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Methods Used to Enhance the Conversion Efficiency of Exhaust Based Thermoelectric Generator

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Abstract— ***Majority of the current thermal power generation technologies first convert thermal energy into mechanical energy before producing electricity. Thermoelectric Generation Technology therefore, is one of the budding conversion method, which can directly convert low-grade thermal energy into electrical energy by using thermoelectric compounds (materials). But energy generated by such a system is very low making it difficult for implementation.***

Therefore the focus of this study is to review the basic principle of thermoelectricity and it's process to convert waste heat from exhaust of automobiles into electricity. Furthermore, the study delves into the methods to enhance the conversion efficiency of automotive exhaust thermoelectric generators.

Index Terms—Automotive Exhaust, Direct Energy Conversion, Seebeck Effect, Thermoelectric Generator.

I. INTRODUCTION

Thermoelectric power generation is a budding technology in the field of direct conversion of low-grade energy, such as waste heat energy into electrical energy. The basic working principle of thermoelectric power generation was first discovered by Thomas Johan Seebeck and the principle is termed as Seebeck Effect. TEG (Thermoelectric Generator) has shown ever increasing potential that can be widely used in power generation from automotive exhaust waste heat to industrial waste heat and many more. The advantages of this technology over other technologies are [1]:

- No mechanical parts involved.
- No noise and vibration related problem.
- Simple, compact and safe design.
- Low maintenance.

In spite of these advantages, a major drawback of thermoelectric generator is relatively low conversion efficiency as comparison to other methods that's why this method is overlooked for a large of time [2].

II. BASIC PRINCIPLE

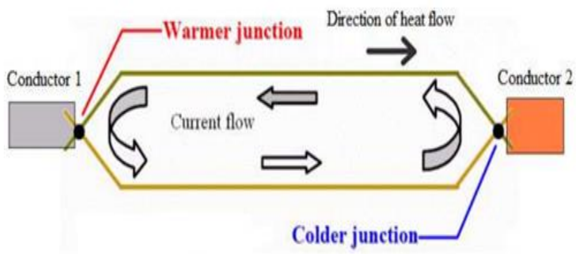


Fig. 1: Schematic diagram showing power generation based on Seebeck Effect

The basic concept of thermoelectric power generation is simply based on the principle of Seebeck Effect. According to Seebeck effect, "If a closed circuit is made up of two dissimilar metals and both the junctions are maintained at different temperature then a voltage is generated between them known as Seebeck Voltage."

On the basis of this effect, TE (Thermoelectric) devices can be used as electrical power generator. The amount of Power generation is directly related to a dimensionless quantity known as Figure of Merit (ZT) and represented as $ZT = \frac{S^2 \sigma T}{k}$, where S is Seebeck coefficient, σ is electrical conductivity, k is thermal conductivity of thermoelectric material and T is mean temperature of material [1].

III. ENERGY CONVERSION PROCESS FROM EXHAUST OF AUTOMOBILE

Thermoelectric module is an integral part of Thermoelectric power generation system made of several pairs of p and n-type legs of thermoelectric materials connected electrically in series and thermally in parallel having two sides as hot side and cold side. The hotter side of module is mounted on the exhaust pipe of an automobile, so that it can extract heat from the exhaust gas by convection.

On the colder side of module heat sink is placed through which coolant flows. The coolant could be air or water and is used to dissipate the rejected heat. The temperature gradient is created due to different temperatures on both sides of module and because of this temperature difference a voltage is induced known as Seebeck voltage. This is the basic working principle of Thermoelectric Generator System [3].

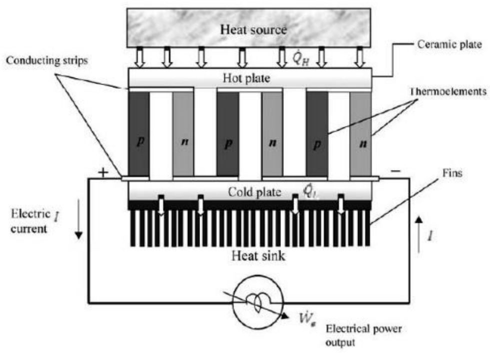


Fig. 2: Schematic diagram of Single – Stage Thermoelectric power generation

On the basis of the temperature gradient created by the system, conversion efficiency of thermoelectric generator is calculated as,

$$\eta_{max} = \left(1 - \frac{T_C}{T_H}\right) \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_H}{T_C}} = \eta_{carnot} \left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_H}{T_C}} \right)$$

Where, T_c is temperature of cold side, T_H is temperature of hotter side and ZT is dimensionless figure of merit. The maximum energy conversion efficiency calculated by above formula is very low (nearly 5-10 %). So there comes the need of enhancing the efficiency of this system to make it feasible.

