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Various Performance Datum that Affect the Working of TEG

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Abstract: ***"Waste heat recovery with thermoelectric power generators can improve energy efficiency & provide distributed electricity generation." The strategy of how to recover this heat depends on the temperature of waste heat gases and economics involved. The energy lost in exhaust gases cannot be fully recovered. However, much of the heat could be recovered & loss minimizes by adopting ideal performance conditions at the system level. The performance of TEG relies on more factors than traditional Thermoelectric (TE) material performance metrics alone, Positioning within the automotive system, Module Structure and Electrical Performance of one whole Thermoelectric (TE) system decides the efficiency of heat recovered. This review discusses the performance of TEG in different practical cases & what could be the best arrangement of the array of modules, Placement or Positioning & Conditions for a TEG setup to work in an Automotive System."***

Keywords**:** ***Phase-Change Material (PCM), Thermoelectric Generator (TEG), Thermoelectric Module (TEM), Quantum well (QW).***

I. INTRODUCTION

"It is better to be a part of the solution than be a part of pollution". The world is facing drastic deterioration in the quality of air. The major part of this decline is due to the use of fossil fuel burnt by industries, among them specifically is automotive industries. There have been countless efforts made to maximize the power generated by fuels but no cognizance towards recovering the waste created by fuels. Rather than eliminating fuel-powered vehicles, small steps are needed to be taken to recover a part of this waste heat that is getting exhausted into the environment. One such technology that is promising regarding waste heat recovery is Thermoelectric Generator. TEGs recover heat from the exhaust and use it for providing support to the alternator for electricity production thus reducing the work of the engine and consequently the reduction in gas emission.

TEGs are the most effective set-up out of all commercially available waste heat recovery technologies. Researchers are trying to efficiently integrate TEG into automobiles to utilize Heat Loss which can't be harnessed due to various mechanical reasons like loss of heat from the wall of the engine, Exhaust Conduit, loss of heat from the cooling system. TEGs are compact solid-state clean Semiconductor device which works on the principle of Seebeck effect, the temperature gradient thus created leads to the generation of the voltage difference. According to the Seebeck Effect, when two semiconductors are introduced in a temperature gradient, there develops a voltage difference between those two semiconductors. If these semiconductors get connected together through a circuit, electric energy can be harnessed. TEGs in a Waste Heat Recovery system has many advantageous attributes as compared to traditional

Waste heat recovery systems are silent as it has no moving parts, size, scalability, and most importantly durability which results in significantly low maintenance. In TEG devices, P-type and N-type semiconductors suitably doped elements are shunted to form an electric circuit, the shunts are made up of excellent conductors. These shunted semiconductors are sandwiched between layers of non-conductors (ceramics, etc.) having low electrical conductivity and high thermal conductivity, on the contrary, the semiconductors have high electrical conductivity and low thermal conductivity. These modules are connected together to form a Thermoelectric generator [1]. In this review, an overview of Thermoelectric Generator is elucidated by categorizing various aspects like characteristics of thermoelectric materials, Design/Structure of TEG module and Positioning/Placement of the TEG within an automotive system. For an optimum performance of TEG these factors act as a major contributor in determining TEG system performance as well as vehicle performance as a whole. The targeted readers for this overview are those who belong to other fields than the thermoelectric research or want to have an understanding of underlying key issues with thermoelectric materials and system development. Lastly, an overview of the prime aspects and comparisons are given under different topics related to thermoelectric Generators discussed within the review.

II. MATERIALS

Thermoelectric devices offer distinctive power generation solution as they convert thermal energy into Electrical energy without requiring any moving constituents.

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As thermoelectric generators are passive devices comprises of no moving parts, leaving us with the development of materials and design for improving performance of TEG.

Materials used in construction of TEG plays an important role in determining the performance of these devices. The material performance has been described by many features to make them suitable for TEG device manufacture.

In order to understand material significance within TEG system, Firstly, the criterion for selection of material requires emphasis. Thermoelectric figure of merit or ZT can be used for the efficiency comparison of different TEGs working at same temperature. Higher the value of ZT, the better the TEG will be.

$$ZT = S^2 \sigma T / k$$

Where, Seebeck coefficient '*S*', Electrical conductivity 'σ' and Thermal conductivity '*k*' and '*T*' stands for temperature.

