Design and Analysis of Heat Exchanger for Automotive Exhaust based Thermoelectric Generator [TEG]

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Abstract

In internal combustion engines the thermal efficiency is around 30 %, roughly 30% of the fuel energy is wasted in exhaust gases, and 30% in cooling water and 10% are unaccountable losses. Efforts are made to catch this 30 % energy of exhaust gases. If this waste heat energy is tapped and converted into usable energy, the overall efficiency of an engine can be improved. Thermoelectric modules which are solid state devices that are used to convert thermal energy to electrical energy from a temperature gradient and it work on principle of Seebeck effect. This paper demonstrates the potential of thermoelectric generation. A hot side heat exchanger as well as cold side heat exchanger was designed and analyzed. After certain analytical studies it is found that heat exchanger positioned between catalytic converter and muffler has higher surface temperature. Thermoelectric modules of Bismuth Telluride (Bi2Te3) were selected according to the temperature difference between exhaust gases side (between catalytic converter and muffler) and the engine air conditioner evaporator as cold side. A circular heat exchanger with fins was designed and the thermo electric modules were placed on the heat exchanger for performance analysis. The study showed that energy can be tapped from engine exhaust.

Keywords: Seebeck Effect, Thermoelectric Generator, Heat Exchanger, Thermoelectric Materials and Bismuth Telluride

I. INTRODUCTION

The "Energy Crisis" has become a major challenge in front of engineers across the globe due to rapidly increasing demands and consumption of energy. For almost two hundred years, the main energy resource has been fossil fuel and will continue to supply much of the energy for the next two and half decades. Worldwide oil consumption is expected to rise from 80 million barrels per day in 2003 to 98 million barrels per day in 2015 and then to 118 million barrels per day in 2030.

Most of the worldwide increase in oil demand will come from the transport sector. The transport sector will share 54% of global primary oil consumption in 2030 compared to 47% today and 33% in 1971. The share of oil products in transportation sector of energy consumption will remain almost constant over the projection period (WEO, 2004). In gasoline powered internal combustion engines; around 30% of the fuel energy is wasted in the form of exhaust gases, and 30% in coolant as shown in figure 1.

One potential solution is the usage of the exhaust waste heat of combustion engines. This is possible by the waste heat recovery using thermoelectric generator [1]. A thermoelectric generator converts the temperature gradient into useful voltage that can used for providing power for auxiliary systems such as minor car electronics. As shown in the figure 2, the proposed system consists of one hot side heat exchanger and one cold side heat exchanger [2]. Between the two heat exchangers the thermoelectric modules (TEG) are placed. The exhaust gas from engine passes through hot side heat exchanger and air condition refrigerant passes through cold side heat sink. According to the principle of Seebeck effect, thermoelectric modules convert the heat into useful electricity.

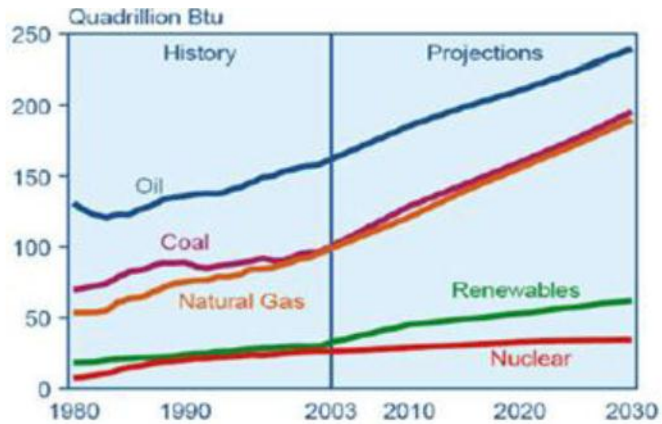

Fig. 1: World Marketed Energy Use by Fuel Type 1980 – 2030, (IEO, 2006)

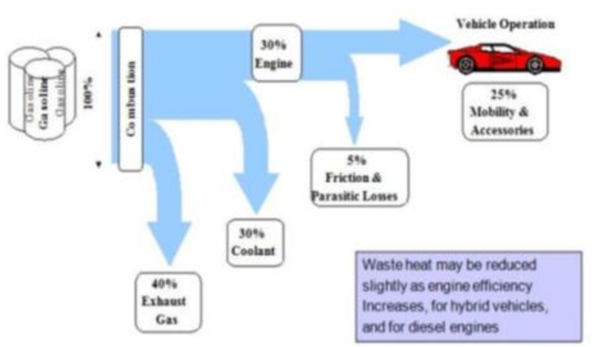

Fig. 2: Thermoelectric Waste Heat Recovery as a Potential Energy Efficiency Option in Ground Vehicles