IV. METHOD TO ENHANCE THE CONVERSION EFFICIENCY

Previous studies showed that the energy generated by Automotive Exhaust Thermoelectric Generator was very low and because of this it cannot be used for further processes. Hence, the enhancement in the conversion efficiency is the most important factor for proper use of generated energy which can be done by number of ways. Some of them are:

- Locating the proper position of TEG on the exhaust pipe of vehicle.
- Thermal optimization of heat exchanger.
- Connecting DC-DC boost converter to the output of Thermoelectric Generator.
- By developing the thermoelectric material with high figure of merit.

The objective of this study is to determine the proper position of TEG and best design of heat exchanger for TEG with the help of thermal optimization.

1. Installation Location of TEG: -

Power Generation of TEG depends on heat generated and it's conversion efficiency. But there is a problem between installation location of TEG, Catalytic Converter (CC) and Muffler (muff). Both TEG and CC need heat for normal working in exhaust system of a vehicle. So the main aim was to find out the perfect location of all these so that the conversion efficiency of TEG is good enough and also CC and Muffler work in proper ways. To find out the solution of this problem ANSYS simulation seemed to be the best option so the ANSYS simulation of this was done.

The proposed installation position of TEG for simulation were:

Case 1: TEG at the end of exhaust system.
Case 2: TEG between CC and Muffler.
Case 3: TEG at left most side of exhaust system [4].

1.1 Geometry: -

3-D geometry of above three cases are designed with the help of ANSYS design modeler. Surface thickness in all cases is 2mm.

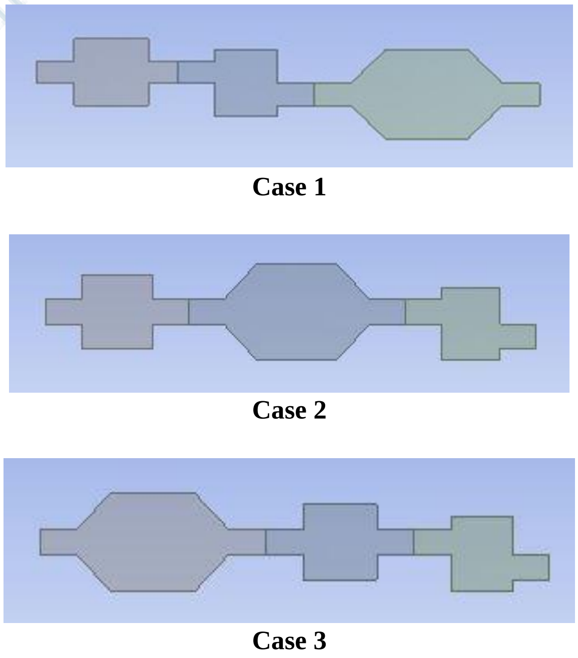


Fig. 3: Structure of Three Cases

1.2 Simulation: -

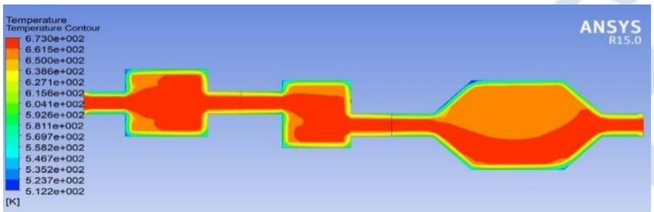
Boundary Condition:

Table I: Boundary Condition for Simulation

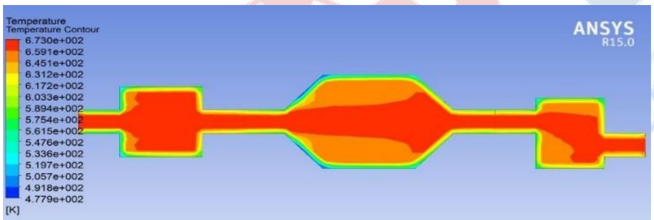
Parameters	Value
Inlet Velocity of Exhaust Gas	20 m/s
Inlet Temperature of Exhaust Gas	673 K
Pressure at Exit Section	P_{atm}
Convective Heat Transfer Coefficient Between Outer Face of Exchanger and Air	20 W/m^2
Convective Heat Transfer Coefficient Between Outer Face of CC and Muffler to Air	16 W/m^2