(Twaha et al)[2] mentioned that ZT is inefficient at about 1 and able to recover heat when ZT is approaching 2.

It has been found that material performance or Figure of merit (ZT) determines what material is fit or compatible within a Thermoelectric Generator system.

Thermoelectric material is typically classified by material composition and its lattice structure. Exceptional reviews of Thermoelectric materials have provided an insight of both the material classification and relationship between material structure and Thermoelectric properties [3]. So, comprehensive details are not mentioned here, materials like Bi_2Te_3, PbTe, Skutterdite etc. which are commercially used within an Automotive system are elaborated here as it is the focus of the review.

While considering automobile application, the relation of TE module with automotive system shows a considerably interdependency on the operating temperature as the Hot side of the TEG is in contact with exhaust conduit of the vehicle resulting in the temperature values of both TEG (hot side) to be nearly equal to the surface temperature of the exhaust.

A material with high ZT at higher temperature is used on the hot-side i.e., Lead Telluride (PbTe) while a material with a high ZT at lower temperature is used on the cold side, Bismuth Telluride (Bi_2Te_3). Also, it has been found that materials with ZT>1 have lattice thermal conductivity lower than other materials having low ZT [2].

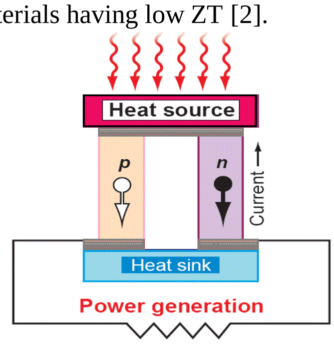

Figure1 Thermoelectric Generator Working [1].

As discussed in the later section of this paper segmented elements have been used in the Thermoelectric Generator Module (TEM) design to attain highest average value of ZT. To design a TEG, integration of thermoelectric materials into devices also requires consideration of both n-type (majority charge carrier electrons) and p-type (majority charge carrier holes) thermoelectric materials. For a TE module to work it is important that semiconductors are connected thermally in parallel and in series electrically.

Bi_2Te_3 is typically applied for operating temperature below 150 degrees Celsius at the position of p-type and n-type elements. For temperature range of 150 degrees to 500 degrees PbTe is the best n-type material. Additionally, Zn_4Sb_3 is one more option for approximately same temperature range but for p-type material. Zn_4Sb_3 has also been reported as one of the most —efficient TE materials known with high efficiency because of its extraordinary low thermal conductivity [4].

Another material that has shown promising results n Skutterdite (p-type CeFeSb_{12} and n-type CoSb_3). Apart from using Skutterdite discreetly it has also been used along with Clathrates in void filling within a TEM or guest atoms into a bas structure.

These additions can optimize electron concentration into a base structure achieving a glass like thermal conductivity along with good Electrical Conductivity.

Another way of improving efficiency is sometimes using a solid filler, but solid filler media are subjected to undergo sublimation. It is not a viable idea to use filler media in high-temperature applications as abrupt spikes in temperature values can result in performance deterioration or even product failure[1].

Another method of optimizing efficiency of TEG is by integrating Phase-Change Materials into Automotive TEG's. A PCM is a material which can hold and emit the heat by phase-changing. Liquid to Solid or vice versa. The various aspects about Phase-Change Materials and its constituents have been clearly discussed [5].

While positioning a TEG within an automotive system it has been found that the momentary behavior of the heat emitted by flue gas from the exhaust conduit poses a challenge for the working of TEG because TEG requires consistency in temperature gradient for better efficiency and smooth operation.

Typical TEGs currently are intended for specific application, the hot-side temperature is designed to reach maximum value under one set of operating condition.

(Altstedde et al)[6] suggested that there can be less than ideal scenarios i.e. at loads above design point where a bypass is used to divert a subsequently unused portion of flue gas to protect its components from damaging and at loads below design point the maximum temperature potential of flue gas cannot be utilized.