The driving principle behind thermoelectric generation is the known as the Seebeck effect [3]. Whenever a temperature gradient is applied to a thermoelectric material, specifically metals or semiconductors, the heat passing through is conducted by the same particles that carry charge. The movement of charge produces a voltage. The junctions of the different conductors are kept at different temperatures which cause an open circuit electromotive force (e.m.f) to develop as follows:

$$V = \alpha(T_H - T_C)$$

Where α is the difference in Seebeck coefficient of two leg materials and has the units of V/K, and are the hot and cold side absolute temperatures both measured in Kelvin. A German Physicist, Thomas Johann Seebeck, discovered this effect in the early 1800s

An important unit less constant to evaluate the performance of thermoelectric materials is the thermoelectric figure of merit, ZT. It describes the effectiveness of a specific thermoelectric material in terms of its electrical and thermal material properties.

The figure of merit is expressed as ZT for materials has remained below 1 for decades, but in recent years, ZT of new materials has reached values greater than 2.

II. OBJECTIVES

The main objective of this project is to design and analyse the heat exchangers for Thermo Electric Generator [TEG]. The TEG has two sides' one hot side and cold side. The hot side is selected as the exhaust system and the cold side is selected as automobile air condition evaporator side. The heat exchangers are placed in the hot side and cold side as mentioned above. In this project two modules of thermo electric materials [Bi_2Te_3] are placed in series.

To determine the best installation positions for heat exchangers in exhaust system of automobiles. The power generation of an exhaust TEG (thermoelectric generator) depends on heat energy and thermoelectric conversion efficiency. However, there are compatibility problems among TEG, CC (catalytic converter) and muf (muffler). The present work tried to vary the installation position of TEG and propose three different cases. Case 1: TEG is located at the end of the exhaust system; case 2: TEG is located between CC and muf; case 3: TEG is located upstream of CC and muf.

To theoretically determine voltage developed using TEG. That is by Seebeck effect the voltage produced is given by the equation

$$V = \alpha (T_H - T_C)$$

Where α is the difference in Seebeck coefficient of two leg materials and has the units of V/K, and T_H and T_C are the hot and cold side absolute temperatures both measured in Kelvin.

III. DESIGN

A. Design of Cold Side Heat Exchangers:

The cold side heat exchanger is designed according to the following specifications given below. This design does not develop any back pressure which will distort the air conditioning system.

Outer diameter of pipe, d

- Height of fin, h = 0.25d
- Breadth of fin, b = 0.5d
- Width of fin, w = 0.75xPipe length

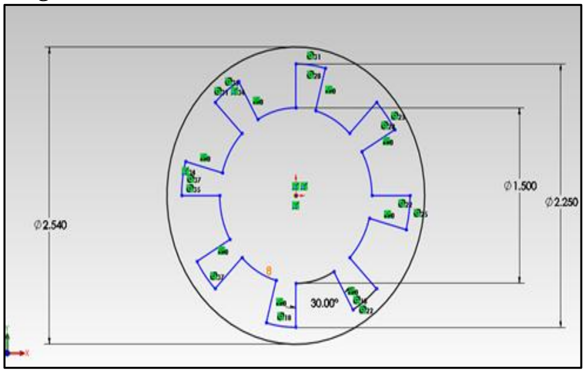

Fig. 3: Design of cold side heat exchanger

The above designed heat exchanger is developed to a 3 Dimensional model by using Solidworks software as shown in figure 4. The figure 4 is designed with 2.54cm diameter which is common size of AC evaporator tube. In figure 4 the design is extruded to 2.54cm. The figure 4 shows the three-dimensional view of the cold heat exchanger developed in Solidworks software.

