Performance Evaluation of Automotive Exhaust Gas Waste-Heat Recovery module using Thermo-electric Generator

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Abstract

The research is based on data analysis into the configuration of a thermoelectric generator device that can be installed on the IC engine exhaust tube, i.e., to collect the volume of waste heat from the exhaust by producing temperature difference in the generator using the concept of thermoelectric conversion. The arrangement of staggered fins was applied to both the heat sink and the heat absorber. The staggered pin-fin is inserted into the duct to form the heat absorber since the duct is mounted at the engine's exhaust so that heat flows into the heat absorber continuously. By increasing thermoelectric conversion, the staggered fins on the heat absorber may increase the heat-exchange surface area. In order to analyse the relationship between available power and projected power output, empirical results are obtained.

Keywords: Thermoelectric, Exhaust, Convective heat transfer coefficient, Waste Heat Recovery

1. INTRODUCTION

A thermoelectric generator a system that produces electricity by heat, it also operates on squander fuel, a transition in a thermoelectric generator occurred directly heat into electricity. For most power stations, a thermoelectric generator generates a few discernible points of concern. The working conditions behind the thermoelectric generator are a "see beck effect" which is described as "whenever there is a difference in temperature between the two junctions in a loop, consisting of two different conductors, the loop produces thermal electromotive force." As a thermoelectric generator, such a loop is known. Olle et al. [1] system setup uses Open circuit data with Joules, Peltier and Thomson heating showed resultant heat flow through the setup. Jianlin Yu et al. [2] conducted experiment on counter fluid flow of hot and cold regimes with thermoelectric generator to find the models power output using Nusselt and Reynolds number at specific location for summing up throughout the model. Shengqiang Bai [3] observed and found that series type of structure is effective as compared to others. Power output and pressure drop relation suggested that if engine fails due to pressure drop by-pass mechanism need to be implemented. Andrea et al. [4] simulation of power generation considering the Peltier effect and comeup with the relation to compute the efficiency for different thermoelectric materials. Senol Baskaya et al. [5] in their experimental and numerical study on condensing combi boiler and suggested that there are possibilities to get much more temperature difference to produce maximum amount of power at max load condition. Chi Lu et al. [6] in his study concluded that the highly porous metal foam gave drastic decrease in pressure drop and helped in knowing that less porous foams are best in satisfying the net output power. Ki. Hyun Kim et al. [7] study of automotive exhaust thermoelectric generator of gas showed that the flow has decrease in pressure drop. M.A. Karri et al. [8] this case studies comparing about the fuel savings for stationary compressed natural gas engine and sports utility vehicle. Cheng-Ting Hsu et al. [9] waste heat recovery from low temperature using block to distribute the streams evenly. Ryosuke O. Suzuki et al [10] numerically analyses for six systems of cylindrical multi tube to increase the max power output were done. Young Kim et al. [11] direct contact thermoelectric generator is experimentally tested for diesel engine. And based on the Conversion efficiency of generator, they showed increase of 0.25% with 10 K decrease in the coolant range. Yadav et al. [12] TEG on flexible fibber substrate is intended and demonstrated. Mins et al. [13] created a novel tube-shape thermoelectric module for the generation of electricity and showed an increase in power generation in comparison to conventional type thermoelectric design. Jang et al. [14] paper investigates the three-dimensional turbulent flow in a chimney and concluded that keeping some downstream part of heat exchanger uncovered by thermoelectric generator the efficiency of the system increased. Downstream TEGs reduce the temperature difference across the upstream TEG. Jeng et al. [15] investigation of an actual four-stroke single cylinder and concluded that power 2.5W generated at a speed of the engine is 5400 rpm. Thermoelectric modules are used in utilizing the waste heat available at exhaust.

Therefore, for approximation, a compact architecture based on a staggered pin-fin structure with a thermoelectric generator module was proposed. According to the suggested module, the analysis deals with the association of findings that can be planned more efficiently with low costs for experimental progression. The main objective of the analysis is therefore focused on empirical and mathematical studies which focused on Voltage Generation versus Temperature Difference across the absorber and sink followed by comparison of actual and available Power output with variation in temperature difference of the absorber as well as sink

2. RESEARCH METHODOLOGY:

Module Specifications: The device is built in the CATIA V5 parts design workbench. Geometry is divided to make the analysis simple with less time consumption. The device is created with the heat absorber and heat sink section consisting of pin-fin arrangement considering all internal assembly with the housing. Further number of fins modeled for the heat absorber sections are 82. Similarly, total number of fins at heat sink is 82.

