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DESIGN AND ANALYSIS OF THERMOELECTRIC GENERATOR FOR WASTE HEAT RECOVERY FROM AUTOMOBILE EXHAUST

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Abstract

Energy loss is the crucial bottleneck in the world of automobile. It often rose as crisis all across the globe. Thus for reducing energy consumption various technologies have been invented. Thermoelectric Generation is one of them which are rapidly developing technology used for recovering the energy. As in automobile sector the low efficiency being the paramount demerit due to this lots of heat energy is getting wasted. Taking this concept into mind the objective of this paper is to utilize the waste heat energy using Thermoelectric Generation.

Thermoelectric Generation being the promising technology had focused on various thermoelectric materials that are used to recover the heat. The recovery of energy is in much less amount but the start is always required that accelerates the future work. Thus this work has a simple objective to get back the energy from exhaust in the form of electricity that can be used for various accessories in an automobile. This project works on the exhaust of Bajaj Pulsar 150 model to mount the Thermoelectric Generator (TEG). Also, the paper focuses on the optimized design of the Thermoelectric Generator followed by the thermal analysis to generate electricity produced during running of an automobile. The ultimate aim is to recover the maximum energy in the form of electricity.

Keywords: Thermoelectric, generation, Seebeck

1. Introduction

The automobile consumes vast amount of energy and around its half eventually lost as waste heat to the environment in the form of exhaust and radiant heat energy. There is a clear need to improve the situation by capturing at least some of the waste heat and converting it into useful energy such as electricity to supply for instance small sensing electronic devices of the vehicle. The increased interest had led to the significant research effort towards finding novel technologies in clean energy production. There are lot of technologies which are being used to capture the waste heat; these different methods which are normally used to recover waste heat, differ each other with respect to the intensity of waste heat, for instance some of them are not adequate for low temperature, others require moving part to convert waste heat into useful energy and others are not environmental friendly. With reference to all of aforementioned concerns, thermoelectric generation came up with bypassing these parameters and filling in the space between waste heats and their recovery.

A thermoelectric generator which works on the principle of thermoelectric generation has long been recognized as a unique energy conversion device due to their capability to convert heat directly into electricity with no moving parts. In 1821, Thomas Johann Seebeck rediscovered that a thermal gradient formed between two dissimilar conductors can produce electricity. In 1988, Birkholz published the results of their work in collaboration with Porsche. These results described an exhaust-based Automobile Thermoelectric Generator (ATEG) which integrated iron- based thermoelectric materials between a carbon steel hot-side heat exchanger and an aluminium cold-side heat exchanger. This ATEG could produce tens of watts out of a Porsche 944 exhaust system. In the early 1990s, Hi-Z Inc designed an ATEG which could produce 1 kW from a diesel truck exhaust system. Since the early-2000s, nearly every major automaker and exhaust supplier has experimented or studied thermoelectric generators, and companies including General Motors, BMW, Daimler, Ford, Renault, Honda, Toyota, Hyundai and numerous others have built and tested prototypes.

Conversion efficiency is the crucial parameter in the principle of thermoelectric generation which is the efficiency of a thermoelectric material to convert the applied temperature gradient into corresponding electricity. Conversion efficiency differs from material to material which directly affects the performance of thermoelectric module which is measured in the form of Figure-of-Merit. Many efforts have been made over recent years to improve the conversion efficiency of thermoelectric modules (TEM) by increasing their Figure-of-Merit (*ZT*), with only marginal success. The *ZT* can also be improved if the temperature gradient is as large as possible which is achieved by experimenting with structure of TEG like using the fins with the thermoelectric modules, using fans to improve the overall heat transfer coefficient, also by increasing the electrical conductivity of thermoelectric material etc. With the use of fins, the efficiency of conversion increases about 43% higher than without fins but with use of fins the Figure-of-Merit (*ZT)* achieved still less than 4[1].

2. Methodology

Thermoelectric generation deals with the various TEM's that are preferably made of semiconductors, polymers and sometimes ceramics as well. The basic working principle

1.1 Need

As far as the conventional IC engine is concern lots of effort are required to increase the overall efficiency of the engine. Thus the work is to be done to overcome this particular demerit. Currently lots of research work is going on. Now-a-days, the rapid development of the automotive market has gone worse energy crisis problem. Currently, the average efficiency of internal combustion engines (ICEs) under driving conditions is around 50%.About 40% of the energy is discharged into the atmosphere through the exhaust by convection and radiation which is significantly a huge amount in the field of automobile. Thus it strongly indicates to have a research work regarding increasing the efficiency of an internal combustion engine of an automobile by reducing the waste heat energy. Thus reusing the automobile waste heat becomes necessary.