Thermal Analysis:

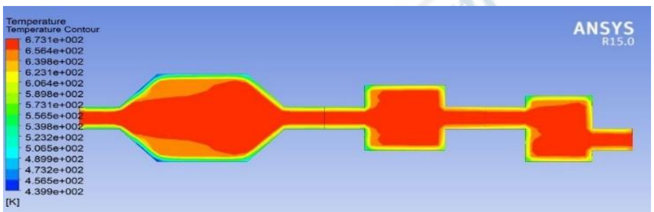
Temperature distribution of exchanger plays a very crucial role in the energy conversion efficiency in addition to that it also develops thermal stress in device and TE module. Development of non-uniform thermal stress between module and exchanger results in the damage of module.



Case 1



Case 2



Case 3

Fig. 4: Result from Fluent Simulation

The Fluent Simulation results of three cases are shown in figure 4. In case 1, the average surface temperature of heat exchanger was found to be 621 K. In case 2 i.e. TEG located between CC and Muffler, the average surface temperature of heat exchanger was 660 K which is uniformly distributed over the surface. In case 3 i.e. TEG located at left end of exhaust system, the surface temperature of heat exchanger was 663 K.

Among all the three cases, in case 3 i.e. TEG at left most side of exhaust system, the average interface temperature is more as compare to other but in this case when TEG is located at starting of exhaust system it decreases the temperature of exhaust gas because of which efficiency of catalytic converter decreases. Hence, Case 2 is most suitable installation location of TEG for proper functioning of all the components of exhaust system.

2. Thermal Optimization of Heat Exchanger: -

Thermal efficiency of heat exchanger mainly depends on 2 factors which are internal geometry and type of material used in construction of heat exchanger. The heat transfer from exhaust gas to surface of module takes place by both convection and conduction. Any internal arrangement which increases the heat transfer area increases the hot side temperature of exchanger.

In this section, three different internal structures of heat exchanger (empty cavity, parallel plate structure and fishbone structure) are simulated with the help of ANSYS Fluent. A diverging-converging shell type heat exchanger was used for the analysis.

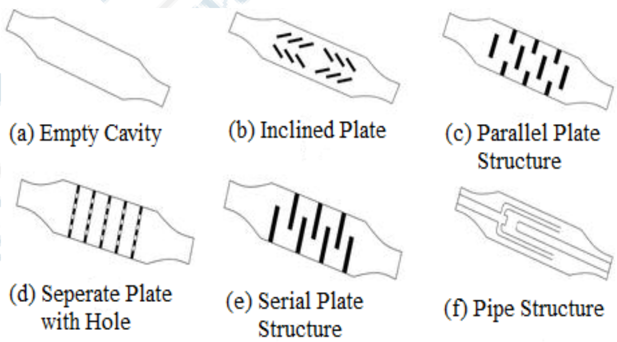


Fig. 5: Different Internal Arrangement for Heat Exchanger [5]

2.1 Thermal Simulation of Heat Exchanger: -

Boundary Condition:

Table II: Boundary Condition for Simulation

Parameters	Values
Model	Viscous Standard, k-Epsilon
Inlet Temperature of Exhaust Gas	720 K
Mass Flow Rate	0.5 kg/s
Pressure at Outlet	Gauge Pressure (0 Pa)
Temperature at Outlet	300 K

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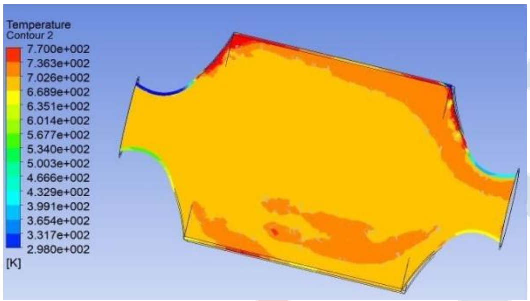
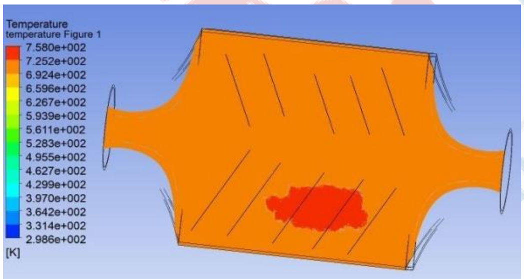
Thermal Analysis:

In order to increase the electricity generation of TEG empty cavity, parallel plate structure and fishbone structure of heat exchanger is simulated with the help of ANSYS fluent and the temperature contour generated by simulation is shown in figure 6.