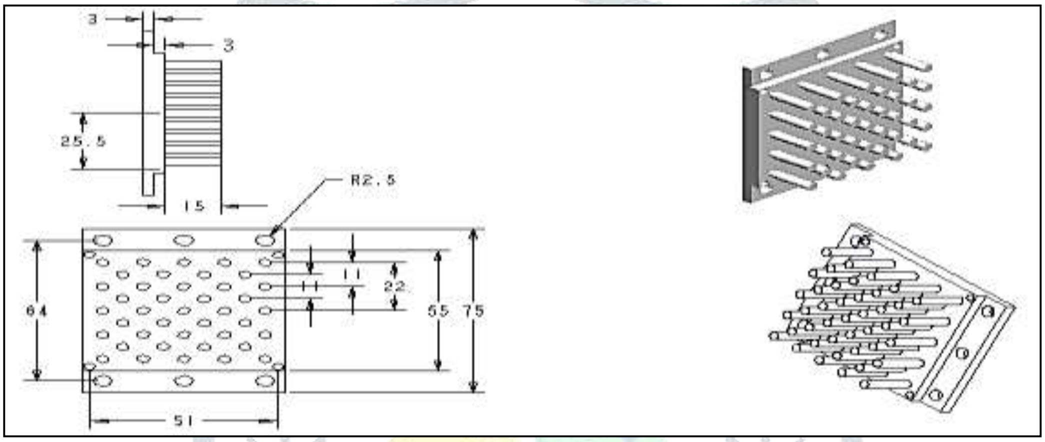

Fig 1. Staggered Arrangement of Pin-Fin Absorber

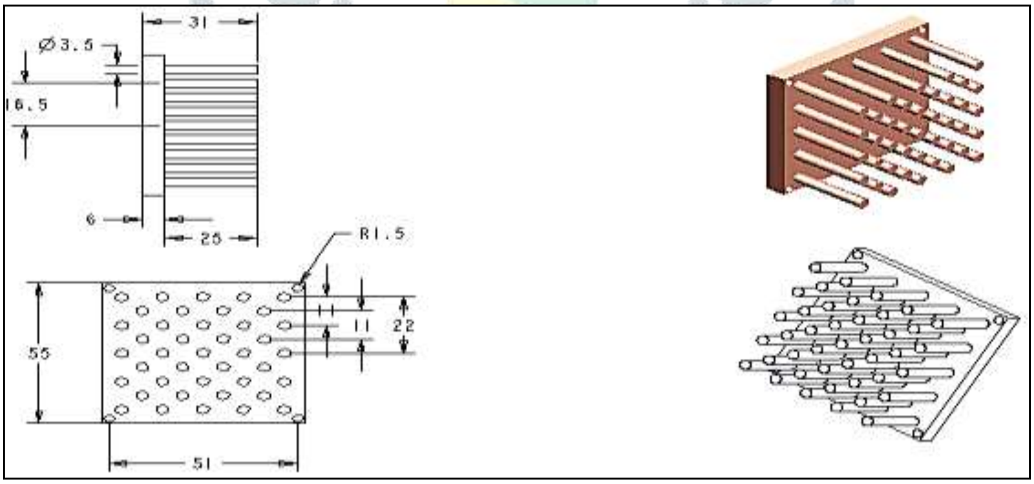

Fig 2. Staggered Arrangement of Heat Sink

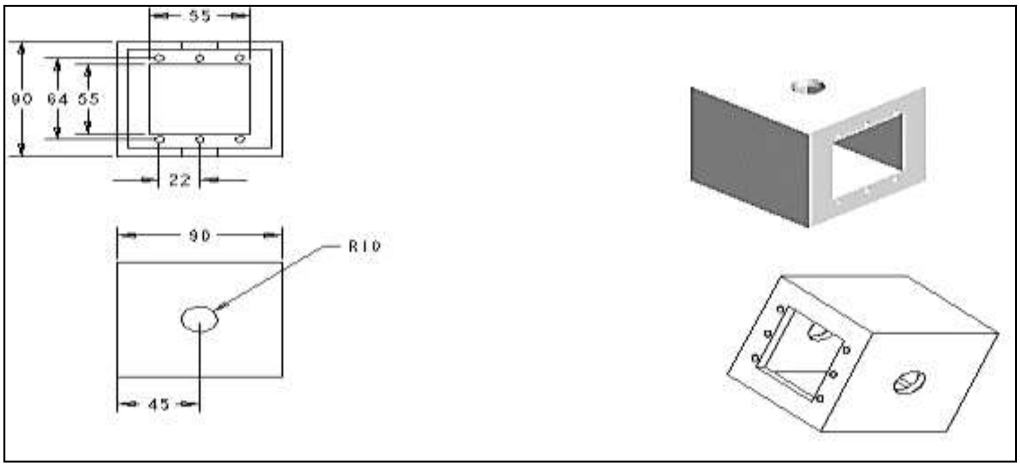

Fig 3. Main duct of thermoelectric conversion device

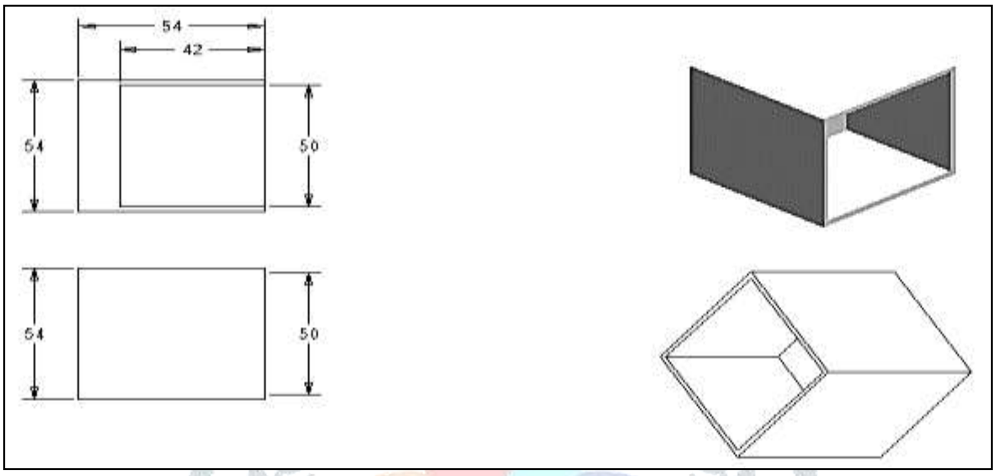

Fig 4. Central Baffle Inside the TEG Device

Boundary conditions are used according to the need of the experimental setup. The inlet and outlet conditions are defined as velocity inlet and pressure outlet. No slip condition is considered at walls. The analysis ran for tabulated inlet conditions. Assuming that setup is testing at stationary position so convective heat transfer coefficient for air is calculated at 1m/s. This coefficient used in simulation to find the heat dissipation from the heat sink to the atmosphere. Engine considered for the simulation parameters is of 120 cc / 500 series and have below parameters

Table 1. Engine Data

Sl. No.	**Maximum rpm**	**Bore dia** (m)	**Stroke length** (m)	**Inlet dia.of device** (m)
1.	3600	0.062	0.042	0.016

While engine running at maximum rpm there are 3600 rotations per minute for the crankshaft. Therefore, piston completes 7200 strokes per minute.

Velocity of exhaust leaving the cylinder

$$V_e = 0.042\, m \times (7200/60)\, strokes/s$$
$$V_e = 5.04\, m/s$$

Applying continuity to find out the velocity at inlet of the module

$$A_b V_e = A_d V_i \qquad (1)$$

Where A_b is bore area and A_d is the device inlet area and their values are