So, it has been found that he operating point for TEG within the operation cycle is just for a fraction of the time spent in active operation. In order to have consistency, PCM are introduced. The placement of Phase-Change Materials is optimum between Exhaust Gas Heat Exchanger and thermoelectric Module.

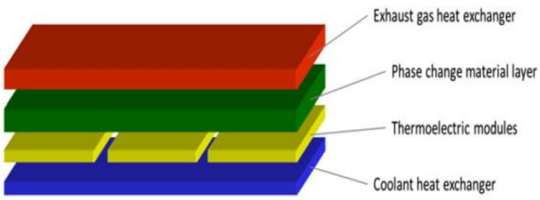

Figure2 Schematic illustration of concept for stabilising dynamic exhaust behaviour [6]

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(Hoshi et al) [7] reviewed potential PCMs; ***Figure3*** shows the heat capacity of commercially available materials, sorted by melting point. The given heat capacity is determined by latent heat and sensible heat of the PCM[7].

During operation cycle of high loads, Phase-Change Materials ought to absorb excess heat which further gets transmitted to the Thermoelectric Module when the automotive system is running at low operation cycle. Positioning of PCM with the TEG resulted in a 29% higher energy yield [6]

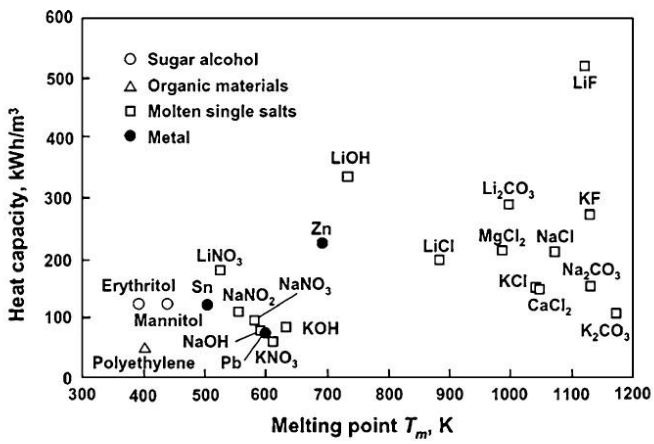

Figure3 Heat Capacity Of High-Melting-Point PCM [7]

During operation cycle of high loads, Phase-Change Materials ought to absorb excess heat which further gets transmitted to the Thermoelectric Module when the automotive system is running at low operation cycle. Positioning of PCM with the TEG resulted in a 29% higher energy yield [6].

It was found through the study that although there is significant change in output of TEG when the material properties are substituted or completely changed still there should be consideration to introduce materials that can contribute in a steady and consistent heat transmission to the TEM hot-side like PCM which resulted in a better efficiency subsequently.

III. DESIGN

In the case of TEG, the design is very closely governed by optimization. It might be the case that some parameters for a device-level model are optimized but when installing in a waste heat recovery system it might not be best suited. To develop an optimized TEG with optimum performance, a more wholesome system with the other components of the waste heat recovery system needs to consider.

Leg length refers to the length of the semiconductor module in the TEG. The increase in the leg length increases both thermal and electrical resistance, and hence have both positive and negative effects on the output performance. The effects depend on the relative thermal resistance between TEMs and heat exchangers. The leg length should be set differently for the high or low heat transfer coefficient of the heat exchanger[8].

The weight of the TEG modules should be kept in check such that the weight of the modules doesn't completely overthrow the effect of improved efficiency of the device via TEG. This becomes even more evident in airborne vehicles when. the effort has been put to define this limit. It was stated in the research by [9]suggested that "In order to reach a range of invariant implementation of TEG an increased electrical power density > 520wkg^-1 is required".

The TEG is used in the modules or grouped together circuits of thermoelectric generators to produce the large enough electric current which is usable, the correct designing of the module and arrangement of the TEGs can help to minimize or even eliminate heat loss between cold and hot side, and thus, to enhance the module performance. The module design can enhance the power generation by 8-30% and the efficiency by 40-60%[10]. It is not necessary that by increasing the module number, the output power will be increased, as illustrated in the ***Figure4*** by (Dong Xu Ji et al)[8] that after increasing TEM to a certain number, the output power stops increasing, but rather decreases. This is because with an increase in the number of TEM the relative thermal resistance of TEMs drops, with a decrease in the relative thermal resistance of TEM, the power output stops increasing but rather decreases.