This specific demerit affects the engine performance in particular ways like engine overheating, battery discharge during long running, reduced battery life, greater fuel consumption and ultimately reduction in the overall efficiency of engine etc. As discussed earlier, energy wastage is a universal crisis all over the globe. Considering these parameters there has to be an effective way which will cross these boundaries to utilize the waste heat from various sources like exhaust outlet, exhaust manifold surface, engine body etc. Amongst these parameters the one which provides maximum area for heat transfer has to be chosen. Considering the maximum heat source in an application, thermoelectric generation principle has to be used.

and the typical materials for the thermoelectric module are discussed further along with the temperature distribution on exhaust manifold of Bajaj Pulsar 150. Taking these parameters into consideration, the proposed model of TEG, CAD model is created followed by the thermal analysis of the design when exposed to real time constraints. The results were analysed with respect to various related constraints using graphs.

2.1 Principle of Thermoelectric Generation

Thermoelectric generation works on the basic phenomenon of Seebeck Effect which states "If there is a temperature gradient between two dissimilar electrical conductors or semiconductors, it produces the voltage difference between the two substances". Figure 1 shows the basic working principle of Seebeck Effect.

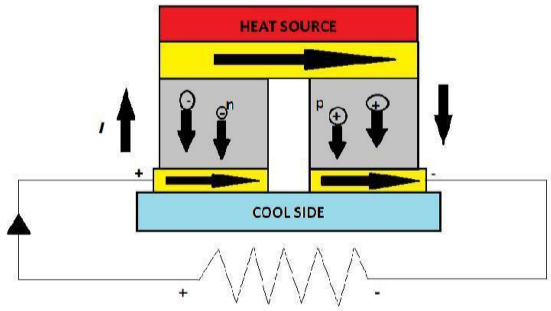

Fig. 1: Schematic diagram of thermoelectric generator[2]

Thermoelectric generator systems are one of the most promising options, to face the needs for environmental protection and for reducing energy consumption. A thermoelectric generator is a heat engine in which charge carriers serve as the working fluid. It is silent in operation, has no moving parts and is very reliable. TEG consists of a large number of thermocouples connected electrically in series and thermally in parallel to form a thermoelectric module. The module is the backbone of the generator and it is available commercially. Heat is supplied by a variety of sources to the hot side of the module (heat source) and is rejected at a cooling side of the module. If a temperature difference is maintained across the module, electric power output will be delivered to an external load.

The thermodynamic conversion of heat to work actually involves four distinct processes, only two of which are reversible. The reversible processes are Peltier and Thomson effects. The irreversible ones are the Fourier effect (heat conduction) and the Joule effect (electrical resistance) . Thermoelectric devices can convert thermal energy into electrical energy and vice versa. Generally, two main physical phenomena are relative, such as the See beck Effect and Peltier Effect. A certain open-circuit voltage is generated in a material kept between the two different temperatures. The Seebeck coefficient α (V/K) is a property of the material that relates to the open-circuit voltage VOC (V) with the temperature difference ΔT (K). Equation 1 shows the relationship between open circuit voltage and temperature difference which is used to calculate the voltage produced during the thermoelectric generation.

$$V_0=\alpha \Delta T \quad (1)$$

2.2 Thermoelectric Module (TEM)

A thermoelectric module (TEM) consist legs of n-type and p-type semiconducting materials connected thermally in parallel and electrically in series. Material structures and compositions are used to classify thermoelectric materials. The Figure of Merit (ZT) describes thermoelectric material performance. It depends on the thermoelectric material properties such as, Seebeck coefficient α, thermal conductivity κ, and electrical conductivity σ, where Figure-of-merit (ZT) can be calculated using equation 2,

$$ZT=\alpha^2 \sigma T \kappa/2 \quad (2)$$

A thermoelectric couple is a pair of n-type and p-type legs, and a thermoelectric module generally has several couples. These couples and their electrical interconnects are covered by an electrical insulator, typically a ceramic. Thermoelectric conversion efficiency can be improved by maximizing the Seebeck coefficient and by lowering the electrical resistivity and thermal conductivity. Heavily doped semiconductors can be used as thermoelectric materials and can be grouped into three technologies depending on the temperature range of the operation. Those based on Bismuth Telluride materials, Lead Telluride and Silicon-Germanium alloys. The variation of the Seebeck coefficient and the electrical conductivity as a function of the reduced Fermi energy, serves for the optimization of the power factor.