$$A_b = 3.019 \times 10^{-3} m^2$$

$$A_d = 2.011 \times 10^{-4} m^2$$

Hence, value of maximum velocity (V_i) is 75.66 m/s which is used as a limiting parameter to assign the inlet boundary conditions for the setup of numerical analysis.

2.1 *Analytical Investigation*

The main purpose of doing the analytical study is to calculate the heat utilized which will be found by including the numerical data. Assuming heated air as our working fluid properties of air are taken into consideration for the purpose of calculation.

Voltage and power extracted at junctions

$$E = I \times R \quad (2)$$

$$I = \frac{\alpha \times \Delta T}{R} \quad (3)$$

$$P = V \times I \quad (4)$$

where P is power in watt

I is current in amperes

- ***Convective heat transfer coefficient for air***

The convective heat transfer coefficient for **air** flow can be approximated to

$$h_c = 10.45 - v + 10\sqrt{v} \quad (5)$$

where v is relative speed between object surface and air (m/s)

To accomplish the purpose of analytical study, sections near thermoelectric generator are considered. The heat flow is assumed to be in transverse direction only. As the values of temperature throughout the thermoelectric module is analysed using simulation. To calculate the current produced for the open circuit, material electrical resistance and thermal conductance of thermoelectric generator are found using the formula and are tabulated below with few other parameters.