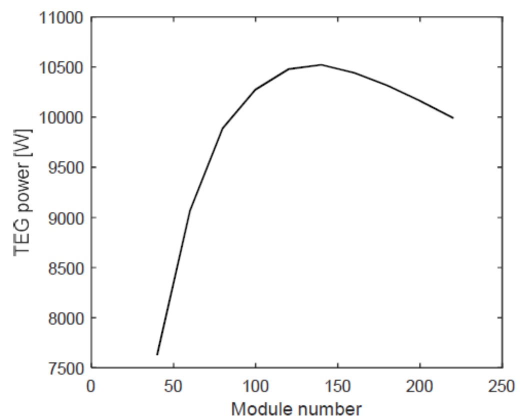

Figure4 TEG power change with module number installed [8].

Traditionally elements of TEGs i.e. p-type and n-type parts, are separated by module gap determined by module fill factor which is defined as the area occupied by the elements divided by the area of the module substrate.

Also, the previous research has shown that the shape of the cross-section area of the elements does not make a difference in module performance. So, the varying shapes of the cross-section of the element are effect less. But on the other hand, the variable cross-section area could improve the couple's performance.

The gap air between legs lead to loss of heat, Zhang et al., proposed that the porous semiconductor legs should be used. That doesn't only reduce the heat loss which we have observed at the junction or gaps of TE modules but also as a result the gap between the legs which was left previously for proper ventilation so that legs don't heat and as a result pass the heat from the hotter to cooler side, is also drastically reduces the gaps or spacing between the elements of TEGs as seen in the Figure 5. It is important to choose the correct material, as the upper limit of the performance of the TE couple is the same as temperature-dependent material properties and the optimal working can maximize to that value for a certain geometry.

If the correct optimization is done by keeping TE material, element geometry, and working conditions we can see up to a 29% hike in the volumetric power density and a 12% increase in volumetric efficiency.

In the practical conditions, TEGs have to work in the comparatively wider range of the temperatures, and therefore the single-stage and not optimal for working, for these conditions previous researches have mentioned alternatives. For wider temperature ranges the TEG modules can be designed in cascaded or segmented ways.

For Segmented element design, a material with the highest ZT for that specific temperature range is used but this system has higher heat and electric losses at the interfaces as well as material compatibility issues. For overcoming this alternative design method is devised. In the cascaded element design method, the different stages of modules are to be stacked onto one another with different materials to form a cascaded TEG power generator. In the cascaded system, each stage has a separate electric circuit which avoids the serialized circuit used in the segmented devices. The total efficiency of the cascaded module becomes roughly equal to the sum of efficiencies of individual modules [10].

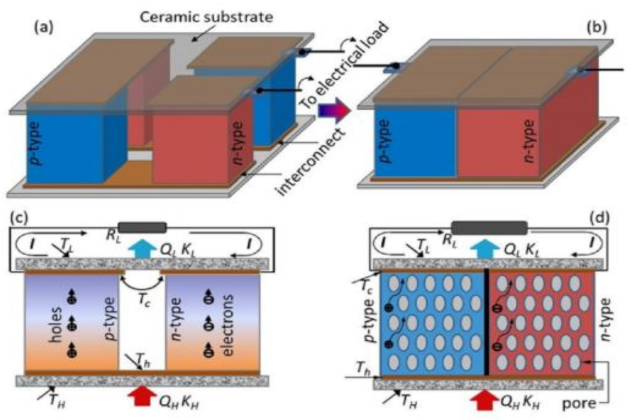

Figure5 Schematic diagrams of the thermoelectric power generators. (a) Traditional TE module design for 2 TE couples. (b) Proposed TE module design which transforms the external gases between legs and the two TE couples in the traditional design, respectively, into the internal space/pores and one TE couples in the proposed design. (c) Representative vertical section of the TE couple in the traditional module design. (d) Vertical section of the TE couple in the proposed module design [10].