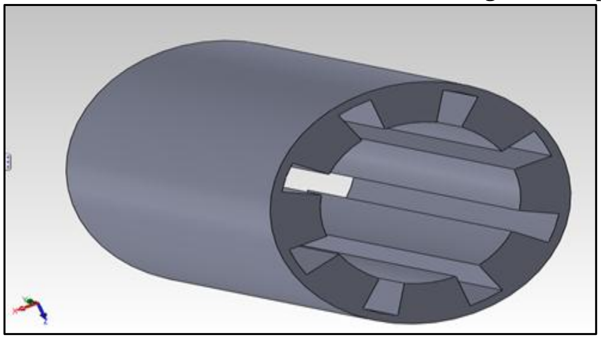

Fig. 4: 3D model of cold side heat exchanger (Extrude 2.54cm)

B. Design of Hot Side Heat Exchanger:

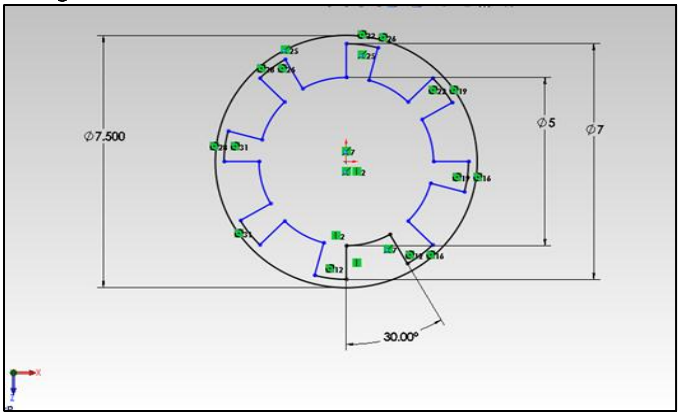

Fig. 5: Design of hot side heat exchanger

The hot side heat exchanger is designed. It is designed as it doesn't distort the flow of exhaust gas. This design does not develop any back pressure which will distort the exhaust system.

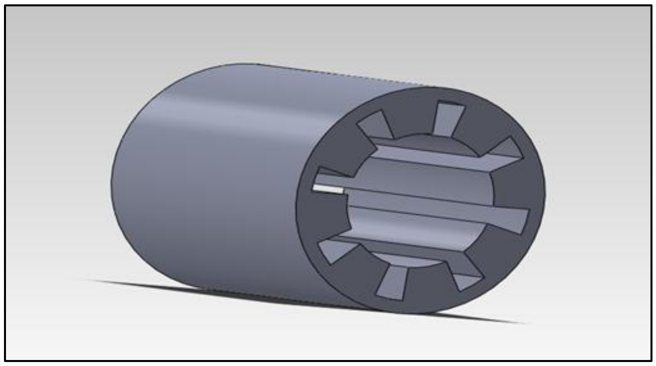

Fig. 6: 3D model of hot side heat exchanger (Extrude 10cm)

The above designed heat exchanger is developed to a 3 Dimensional model by using Solid works software as shown in figure 6. The figure 5 is designed with 7.5cm diameter which is common size of AC evaporator tube. In figure 6 the design is extruded to 10cm.

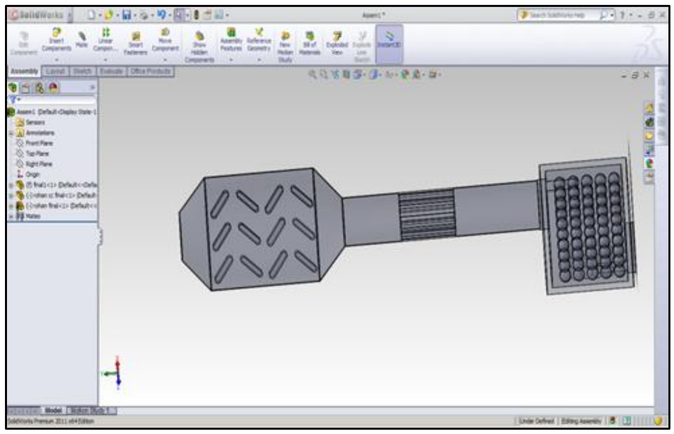

Fig. 7: Heat exchanger installed between catalytic converter and muffler

The figure 7 shows the installation position of heat exchanger in exhaust system. It was found out that the heat exchanger placed between catalytic converter and muffler has high temperature gradient in exhaust system.