Table 2. Bi_2Te_3 Semiconductor Properties

Sr.No.	Thermal conductivity Z_s (W/mK)	Electrical resistivity r_s (Ωm)
1.	1.5	1.0×10^{-5}

Table 3. Combined Conductance and Electrical Resistance for Single Pair

Sr.No.	Combined Conductance k_s (W/K)	Electrical resistance R_s (Ω)	Seebeck coefficient α_s (V/K)
1.	5.013×10^{-3}	2.992×10^{-3}	2.2×10^{-4}

Table 4. Combined Conductance and Electric resistance for TEG

Sr.No.	Combined Conductance k_W (W/K)	Electrical resistance R_W (Ω)	Seebeck coefficient $\alpha_W (V/K)$
1.	0.6316	0.377	0.02772

To calculate the power production using the data acquired from simulation results, planes near the source and sink fins are made. Thereafter average of these distributive temperature values is tabulated and applied for the calculation purpose as follow

Table 5. Temperature data with respective inlet conditions

Sr.No.	Velocity V_i (m/s)	Source temp. T_{source} (K)	Sink temp. T_{sink} (K)	Temp. difference $\Delta T(K)$
1.	50	453	443	10
2.	57	513	499	14
3.	66	581	562	19
4.	74	653	628	25

Temperature difference values from the above tabulation are further utilized in the above equations (2), (3), (4) to determine voltage, current and power for single thermoelectric generator.

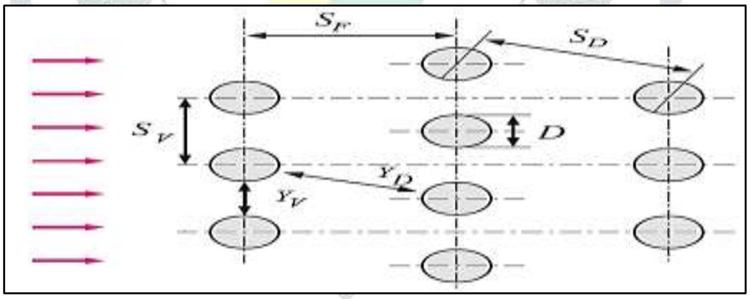

Fig 5. Staggered Fins Arrangement

Table 6. Voltage, Current and Power output for TEGs

Sr. No.	Temp. difference ΔT (K)	Voltage E (V)	Current I (A)	Power output P (W)
1.	10	0.5544	0.7253	0.4021
2.	14	0.7762	1.029	0.7987
3.	19	1.0534	1.397	1.4516
4.	25	1.386	1.805	2.5

2.2) Theoretical power available to thermoelectric generator

2.2.1. Fins study: Staggered fins

- **Case 1** If $Y_T < 2Y_D$,

$$V_{max} = \frac{S_V \times V_U}{S_V - D} \tag{6}$$

Where, l is length
S_V is transverse pitch
S_F is longitudinal pitch
D is the diameter of fin

- **Case 2** If $2Y_D < Y_V$,

$$V_{max} = \frac{S_V \times V_U}{2 \times (S_D - D)} \tag{7}$$

Fins used in thermoelectric module satisfy with the second case, therefore the velocity ahead of the fins is gathered from the simulation and maximum velocity through the fins is calculated. Following is the data tabulation of the 41 fins placed on 54×54 mm cross sectional area.

Table 7. Y_D, Y_T, S_V and S_D values with fins of 3mm diameter

Sr.No.	Y_D (m)	Y_T (m)	S_V (m)	S_D (m)
1.	3.759×10^{-3}	8×10^{-3}	11×10^{-3}	6.759×10^{-3}

Table 8. Maximum velocity with respective velocity ahead of fins

Sr.No.	Upstream velocity V_U (m/s)	Maximum velocity V_{max} (m/s)
1.	2.87	4.19
2.	4.45	6.51
3.	5.96	8.72
4.	8.56	12.52

As the flow of heated air is considered for simulation purpose therefore above parameters are combined with air properties at average temperature for upstream and downstream sections in order to calculate the values like Reynolds number, Nusselt number, and convection heat transfer coefficient etc.