Sometimes coolant is circulated around the cool side of TEGs to maintain lower temperature. It was investigated that when coolant flow is kept in the turbulent region with Reynold number around 2300, an improved power output observed because the turbulent flow has a better heat transfer coefficient than laminar flows. Also, it has been found out SiO_2 Nano-fluid attains lower temperature compared to EG water solution and ZnO. Nano-fluid Coolants increase the power output of TEGs as compared to the use of water coolant or without. With the use of the Nano-fluids as coolants the TEM area decreases by 33%, which is the cost of TEGs system. Using of the coolants can led to overloading on cooling systems so the proper calculations and considerations should be done before using them[11][12].

IV. POSITIONING

The positioning of the TEG can be understood as the proper and the most optimal placement of the TEG in the vehicle, which won't affect the efficiency and working of the engine is a negative way as well as the TEG's efficiency and power output. It is preferred to place the TEG systems where a larger temperature difference is present because it can generate higher efficiency and power.

To integrate TEG setup in a vehicle, there are 3 possible location investigated

- Internal combustion engine: In the application of TEG in ICE, there is need of heat exchangers at hot and cold sides of the TEG. The involvement of heat exchanger complicates the designing and application of TEG.
- Cooling system: the installation of TEG on the cooling system can cause damage to ICE as cooling system is very important component in optimal efficiency. Installation of TEG on cooling system leads to overloading of CS, and hence affect the working of the ICE
- Exhaust system: Exhaust pipe is a part of ICE which is used to reduce temperature and noise of exhaust gas, the efficiency of ICE can be increased by 5% or more by fine tuning of engine pumping to the resonant frequencies of EP. By placing the TEG on the exhaust pipe, the TEG has access of direct heat flow coming from the engine via exhaust gas but there is minimal interaction between TEG and ICE. But, by placing the TEG on the exhaust system, there is loss of backpressure and hence leading to reducing efficiency of TEG [11].

In the exhaust system there are three locations that are analyzed in the study done by (X. Liu et al) [13], a study was done, in which the TEG modules were placed in three different locations that

- Case1: TEG is located at the end of the exhaust system;
- Case 2: TEG is located between catalytic converter and muffler;
- Case3: TEG is located upstream of catalytic converter and muffler.

Within an Automotive system, the TEG cannot be placed directly at the Exhaust, they are integral parts in a commercial automotive that cannot be left for compromise, there are compatibility problems among TEG, CC (catalytic converter) and muffler. Both TEG and CC need heat to keep normal working in the vehicle Exhaust System.

In case 1, TEG was placed at the end of the exhaust system, so the interface temperature of the heat exchanger was just 210 C on average. The highest temperature was 240 C at the inlet and the minimum temperature was approximately 170 C at the outlet. For generally available low temperature thermoelectric modules, the appropriate working temperature range is from 250 to 350 C, if these modules are used in the TEG, the temperature at the end of the exhaust system cannot meet the module's demand. Also, in terms of surface temperature, the heat exchanger has a lower average temperature and max. Temperature.

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In case 2, TEG is located between catalytic converter and muffler where the average surface temperature of the exhaust heat exchangers is observed around 270 C. This temperature is well in the range of the optimal working of the TEG and even higher temperature which is a positive factor for increasing the output power. The availability of uniformly distributed temperature gives a better overall advantage in TEG performance.

In case 3, TEG is located upstream of the catalytic converter and muffler; the interface temperature is observed at 280 C on average, which was beneficial for the arrangement of the thermoelectric modules. However, the highest temperature of Catalytic Converter was 230 C, while the lowest was 160 C; the average temperature of Catalytic Converter was just 190 C, which could not reach the ignition temperature (250 C) of harmful exhaust gas; CC was working under an abnormal condition. In this condition, the temperature range is high and well-distributed but cc working in the abnormal condition[13].

The most optimum for the installation positioning was calculated between catalytic converter and muffler because of the availability of uniform high surface temperature. No effect was seen on the catalytic converter, muffler, and heat exchanger due to backpressure and hence exhaust system was working properly.

V. COMMERCIAL VIABILITY

Since, a lot of optimization in design and material of Thermoelectric Generator has been in progress from last 2 decades, there has been a lot of effort in making the technology commercially viable. While deciding whether the device is commercially applicable and also effective, various norms about attributes linked to materials and design should be kept in mind.