The material used for thermoelectric modules are basically classified in three sections that are semiconductors, ceramics and polymers. For the semiconductors to be used in TEG should have Seebeck coefficient more than $100\mu V/K$. The examples of semiconductors are Bismuth Telluride (Bi_2Te_3), Lead Telluride ($PbTe$) and silicon germanium alloys ($SiGe$). Ceramics of metal oxides have advantages like less toxic in nature, it has good chemical stability and oxidation resistance moreover it is comparatively cheaper. But the main barrier for TEG using ceramics is that it possesses the Figure-of-Merit always less than 2 [1].

Polymers can also be the option for TEMs as they are flexible and most importantly they are widely available. The power factor of the thermoelectric polymer is continuously rising and the higher ZT value is more than 0.25 at room temperature Figure-of-merit (ZT) for polymers is less than 1. A class of polymers known as Electrically Conducting Polymers (ECP) is best suited for this application. Among all of this Polypyrol (PPY) is the best candidate. Their advantages comprise good electronic conductivity, low thermal conductivity, low cost. As far as the Figure-of-merit is considered the semiconductors are best suited for Thermoelectric Generators.

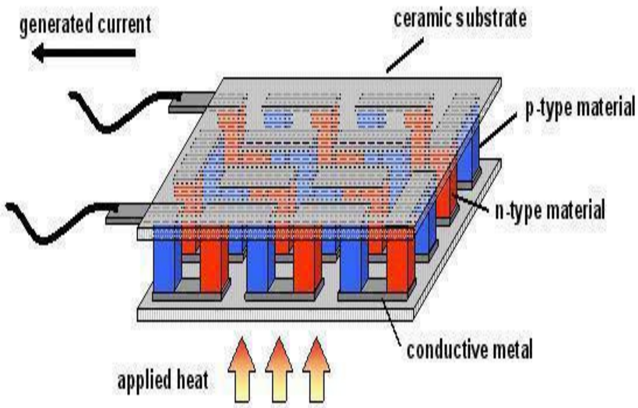

Fig. 2: Constructional details of thermoelectric modules[3]

For the effective conversion efficiency the temperature gradient should be as high as possible but this ideal parameter is the major drawback of these semiconductors. The crucial temperature range for these materials is discussed below;

Table 1: Comparison of various Thermoelectric Materials[4]

Sr. No.	Thermoelectric Material	Figure-of-Merit	Critical Working Temperature
1.	Bismuth Telluride	3.5	Below 350
2.	Lead Telluride	1.5	Below 500
3.	Silicon Germanium	0.5	Below 1000

From Table 1, it is clearly seen that the Figure-of-merit and critical working temperature of material are inversely proportional to each other. With this, project work is going to focus around Bismuth Telluride material as Thermoelectric Module which is best suited when operated below 250^oC

Bismuth Telluride is a type of semiconductor which is a compound of Bismuth Bi and Tellurium Te . This type of semiconductor which when alloyed with antimony or selenium for portable power generation as after alloying it possesses high atomic weight. It is soluble in ethanol but insoluble in water. The mineral form of Bi_2Te_3 is tellurobismuthite which is moderately rare. There are many natural Bismuth Tellurides of different stoichiometry as well as compounds of Bismuth, Tellurium and Selenium. Reduction of the thermal conductivity is one important possibility to increase the figure of merit. However, the according maximum figure of merit is obtained at higher antimony content due to the contra-productive evolution of the electrical conductivity and the carrier contribution to the total thermal conductivity.

2.3 Performance Parameters

The various key parameters affecting the conversion efficiency and performance of TEM are listed as follows:

1. Temperature variation throughout length.
2. Exhaust mass flow rate.
3. Velocity of exhaust gas.
4. Cooling method.
5. Space utilization.
6. Number of thermoelectric modules
7. Distribution of temperature gradient over TEM.