Table 9. Air Properties for Average Temperature

Sr. No.	Average Temp. T_{avg} (K)	Density ρ (kg/m³)	Thermal Conductivity Z_a (W/m. K)	Dynamic Viscosity μ (kg/m.s)	Prandtl Number Pr	Surface Temp. T_O (K)	Surface Prandtl Number Pr_O
1.	464	0.7607	0.03719	2.544×10^{-5}	0.6982	450	0.6995
2.	525	0.6722	0.04116	2.767×10^{-5}	0.6945	509	0.6954
3.	590	0.5989	0.04521	2.991×10^{-5}	0.6935	576	0.6935
4.	667	0.5355	0.04936	3.218×10^{-5}	0.6945	645	0.6942

Correlation based on experimental data for calculating the Nusselt number depends on Reynolds number, therefore

Reynolds number is given as

$$Re = \frac{\rho V_{max} D}{\mu} \quad (8)$$

Nusselt number correlation is as follow

$$Nu = \frac{h_H D}{Z_a} = B Re^m Pr^n (Pr/Pr_O)^{0.25} \quad (9)$$

Where C, m and n are the values of constants and depend on Reynolds number.

B= 1.04, m = 0.4, n = 0.36 when Re< 500

B= 0.71, m = 0.5, n = 0.36 when 500<Re>1000

Table 10. Reynolds and Nusselt number

Average Temp. $T_{avg}(K)$	464	525	590	667
Reynolds number, Re	376	474	524	625
Nusselt number. Nu	9.789	10.72	14.245	15.567

Also, actual value of Nusselt number depends upon the total number of rows across the flow region. Therefore, correction factor of 0.973 is multiplied to above value of Nusselt number in order acquire the actual value of Nusselt number for 9 rows. Actual values of Nusselt number incorporate in the respective equation of convection heat transfer coefficient and following table is formed

Table11. Convection Heat Transfer Coefficient

Sr. No.	**Average Temp.** $T_{avg}\,(K)$	**Actual Nusselt Number** Nu_A	**Convective Heat Transfer Coefficient** $h_H\,(W/m^2K)$
1.	464	9.524	118.06
2.	525	10.43	143.09
3.	590	13.86	208.87
4.	667	15.14	249.1

Table 12. Copper and Aluminium Property with Fin Parameters

Sr. No.	**Material**	**Perimeter** $C\,(m)$	**Area** $A_f\,(m^2)$	**Length** $l\,(m)$	**Thermal Conductivity** $Z_f\,(W/mK)$
1.	Copper	9.42×10^{-3}	7.0683×10^{-6}	25×10^{-3}	385
2.	Aluminium	9.42×10^{-3}	7.0683×10^{-6}	14×10^{-3}	205

Table 13. Temperature Difference of Source and Sink with Heat Rates

Sr.No.	Convection Heat Transfer Coefficient $h_H\,(W/m^2K)$	Source Temp. Difference $\Delta T_H\,(K)$	Sink Temp. Difference $\Delta T_C\,(K)$	Heat supply rate $Q_H\,(W)$	Heat removal rate $Q_C\,(W)$
1.	118.06	6	3	7.64	1.14
2.	143.09	8	4	12.22	1.52
3.	208.87	10	5	21.7	1.9
4.	249.1	12	7	30.51	2.66

3. RESULTS AND DISCUSSION

. Detailed interpretations of various parameters are carried out based on source and sink fin sections. Approximated assumptions of temperature and velocity locations incorporated in the analytical evaluation for estimating power generation from the thermoelectric generator by using waste heat recovery from the engine exhaust. With the help of graphical representation, view of various parameters like power available, expected power output with respect to temperature difference.

Table18. Power, Power Loss and Efficiencies of the Thermoelectric Device

Sr. No.	Power available P_{avail} (W)	Expected power output P (W)
1	6.5	0.4021
2	10.7	0.7987
3	20	1.4516
4	27.85	2.5

Power available for thermoelectric module is very large in comparision to power output at stationary condition. Also keeping in mind that rate of heat supply or removal is very much dependent on temperature difference available across the source and sink. rate of heat removal is very important parameter for TEG's as increase of this value directly affect the power available.Suppose if device is fitted to a vehiclen and able to dissipate more amount of heat to the surrounding then there will be increase in the rate of heat removal at sink. This rate of removal will cut down the available power for thermoelectric generator but because of the increase in the value of temperature difference there will be direct increment in the value of expected power output. This clearly explains the fig (6) that power available and expected power output will try to come closer to each other. This state that maximum amount of available power will be utilizable from this device to provide power output.