The heat exchanger is placed between the catalytic converter and muffler because if it was placed after the muffler effective temperature would not be obtained as when the exhaust gases passes through muffler it expands and temperature gets decreased. Thus effective temperature would not be obtained. If it was placed before the catalytic converter the velocity of exhaust gas is very high that heat transfer does not take place effectively. Hence it was observed that the best position to place the heat exchanger was between catalytic converter and muffler, because at this point the velocity is less and also more heat transfer takes place. Even if back pressure occurs the exhaust gases enters only the catalytic converter which creates no harmful effects.

IV. ANALYSIS

The analyses of heat exchangers are done on Ansys software. Ansys is numerical analysis software. The boundary conditions of heat exchangers placed in exhaust system [between catalytic converter and muffler] which is the hot side and the heat exchanger on evaporator of air condition as cold side are shown in tables 5.1 and 5.2.

A. Cold Side Heat Exchanger:

The boundary conditions of cold side heat exchanger placed in evaporator of air condition system are given in table 1. The temperature of AC ranges from 0 ºC to -4ºC.Thus we take -4 ºC is taken. Velocity is considered as 0.02m/s. The analysis done with the given boundary conditions and is meshed to finite element size. The governing equations are continuity equation, energy equation, momentum equation and k-ε equation as the flow is turbulent.

Table 1
Boundary Condition of cold side heat exchanger

TEMPERATURE [K]	*VELOCITY [m/s]*
269	*.02*

In Ansys software the outlet boundary condition is opening option and the interface is coupled wall.

B. Hot Side Heat Exchanger:

The boundary conditions of cold side heat exchanger placed in exhaust system [between catalytic converter and muffler] are given in table 2. The temperature of AC ranges from 400 ºC -1100ºC.Thus we take 600K , 750 K, 900K and 1200K is taken. Velocity is considered as 10m/s. In an automobile exhaust the velocity of exhaust gases ranges from 8-20m/s. Hence we use 10m/s as a moderate value .The analysis done with the given boundary conditions and are meshed to finite element size. The governing equations are continuity equation, energy equation, momentum equation and k-ε equation as the flow is turbulent
Calculations are done to find the flow is laminar or turbulent flow. It can be done using Reynolds number. The boundary conditions are taken as for 600K.For 600K the density, Coefficient of viscosity are taken then calculations are done..In Ansys software the outlet boundary condition is given opening option and the interface coupled wall.

Table – 2
Boundary Condition of hot side heat exchanger

Sl.No:	*TEMPERATURE [K]*	*VELOCITY [m/s]*
1	*650*	*10*
2	*750*	*10*
3	*900*	*10*
4	*1200*	*10*

1) Calculation:

$$Re = \frac{\rho V D}{\mu}$$

Where Re – Reynolds number
- V- Velocity of flow
- D- Diameter of pipe
- ρ – Density
- μ - Coefficient of viscosity
- At 600K:
- $\rho = 0.5905 kg/m^3$
- $V = 10 m/s$
- $D = 0.05 m$
- $\mu = 0.00003054 Ns/m^2$

$$Re = \frac{\rho V D}{\mu} = \frac{0.5905 * 10 * 0.05}{0.00003054} = 9667.64 > 4000$$

(Since Reynolds number is greater than 4000 the flow is Turbulent)
Thus k-epsilon equation is used.

C. Analysis of Cold Side Heat Exchanger:

Heat exchanger placed in the ac evaporator. A portion of evaporator is removed and the heat exchanger is placed. The boundary conditions are applied and governing equations were given. Analysis is done and the results are obtained.

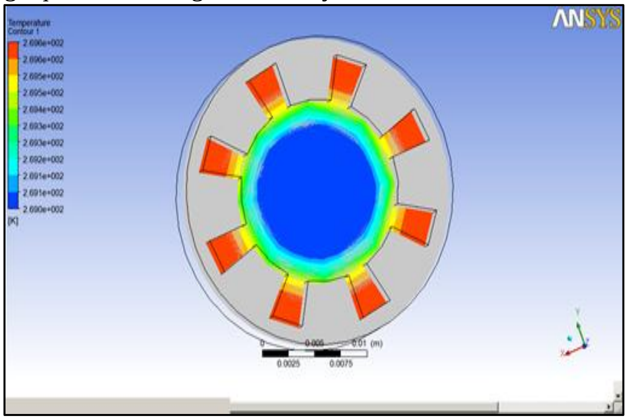

Fig. 8: Analysis of cold side heat exchanger

The figure 8 shows the analysed cold side heat exchanger. When 269K and velocity 0.02m/s boundary condition were given almost 269K was obtained on the surface of heat exchanger. This temperature obtained at surface was conducted to the cold side of TEG with the help of suitable conducting materials. The temperature obtained from cold side heat exchanger will not sustain for long, so the temperature should make use of quickly. Hence the TEG module was placed near to cold side, in an appropriate place between catalytic converter and muffler.