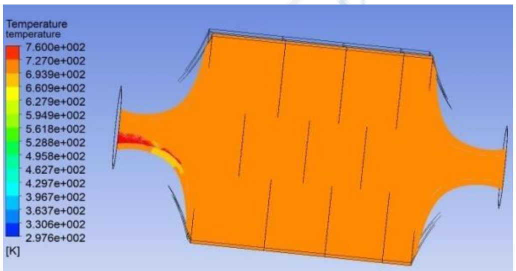
Temperature contour of empty cavity-based heat exchanger indicates that average value of temperature at outer surface of exchanger is around 680 K. For heat exchanger with fishbone structure and parallel plate structure heat transfer area the temperature is more as compare to exchanger with cavity and is around 695 K and 690 K respectively which is higher than of empty cavity exchanger. Hence, if the number of baffle plates increases in the heat exchanger, then the uniformity of temperature distribution would be more at heat exchanger surface which in turn increases the hot side temperature of TEG. So, it could be a better method to increase the heat to electrical conversion efficiency of Thermoelectric Generator System [6].



(a) Temperature Contour of Empty Cavity Structure



(b) Temperature Contour of Fishbone Structure



(c) Temperature Contour of Parallel Plate Structure

Fig. 6: Temperature Contour of Different Arrangements of Heat Exchanger

3. DC-DC Boost Converter: -

DC-DC converters are generally used in power electronics circuit for maintain the voltage supply from the power source to required level of voltage for the target load. Some of them are used to step down the voltage and other are used for step up the induced voltage. The general concept of DC-DC boost converter is related to storage and then release of electrical energy. Boost Converter is one of the DC-DC Converter which is used to step up the induced voltage consisting an inductor, a semiconductor switch diode, a capacitor and a diode.

The ratio by which voltage is converted is known as transfer function and the transfer function for boost converter is given as,

$$T.F. = \frac{1}{1-D}$$

Where, D is the duty cycle for boost converter and it is in the range of 0.45 to 0.6.

In order to increase the voltage level produced by TEG, a boost converter can be used by two methods. First by single stage Topology and other by Multi-Stage topology. Among them multi-stage topology is considered to be more efficient since in multi stage topology, stable power is supplied to target load with high level of induced voltage [7].

4. Effect of Figure of Merit on Conversion Efficiency: -

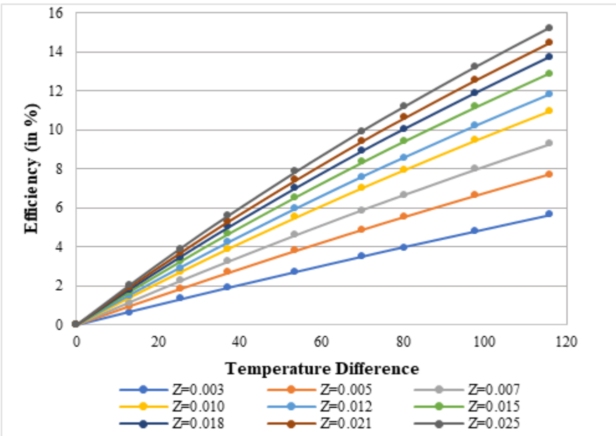


Fig. 7: Conversion Efficiency vs Temperature Difference Curve for Different Value Figure of Merit (Z)

From figure 7 it can be depicted that the conversion efficiency of Thermoelectric Generator greatly depends on figure of merit (Z). Hence as the material with high value of figure of merit is used, high amount of exhaust heat can be converted into useful electrical energy.

V. CONCLUSION

Hence based on above study, the enhancement of conversion efficiency of exhaust based thermoelectric generator can be done by:

1. Installing TEG between catalytic converter and muffler resulting in the maximum possible average surface temperature difference between heat exchanger and efficient working of exhaust's components.
2. Using a Heat Exchanger, internally arrange with a fishbone structure which increases the hot-side temperature of the exchanger.
3. Use of Boost Converter with multi-stage topology which can supply comparatively high stable power to target load.
4. Using thermoelectric material having high value of figure of merit, converting high amount of exhaust heat into electrical energy.

The main advantage of this system is that the consumption of fuel as well as emission will be reduced. As a whole this system is combination of energy conservation as well as environmental security.

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