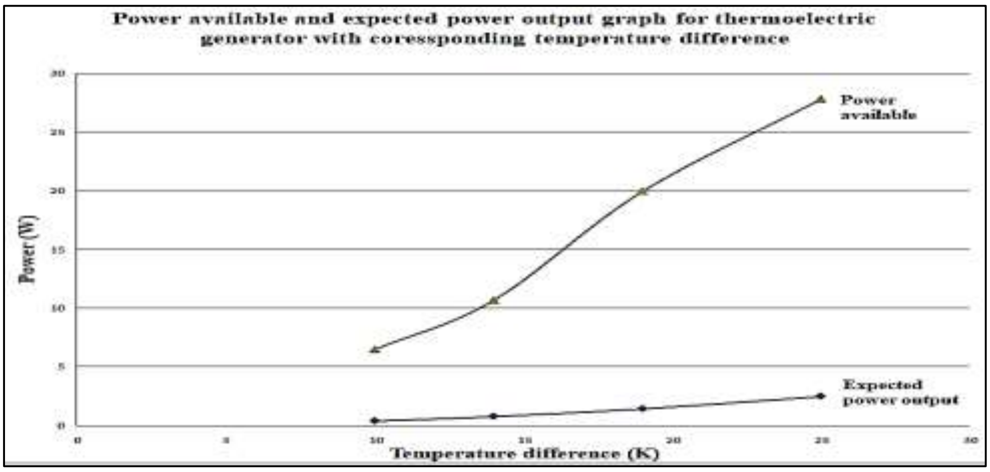

Fig 6. Power Available & Expected Power v/s Temperature Difference

increase in the value of convective heat transfer coefficient (h_H) is not going to affect the efficiency of the device anymore. Therefore, it is very important to note that data obtained for the given device at stationary position is having high value of Carnot efficiency. As TEG's working are purely based on the temperature difference therefore an optimum location of power curve that is between the available and expected power is going to be an effective and optimum condition for this device to operate.

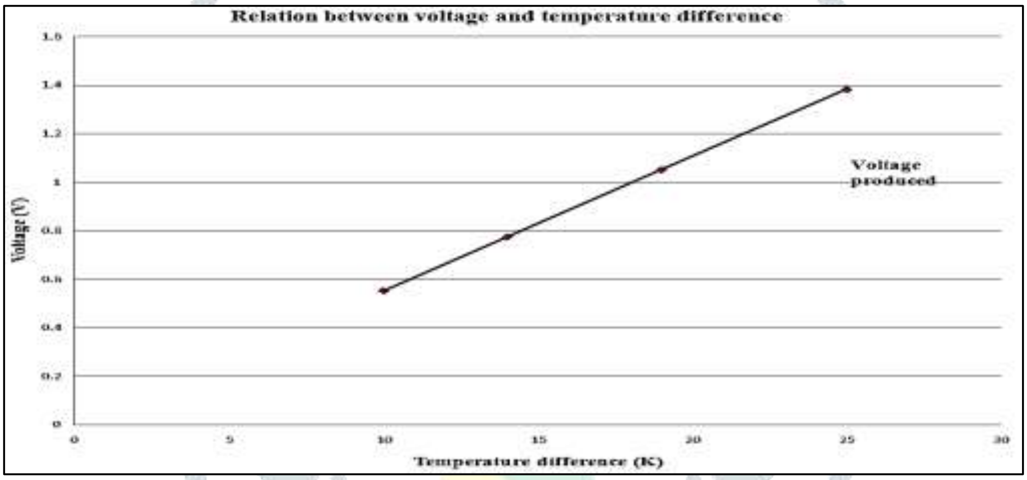

Fig 7. Power Available & Expected Power v/s Temperature Difference

4. CONCLUSION & FUTURE SCOPE

The study also shows that the engine performance is unaffected by designed and used this TEG conversion device and last but not least if a higher temperature is needed then the thermoelectric generator must be changed to a greater temperature range so that power generation also be increased. Thermoelectric generator module can be implemented with Micro Thermal Power plant and also retrofitted to produce electricity in remote areas. There are many ways by which one can try to improve efficiency on which we can work in the future, which are as follow

- Redesigning of inlet exhaust nozzle at device
- Aerodynamically smooth designing around heat sinks of the device
- Possibility to work on the elliptical baffle and number of fins

Also, thermoelectric generator semi-conductor material can be studied in depth which is also one of the important areas to explore and to directly enhance the efficiency of the thermoelectric module.

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