For the effective conversion of exhaust heat into electricity the temperature gradient should remain constant throughout the length of module with is not possible practically this because of atmospheric air flow and behaviour of IC engine in dynamic condition. This project utilizes Bajaj Pulsar 150 exhaust manifold for the mounting of TEG modules. The temperatures reading were taken by running the engine for nearly about 1-2 hours by keeping acceleration was constant at the speed of 40 *kmph.* The temperatures and the velocity were recorded using Probe thermometer and Anemometer respectively. Temperature variation on surface of exhaust manifold is depicted below:

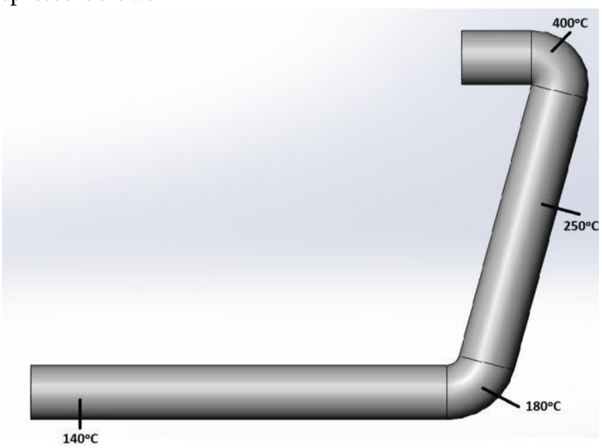

Fig. 3: CAD Model of exhaust manifold of Bajaj Pulsar 150

The velocity of exhaust gas coming out of exhaust manifold is 15-20 *m/s* with the atmospheric temperature of 25°*C*[1]. The pressure drop across the inlet and outlet is nearly about 125*Pa*[1]. The atmospheric temperature is taken as 25°*C.*

The engine specification of Bajaj Pulsar 150 is as follows:

Table 2: Engine and battery specifications of Bajaj Pulsar 150[7]

Sr. No	Parameter	Range
1.	Displacement	149 *cc*
2.	Power	10.29*KW*@ 8000*rpm*
3.	Torque	13.40*N-m*@ 6000*rpm*
4.	Battery	12*V*, 9*Ah*

2.4 Cad models of thermoelectric generator

The various factors that were taken into consideration while designing the CAD Models are space between engine and silencer body, length of silencer, profile of silencer body, temperature gradient that can be achieved, space available for the air flow during running conditions manufacturing feasibility to real time constraints etc. Considering aforementioned parameters and space constraints the design was initiated with CAD modelling of the design. While designing, the main milestone was portable and removable assembly. The problem was solved by the use of adjustable clamp to open and close assembly so that it can be mounted on every vehicle of approximately same exhaust manifold. Following are the various parts used in an assembly of thermoelectric generator:

2.4.1 Exhaust Pipe

As this work is applied to Bajaj Pulsar 150 Model, modelling of exhaust pipe is done using the dimensions of exhaust pipe of Bajaj Pulsar 150 model. The exhaust pipe is made of Chromium Ferritic Stainless Steel. The temperature variations at different locations on exhaust pipe are shown in Figure 3 measured in the conditions as discussed earlier. As exhaust manifold (silencer) isn't linear it has curvature along its length so the assembly couldn't be one entity. Since for the curvature of the exhaust manifold the fabrication cost of the arrangement increases so the curvature part has been avoided as the temperature loss was not significant. So, it was finalized to make the assembly in 3 parts keeping the curvature shape of manifold in mind.

2.4.2 Copper Plates

Copper plate is simple rectangular plate made from pure copper. Copper plates are mounted on exhaust manifold, other surface of which is directly in contact with TEM. Due to excellent heat conductivity, Copper plates act as heat exchanger in TEG which transfers heat from surface of exhaust pipe to the thermoelectric module. Uniform temperature distribution is required for the TEM to generate sufficient amount of electricity using thermoelectric principle if this condition is not followed, voltage produced is not in proper form and the further amplification is required to achieve this condition. This leads to increase in overall cost of project. Thus copper plate assures uniform temperature distribution on the TEM. Two copper plates are used to in between which TEM's are placed using thermal paste to have good thermal contact.