D. Analysis of Hot Side Heat Exchanger:

Heat exchanger is placed in the exhaust system .A portion is removed and heat exchanger is placed. Analysis is done and the results are obtained. The heat exchanger installation position is between the catalytic converter and muffler.

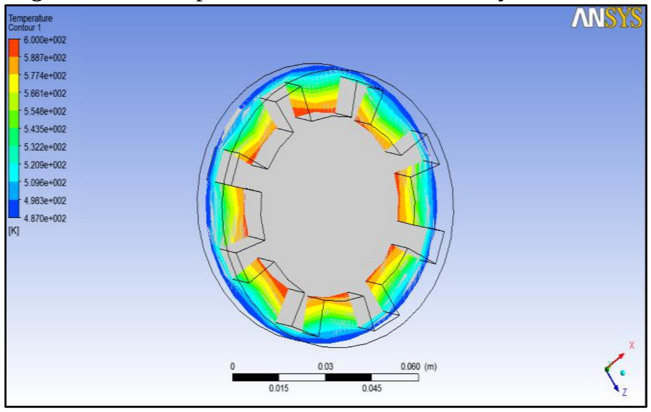

Fig. 9: Analysis of hot side heat exchanger at 600K

The figure 9 shows the analyzed cold side heat exchanger. When 600K and velocity 10m/s boundary condition were given almost 487K was obtained on the surface of heat exchanger

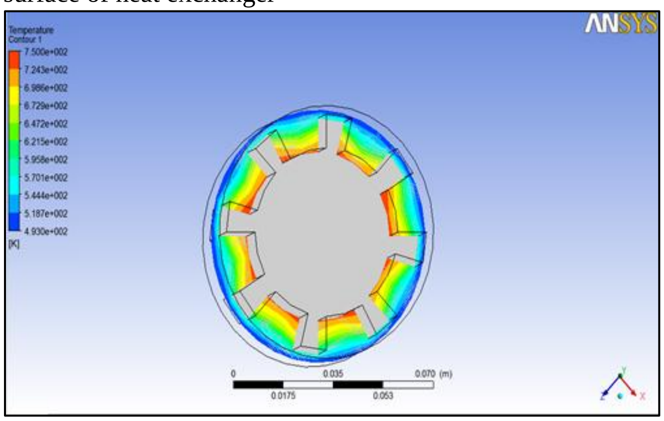

Fig. 10: Analysis of hot side heat exchanger at 750K

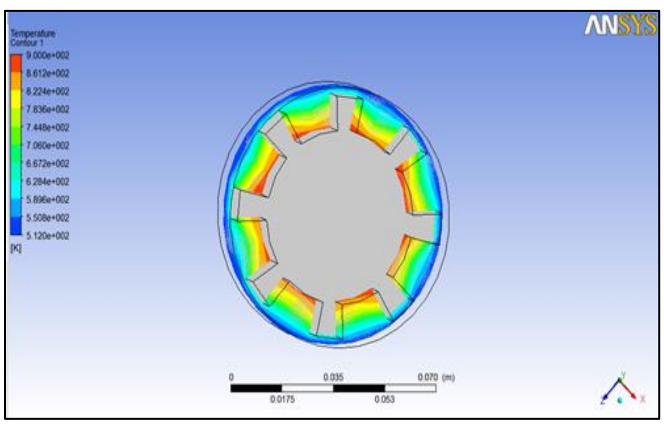

Fig. 11: Analysis of hot side heat exchanger at 900K

The figure 10 shows the analyzed cold side heat exchanger. When 750K and velocity 10m/s boundary condition were given almost 493K was obtained on the surface of heat exchanger.

