negatively charged electrons, the colder end would become negative so that Seebeck coefficient is negative. For a p-type semiconductor on the other hand, holes diffuse towards the lower temperature resulting in a positive Seebeck coefficient.

Performance of a thermocouple is determined by the Seebeck coefficient of the pair of metals forming the thermocouple. As it is impracticable to list the coefficient of all possible pairs, the Seebeck coefficients of metals are usually given with respect to Platinum as standard whose Seebeck coefficient is taken as zero [6].

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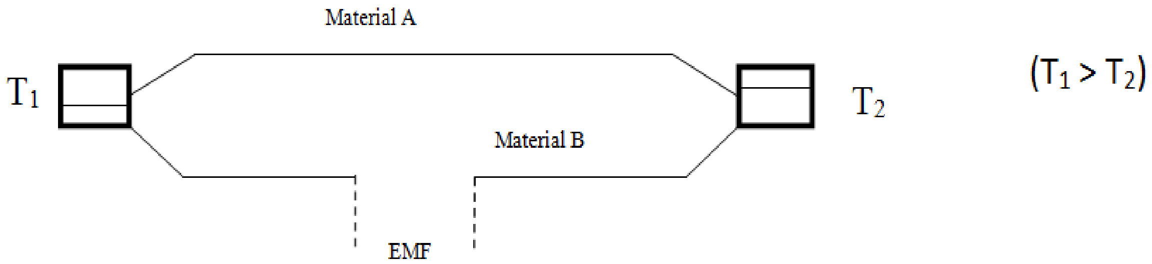

Fig. 1: Thermoelectric Module

IV. THERMOELECTRIC MATERIALS

The ability of thermoelectric material to develop an electric potential with the help of temperature gradient completely depends upon two parameters:

- Temperature gradient
- Seebeck coefficient

The temperature gradient is system dependent and the material used for the TEM is chosen such that it generates maximum possible electric potential with the given temperature gradient by the system. The Seebeck coefficient is a material dependent property and accordingly a suitable material with high Seebeck coefficient has to be selected. The Seebeck coefficiuent of Silicon Germanium and Bismuth-Telluride have been found high; but, Bismuth-Telluride has a low working temperature as compared to that of Silicon Germanium (SiGe). The SiGe has been found to be satisfactory at high working temperature of about 500-600^{o} C and has a high Seebeck coefficient [7-16]. The introduction of SiGe in the thermoelectric field and its further modification and analysis with the time was thus made by many researchers, which contributed to the overall potential of thermoelectric properties of the SiGe material. Theoretical data has been collected from ref. [17] and ref. [18], it is analyzed on thermal stability of the TEM material and the optimal level of potential generation has been achieved for different material at different temperature ranges. The analysis resulted in Silicon-Germanium and Bismuth-Telluride to be satisfactory in generation of optimal voltage generation at different temperature ranges. However, Silicon-Germanium (SiGe) is preferred over Bismuth-Telluride due to high working temperature of over 600^{o}C of the former to that of limitation of temperature of 400^{o}C of the latter [19].

Previous research has been carried out on the properties of p and n-Type $Si_{80}Ge_{20}$ and the material have been found to be useful for Thermoelectric properties. In the 1995th edition of the Thermoelectric Handbook discussed the thermoelectric transport and other physical properties of both n-type and p-type $Si_{80}Ge_{20}$ in detail. In 1921, Vegard proposed that a linear relation exists between the crystal lattice parameter of an alloy and the concentration of its compounds [20] and the further modified work of Vegard has been formulated & slight variation from Vegard's law for SiGe alloys at room temperature given in (4):

$$Si_{1-y}Ge_y = (5.431 + 0.20y + 0.027y^2) \quad (4)$$

The theoretical density of SiGe alloy is composition dependent (5) and its value is 3.00g/cc [21].

$$Si_{1-y}Ge_y(g/cc) = (2.329 + 3.493y - 0.499y^2) \quad (5)$$

The amount of voltage produced due to the temperature difference by the TEM is directly proportional to the Seebeck coefficient. Hence, the Seebeck coefficient plays a vital role in the production of electricity.

V. PROPOSED WORK

The conventional block diagram of diesel locomotive system is shown in Figure 2. The block diagram shows the flow of exhaust gas from the conventional exhaust system of a diesel locomotive. The exhaust gas created from the engine goes to the exhaust duct where there are anti-pollutant filters to reduce the carbon emission rate, from where it is directed to the turbocharger and from it, it is ejected to the atmosphere. The main problem with conventional exhaust system lies with the high wastage of heat energy in the form of exhaust, which considerably decreases the efficiency of the locomotive. The heat energy wastage in the engine of the locomotive is significant and utilization of the heat energy becomes vital to minimize the wastage. Thus, the proposed exhaust system which uses a Thermoelectric Module to utilize the exhaust heat to heat the hot region of the TEM and the cool region being air cooled with the atmosphere. The TEM converts the temperature gradient across its end into the electric potential.