2.4.4 Thermoelectric Module with Fins

TEM are made of various thermoelectric materials. These materials works on the principle of thermoelectric generation using which when TEM is placed across a temperature gradient, it produces electricity. TEM is placed in between two copper plates as shown in Figure 4. Amount of voltage generated is directly proportional to the temperature gradient which in turn indicates to increase the heat dissipation rate from another side of TEM. Hence Aluminium fins are added to copper plate so as to increase the heat transfer area. Aluminium has heat transfer coefficient of 60 W/m^2K. These fins are attached on the copper plate with help of thermal paste which is being good conductor of heat lets the heat flow towards fin area effectively. Aluminium allows the fins to extract as much as possible heat from the copper plate so as to increase the temperature gradient which in turn increases the overall output voltage. Total no of fins is calculated by using thermodynamic calculations which comes out to be 7. Fins allow more surface are to be exposed when the speed of the vehicle is high enough to have better convection[11].

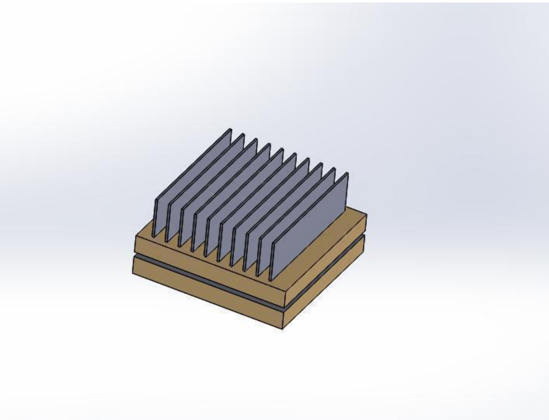

Fig. 4: CAD Model of thermoelectric module with fins

There are various thermoelectric materials and their respective temperature range of working. All the thermoelectric materials possess their own different properties depending in their physical availability, chemical composition, and thermal properties. If the TEM is exposed to a temperature more than its ultimate working temperature its efficiency gets reduced which directs affects the life of thermoelectric module. At the end thermoelectric properties which is most important amongst all. Considering all Bismuth Telluride (Bi_2Te_3) is most suited as its Figure of Merit (ZT) is highest compared to other materials[4]. Specifications of selected Bismuth Telluride Module are given in Table 3.

Table 3: Specifications of Bi_2Te_3 TEM[8]

Sr. No.	Parameter	Unit	Quantity
1.	Max. Current	*Amp*	1.2
2.	Max. Voltage	*Volt*	4.2
3.	Resistance	*Ohm*	2.0
4.	Life Expectancy	*Hrs*	20000
5.	Cost per module	*Rs.*	500

2.4.5 Assembly of Thermoelectric Generator

Assembly of thermoelectric generator comprises of copper plates, thermoelectric modules, adjustable clamp and electrical connections as shown in Figure 5. Total assembly of TEG is attached over exhaust pipe with help of adjustable clamp. Adjustable clamp assures the proper fitting of assembly on exhaust manifold of any of bike having approximate same dimension. Thermoelectric module is sandwiched in between the copper plates which are brazed on a mounting. Aluminium fins are attached on another side of copper plate which is exposed to the environment ambient temperature to increase heat transfer rate.