The figure 11 shows the analyzed cold side heat exchanger. When 900K and velocity 10m/s boundary condition were given almost 512K was obtained on the Surface of heat exchanger.

The figure 12 shows the analysed cold side heat exchanger. When 1200K and velocity 10m/s boundary condition were given almost 642K was obtained on the surface of heat exchanger

The figure 13 shows the analysis of heat exchanger installed between the catalytic converter and muffler. From [1] we studied that heat exchanger placed between catalytic converter and muffler has the maximum heat transfer. Thus maximum temperature difference is obtained at this position. In this case a boundary condition of 750K temperature and 10m/s velocity and we obtained a temperature of 587K at the surface of heat exchanger.

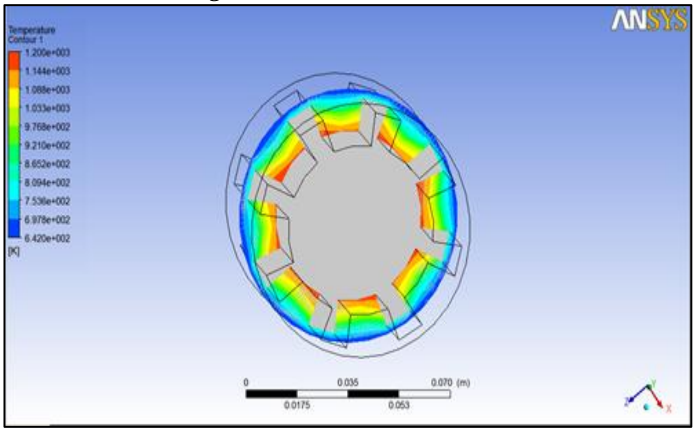

Fig. 12: Analysis of hot side heat exchanger at 1200K

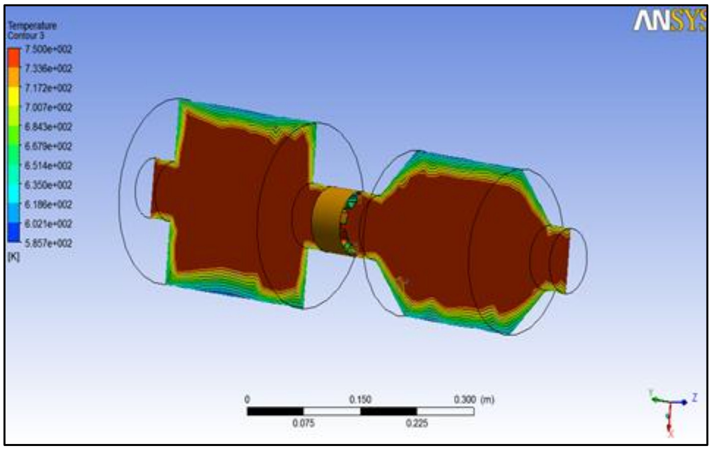

Fig. 13: Analysis of heat exchanger placed between catalytic converter and muffler

V. RESULTS

The results obtained from the analysis were tabulated in the table 3 and 4. The table 3 shows boundary condition temperature with obtained surface temperature.

The table 4 shows the temperature difference and voltage obtained by using Seebeck equation. As temperature increases voltage obtained also increases.

From table 4 a graph plotting voltage and temperature difference as shown in figure 6.1 which provide us the results. As from table we can see that the voltage obtained is very low. But future studies are done to improve this voltage obtained. In this analysis the thermo electric modules of two bismuth telluride are placed parallel. Hence the voltage obtained doubles.

Table – 3:
Temperature obtained from analysis

Set No:	*Temperature (K)*	*Hot Side Temperature T_h (K)*	*Cold Side Temperature T_c (K)*	*Voltage (V) $V=\alpha(T_h-T_c)$*
1	*600*	*487*	*269*	*0.189*
2	*750*	*493*	*269*	*0.275*
3	*900*	*512*	*269*	*0.361*
4	*1200*	*642*	*269*	*0.534*

Table – 4:
Output Voltage Obtained

Set No:	*TEMPERATURE (K)*	*MAXIMUM HOT SIDE TEMPERATURE (K)*	*SURFACE TEMPERATURE (K)*
1	*600*	*600*	*487*
2	*750*	*750*	*493*
3	*900*	*900*	*512*
4	*1200*	*1200*	*642*