The conventional exhaust system is modified to the proposed TEM exhaust system by adding components in the exhaust duct as shown in Figure 3. The thermoelectric module has been installed in the midway of exhaust pipe, with one of its end in contact with the exhaust gas and other end exposed to the atmosphere. In order to give a continuous discharge, a flow control reservoir have to be connected in series with the

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exhaust pipe before TEM, which will ensure the constant flow of exhaust gas to the TEM and thus providing constant high temperature difference. The side in contact with the exhaust gas had a high temperature. In the Modified TEM Exhaust system, the exhaust gas produced from the engine is directed to the exhaust pipe from where it has been passed to the Flow Control Reservoir. After the Flow Control Reservoir, the high temperature exhaust gas reached to the TEM, with one of its end exposed to the exhaust gas and another one exposed to the atmosphere to provide a colder region relative to the exhaust gas. This in turn generated a potential difference and thus electricity has been generated. The collection of the exhaust pipe, flow control reservoir and the TEM were comprised in the exhaust duct. The exhaust gas which passed from the TEM entered to the Turbocharger and through there it has been expelled to the atmosphere.

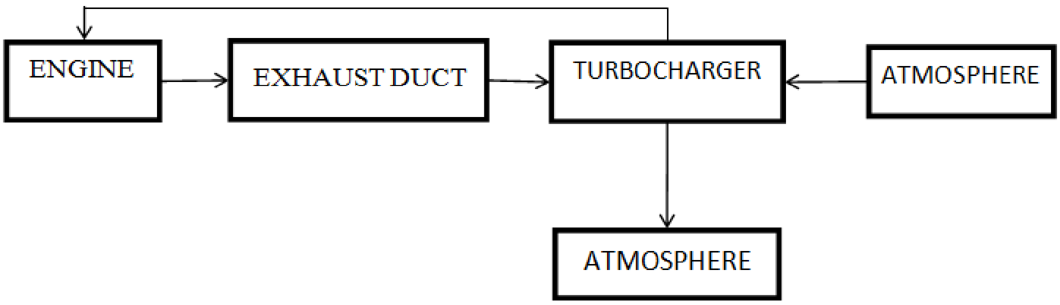

Fig. 2: Block diagram of Conventional Exhaust system of a diesel locomotive

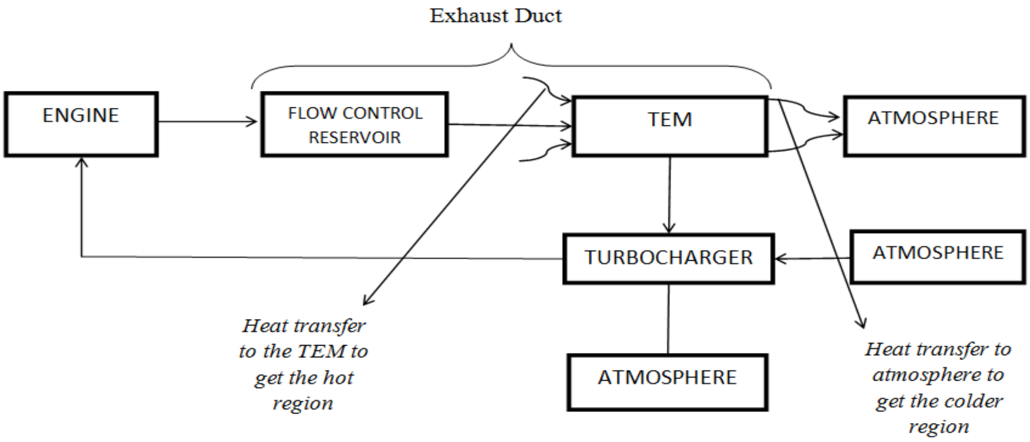

Fig. 3: Block diagram of Modified TEM Exhaust system of the Diesel Locomotive

VI. RESULTS AND CALCULATION

The Exhaust gas from the engine has been passed to the flow control reservoir and through it, a constant temperature difference has been created on the either side of the TEM has been utilized to create a potential difference across the TEM. The potential difference created is directly proportional to the temperature difference across the ends of the TEM. Mathematically,

$$\Delta V \; \alpha \; \Delta T \qquad (6)$$

$$\Delta V = S \, \Delta T \qquad (7)$$

where, S is the constant which is called the Seebeck constant. It depends on the type of material used to make a module of Thermoelectric. The paper proposed the use of SiGe (Silicon-Germanium) material to make a module of TEM as the SiGe is thermally more stable at high temperature and has one of the highest values of the Seebeck constant at high temperature. The Seebeck constant value of SiGe has been considered as [20]:

$$S_{SiGe} = 250 \ \mu V/K$$

For a single module of SiGe TEM, potential difference:

$$\Delta V = S_{SiGe} \, \Delta T \qquad (8)$$

By the data of Table 1, different stages of the exhaust gas temperature has been considered and atmospheric temperature has been taken as 25^0C. The resultant calculations yielded the following data:

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Table 2: Calculation of the SiGe TEM Potential Difference Generation

No. of Modules	Seebeck coefficient of TEM	Potential Generated at temp. 600°C (V)	Potential Generated at temp. 500°C (V)	Potential Generated at temp. 509°C (V)	Potential Generated at temp. 525°C (V)
1	250	0.143	0.118	0.121	0.125
10	250	1.43	1.18	1.21	1.25
100	250	14.3	11.8	12.1	12.5
500	250	71.5	59	60.5	62.5
1000	250	143	118	121	125

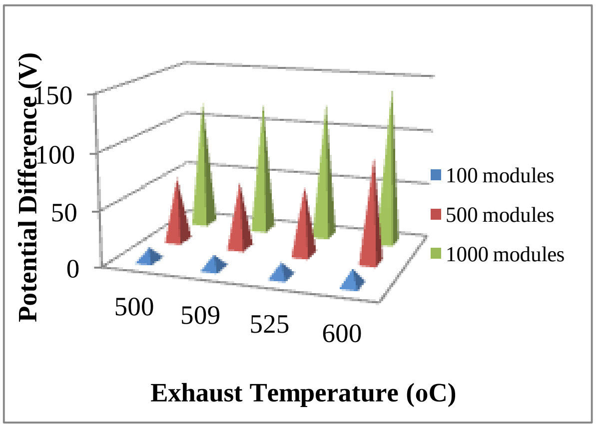

Fig. 5: Potential Difference Generated

As per the Table 2, a single module with the temperature difference of even 500^0 Celsius produced a significant voltage of about 0.118V. Here, the voltage produced has been directly proportional to the number of modules. These modules are of the order of millimeters, thus a number of modules can be installed in series and parallel combination even in any small space. When the number of modules has been increased to 10, 100, 500 & 1000 high voltage has been produced. This voltage thus produced has been used for the auxiliary supply or for charging the batteries of the diesel locomotive. The voltage generated as a result of the temperature difference between the two sides of the TEM can be presented graphically by plotting a graph between the potential differences versus Temperature of the exhaust.

Here, the variation of the voltage generation as per the temperature difference has been plotted for 1 to 4 modules. The graph presented the result of increase in voltage generation with increase in temperature difference. The rate of change in voltage generation with increase in temperature difference increases with the increase in the number of modules of TEM. Thus, a higher number of modules with a sufficiently large temperature difference resulted in higher rate of voltage generation.

In the conventional diesel locomotive which has 16 cylinder engines, the temperature difference as compared to that of in any automobile has been greater and the entire conversion would also depend on the type of the material used in the TEM. The another problem which the TEM faces is the constant maintenance of the temperature difference between the two ends of the module, which has been tackled by the use of a flow control reservoir which has ensured a continuous flow of exhaust to the hot end of the TEM. Moreover in any automobile, the problem of space occupancy, system to vehicle weight ratio and cost efficiency of the system of the TEM is a big concern, but in locomotive we had an advantage of the sufficient space and also the system to locomotive weight ratio of the system is considerably low. Hence, the installation of the proposed analyzed system is practically feasible in a locomotive.

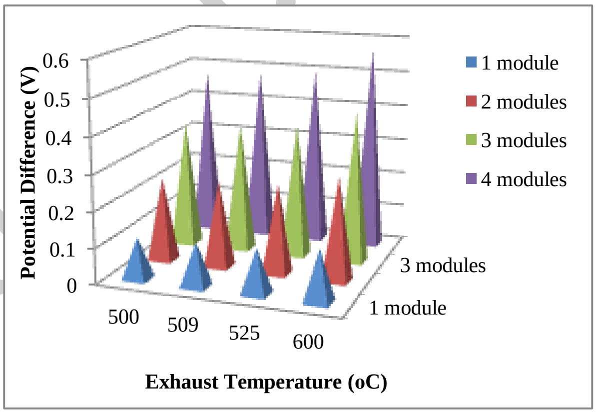

Fig. 6: Potential Difference Generated No. of Modules

VII. CONCLUSION

This paper limelight the utilization of thermal energy of the diesel locos system and tries to use that energy for electricity generation. For that purpose, semiconducting material based thermocouple has been used at different temperature range. This system will reduce the burden of additional cost of battery units and locomotive will have its own generation after the ignition process. The proposed TEM exhaust system will not only improve the efficiency of the engine but will also be very helpful for the eco-friendly use of technology on earth. The detailed calculated analysis of a single module of TEM gives a voltage of about 0.143V at 600° C, 0.118V at 500° C, 0.121V at 509° C and 0.125V at 525° C of exhaust gas, which is significant. This potential difference increases with the increase in the number of modules. Thus, on the behalf of this research, it has been concluded that the TEM module is very helpful for the recovery waste heat into electricity.

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