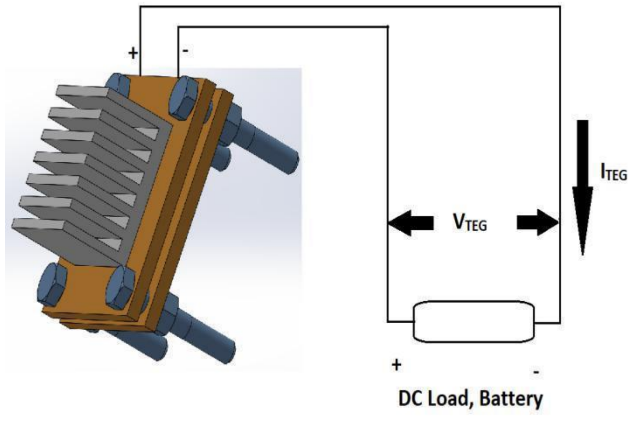

Fig. 5: CAD model of TEG assembly

The high temperature exhaust gas (200*°C*) enters the thermoelectric generator which mounted on the exhaust pipe as shown in above figure. Temperature gradient is created across the Bismuth Telluride module which allows TEG to produce voltage based on the principle of thermo electric generation. Mild Steel mounting carries Bismuth Telluride in between two copper plates to have a proper distribution of the temperature gradient over a module. The generated electricity can be used to recharge the battery whenever necessary or it may also be used to provide electricity to several of accessories of an automobile. As the brake power developed in IC engine is utilised to recharge the battery gets reduced with use of thermoelectric generator. This also helps in the considerable reduction in the fuel consumption because more brake power is available which ultimately improves the overall efficiency of an IC engine.

3. Steady-State Thermal analysis

Temperature gradient is the crucial parameter as discussed in earlier section. With reference to this significance thermal analysis plays a vital role. The motive behind thermal analysis is to target critical thermal areas on the surface of exhaust manifold which plays crucial role in the conversion efficiency of TEM. Thermal analysis points out the maximum temperature with overall distribution, total heat flux all over surface the mounting with high heat flux intensity. This helps to simulate real time results which in turn select permissible limits of Thermoelectric Module. Maximum indicated temperature thus also helps to calculate the desired output electricity.

3.1 Prerequisites for simulation

Simulations were developed to achieve thermal distribution and total heat flux distribution. Finalised CAD model as shown in figure 6 is imported and ferritic stainless steel is assigned for inner surface of the exhaust pipe. The inner surface temperature of exhaust pipe is set to 400*ºC* while the coefficient of convective heat transfer is set to 5e-006 $W/mm^2 ºC$ as it is exposed to gases in free convection having ambient temperature of 28*ºC.*

3.2 Analysis Results

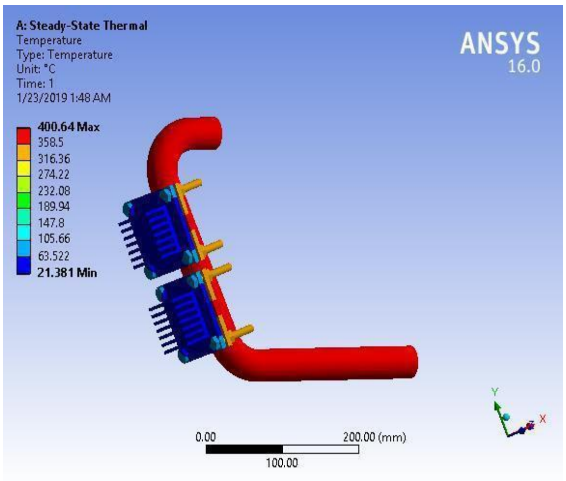

Fig. 6: Temperature distribution on exhaust manifold

Simulation results are shown in figures. The maximum and minimum interface temperature of the assembly ranges between 400*ºC* to 21.381*ºC* as shown in figure 6. Thermal analysis of a TEM structure is also carried out as shown figure 7. From the simulation results, the temperature available at the surface of module is about 210*ºC* and hence bismuth telluride is selected because it is best when used between 180ºC to 220*ºC*[1].

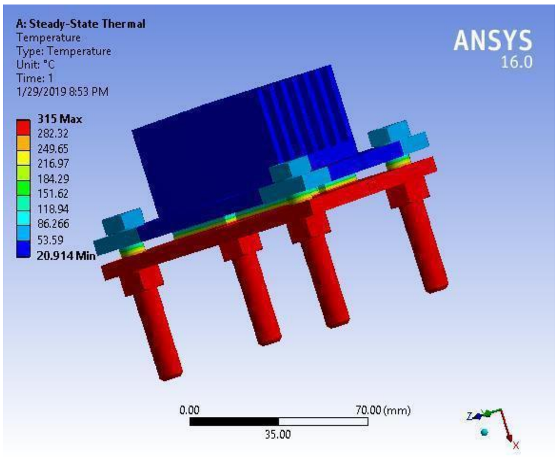

Fig. 7: Temperature distribution on TEG assembly

4. Fabrication

Now, since the CAD models are thoroughly analysed and verified next step is to fabricate it. Fabrication would be the in-house fabrication using conventional machining. Keeping the cost estimation in mind the machining used will be conventional like lathe, grinding, cutting etc. The whole product will be fabricated such that it can be effectively mounted on Pulsar 150 and all other models having approximately same exhaust manifold. The clamping system is also provided for easy mounting. This design of the fixture provides best utilization of space and heat extraction from the exhaust manifold this design could be applied on different bikes considering the specifications of the manifold