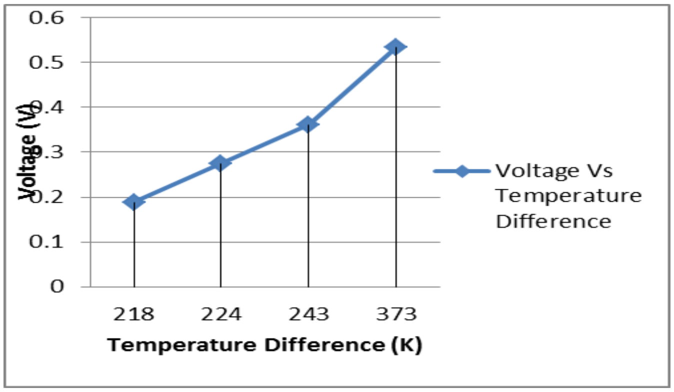

Fig. 14: Voltage Vs Temperature difference

From the figure 14 Voltage vs Temperature difference we can infer that voltage increases as temperature difference increase. That is voltage is proportional to temperature difference. Hence if we obtain more temperature more voltage can be produced.

VI. Conclusions

An Automobile Exhaust Thermoelectric System was designed and analyzed for the waste heat recovery of an automobile engine. The hot side is exhaust system and cold side as AC evaporator. The cold side heat exchanger analysis was done at a temperature of 269K. The hot side heat exchanger was analyzed at temperatures 600K, 750K, 900K, and 1200K. The temperature of heat exchanger surface was obtained and was tabulated. The voltage produced by the TEG was calculated from the temperature difference obtained from hot and cold side heat exchanger analysis. A voltage against temperature difference graph was plotted. It was found that the voltage increase as temperature difference increases. But a limitation is that Bi_2Te3 becomes distorted after 900ºC. That is after 900 ºC tellurium vaporizes at this temperature.

As temperature increases voltage produced also increased as voltage is proportional to the temperature difference. It is also analyzed that heat exchanger installed between catalytic converter and muffler obtained more uniform flow distribution, higher surface temperature and lower back pressure than in other cases.

In this work, the heat exchanger attached with the TEGs for recovering waste heat from an automotive exhaust pipe is analyzed. According to the agreement between the infrared experimental results and the CFD simulation results, an aluminium fin type heat exchanger is selected to form the hot side. It can reduce the thermal resistance and obtain a relatively high surface temperature and uniform temperature distribution to improve the efficiency of the TEG.

The current study focuses on the structural optimization of the heat exchanger and the coolant system to improve the efficiency of the vehicular exhaust gas heat. In the later study the way of the simulation modeling and the infrared experimental verification that has been introduced in this article needs to be combined with the heat transfer theory, to make further structural design and optimization to improve the overall exhaust heat utilization. The main advantage of using TEG is that it does not have a any moving parts.

More power could also be extracted by improving the exhaust gas heat exchanger. However with the current design the hot junction temperatures at or above 250oC were allowed for the given material of TEG (Bi-Te) and results were obtained. Results show that voltage, current, power developed and efficiency of the system increase with the increase in engine speed. Hence the AETEG system traps the waste heat of exhaust gases from engine & generates useful power which can be used to charge the car battery, to power auxiliary systems and minor car electronics. As AETEG reduces the wastage of energy, it improves the overall efficiency of vehicle. TEG system can be profitable in the automobile industry

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References

[1] Prathamesh Ramade, Prathamesh Patil, Prof. Santosh Trimbake , "Automobile Exhaust Thermo-Electric Generator Design and Performance Analysis", Case Studies In Thermal Engineering, Vol. 4 , 2014, pp. 682-691.
[2] X. Liu, Y.D. Deng, S. Chen, W.S. Wang, Y. Xu, C.Q. Su , "A case study on compatibility of automotive exhaust thermoelectric generation system, catalytic converter and muffler ", Case Studies In Thermal Engineering, Vol. 2 ,2014 ,pp. 62-66.
[3] C.Q. Sun, W.S. Wang, X. Liu, Y.D. Deng ,"Simulation and experimental study on thermal optimization of the heat exchanger for automotive exhaust-based thermoelectric generators ", International Journal of Emerging Technology and Advanced Engineering, Vol. 8, 2014 ,pp. 85-91.