- the specific amount of absorbable heat;
- heat conductivity;
- change of volume during thermal expansion;
- specific cost of material;

Waste heat recovery based on Thermoelectric has indicated promising results in countering CO2 emissions. As TEGs reduces off the load on the engine by providing electricity to the alternator as a support for running electrical functions in an automobile.

Most of the vehicles on-road are typical CLASS A, B and C type according to European and American standards. Approximately all the city cars have an exhaust gas temperature of 300 degrees to 500 degrees. A typical TEG fails to deliver desirable results when the temperature of the cold side of the Thermoelectric Module becomes less cold, resulting in a less temperature difference and reducing efficiency of the TEG. The main concern in a traditional TEG is having fluctuating Temperature due to city drive pattern which can result in performance degradation. With the introduction of Heat pipes within a TEG system the consistency of heat flow increases, also it helps in temperature regulation and allows more flexibility in TEG placement within a vehicle where there are space constraints[14].

The primary consideration while making TEG commercially viable is its efficient use within an automotive system. (Nyambayar Baatar et al)[15] proposed replacing traditional car radiator with TEG. It was found that power from proposed TEG setup is about 75W and calculated efficiency of the TEG is about 10.0%, overall efficiency of electric power generation from waste heat of engine coolant is about 0.4% in the driving mode of 80km/h. The proposed TEG will replace typical radiator without extra water pumps or mechanical devices aside from basic parts of legacy water cooling system of radiator. While a normal TEG setup within a vehicle tends to increase its weight, instead the above method resulted in a replacement of traditional automotive part from the vehicle along with increase in the overall vehicle efficiency.

Researchers have found in experiments that integration of TEG within an automobile can increase the vehicle fuel economy up to 20% by capturing waste heat of exhaust gas and converting 10% of it to electricity.

(B. Orr et al)[16] listed the potential benefits of Bi_2Te_3 and QW (Quantum Well) based thermoelectric power generation from the SUV and CNG engine power generator was examined. Under both these applications
the QW based TEG generated more power relative to the Bi_2Te_3 based TEG. For the SUV, the QW based TEG generated about 100–450 W, which should result in a fuel savings of about 2–2.3%. Within a CNG engine power generator (steady state) the optimized QW based TEG stack generated about 5.3–5.8 kW leading to a fuel savings of about 3%. The energy budget showed that, under both the applications, a significant fraction of the exhaust energy was rejected to the coolant [16].

Under all the optimization on commercial vehicle it was observed that the TEG in commercial vehicles (especially lower end) is still in experimental phase, although cost consideration is vital when deciding the product's commercial potential but a traditional TEG has not been improved enough yet for a discreet use without any introduction of another part for the purpose of increasing efficiency in city driving cycle.

VI. CONCLUSION

It has been observed that out of all the materials that are commercially used, Skutterdite has shown promising capabilities as compared to traditional Bi_2Te_3 and PbTe TEG, but because of its cost point of view, there isn't much scope for its application in commercial TEGs yet. On the other hand, introduction of new materials like Phase-Change Materials or other components (heat pipes) increased the TEG system efficiency by compensating with transient behavior of the flue gas and inconsistent heat distribution but also added a drawback of increased design complexity and weight of the TEG structure, instead we can replace a portion of exhaust conduit with a material compatible enough to hold the heat for consistent heat flow.

It has been concluded from various design related data that a properly optimized waste heat recovery system can be generated not just by TEG alone but by considering the effects of other components of the waste heat recovery system and then setting up the parameter of TEGs like leg length, the area available, the weight of the TEG, space available for the installation, number of Thermoelectric Module grouped together to make viable and efficient power generation unit and proper positioning of the TEGs. Using porous semiconductors and reducing the gap between semiconductors have also shown a significant effect on Thermoelectric generator's performance.

Collectively, it can be suggested that there is still research and study that is required to bring the TEGs practical application as a mainstream waste heat recovery system although the small application of TEGs can be seen in the high-end cars but visible change can only be observed when these waste heat recovery systems are introduced in the A, B and C segment cars too as they constitute a large portion of the on-road driven vehicles.

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