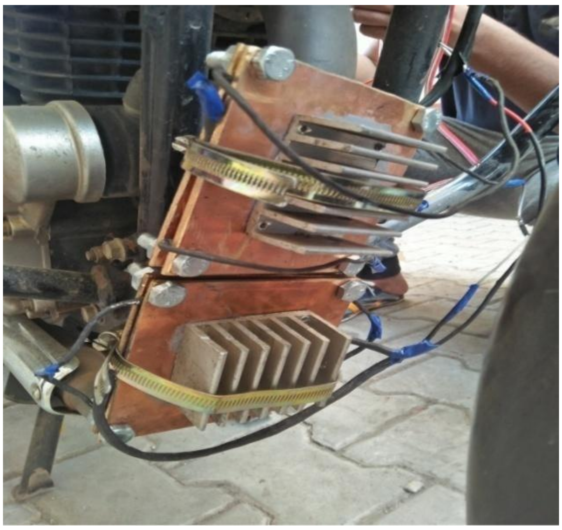

Fig. 8: Actual experimental setup of TEG assembly

This project is based on Thermoelectric Generation and it is mounted on Bajaj Pulsar 150 model with 8 modules of

Bismuth Telluride as shown in figure 8. Fabrication will be made by considering all the dynamic factors affecting the rigidity of TEG. Though the small achievement will be a huge success in the future; similarly, small amount of energy recovered will be a small step towards reducing the energy crisis.

5. Results and Discussion

In order to investigate whether the actual parameters coincides with the designed ones testing of actual TEG is next step forward. Testing allows to critic on specific work based on the outcomes from the same. The model was ready and was tested under certain circumstances and the readings were recorded. The testing was carried on Bajaj Pulsar 150 in static as well as running condition. Below are some parameters and output with respect to them.

5.1 Variation of output voltage with respect to different parameters

The aim of this research was generating voltage which signifies this work. The parameters that were taken into account while testing was temperature speed (*rpm*) and variation of outputs are tabulated below.

5.1.1 Variation of output voltage with respect to temperature

Table 4: Variation of output voltage with respect to temperature

Sr. No.	Temperature (^0C)	Voltage (*V*)	Current (*A*)	Power (*W*)
1	50	2.4	0.13	0.31
2	100	4.7	0.26	1.22
3	150	5.6	0.30	1.70
4	200	6.4	0.34	2.22
5	250	7.2	0.39	2.81
6	300	7.9	0.43	3.4
7	350	8.4	0.45	3.83
8	400	9.2	0.5	4.60

The test was carried in static conditions and readings were taken with equal interval of temperature and alongside power were also calculated by using equation 3;

$$P=VI \quad (3)$$

5.1.2 Variation of output voltage with respect to speed (rpm)

Table 5: Variation of output voltage with respect to speed (*rpm*)

Sr. No	Speed (*rpm*)	Voltage (*V*)	Current (*A*)	Power (*W*)
1	4000	2.2	0.11	0.21
2	5000	2.7	0.14	0.30
3	7500	3.9	0.21	0.81
4	8000	4.2	0.22	0.92

Taking aforementioned parameters into consideration, the vehicle was driven for 30 minutes at every constant speed value. Thus, outputs in form of voltage were recorded and summarized as shown in table 5.

5.2 Comparison of output voltage with respect to other parameters

After the project was exposed to real time constraints, various results were recorded as discussed in earlier section. With reference to above results, they were analysed by plotting various graphs with respective temperature and speed. The total analysis of work is based on comparison of power output, current and voltage by keeping temperatures and speed as dependent constraints.

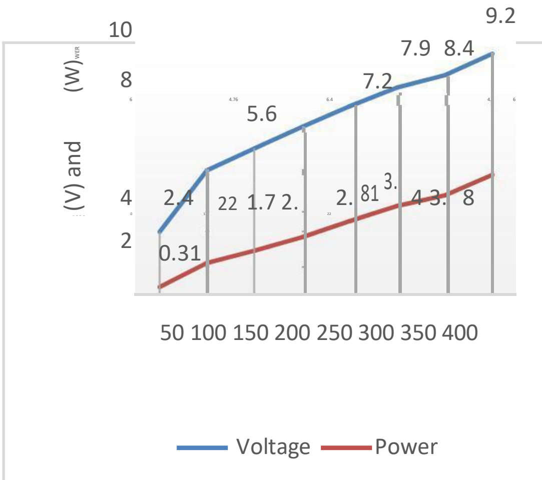

Figure 8: Graph of Temperature vs Voltage and Power

The graph has been plotted taking temperature on abscissa and voltage, power on ordinate. It is observed that power and voltages are directly proportional to temperature.

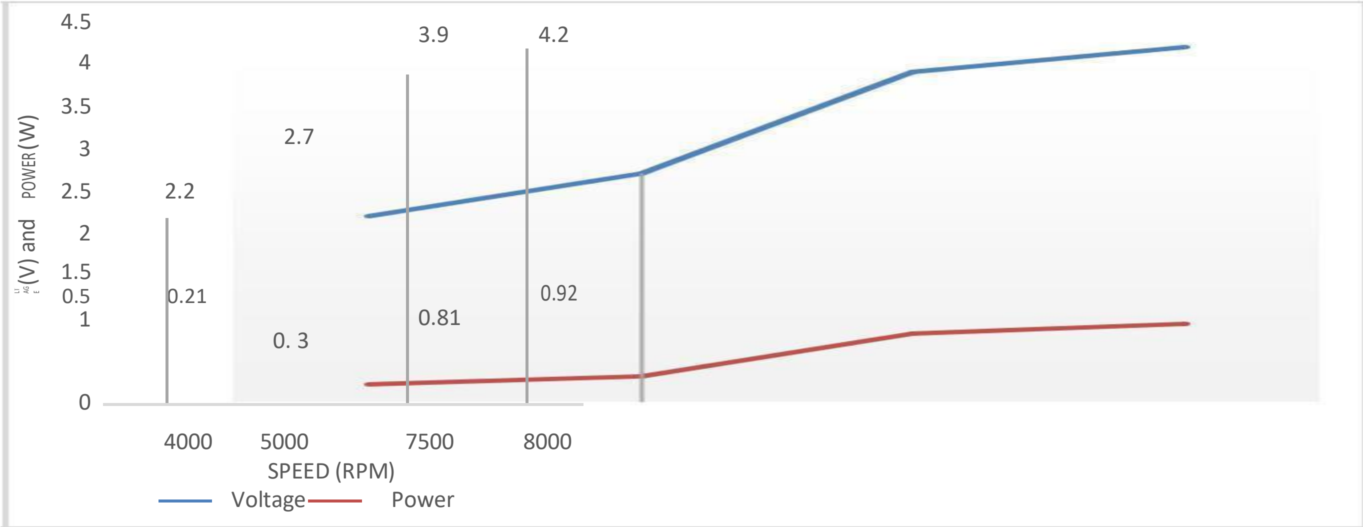

Figure 9: Graph of Speed vs Voltage and Power

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Rate of generation of voltage depends on speed of vehicle as the speed increases voltage decreases because overall heat transfer rate from the surface of assembly increases because it is expose to running air. While in static condition it does not adversely affects the power generation.

6. Conclusion

This paper started with a brief background on the principles and the theories of TEG's, with their significance and applications on waste heat energy reviewed and discussed. The materials used in TEG devoice and their impact on conversion efficiency is also elaborated. The computational methodology presents a net voltage generation of about 9 Volt incorporating fin structures when exposed to natural convection. The overall power generation can be increased by increasing the TEM's with corresponding changes in fins.

It can be seen from the results and respective graphs as in running condition the speed of vehicle increases the voltage output increases to a certain value of speed and once the vehicle attains maximum speed it affects voltage generation adversely as the overall heat transfer increases. Thus, increasing heat transfer to the surrounding the cooling effect is produce on the hot side of module, reducing the temperature gradient by inversely affecting the voltage output. While in static condition the deviation in overall heat transfer rate to surroundings is not dominant since natural convection occurs, the increase in temperature leads to increase in voltage output from the TEG. Also it can be noted that number modules are directly proportional to the output voltage of TEG.

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