Visvesvaraya Technological University

Belgaum, Karnataka-590 018

A Project Report on

"Automotive Waste Heat Harvesting For Electricity Generation"

Project Report submitted in partial fulfillment of the requirement for the award of the degree of

Bachelor of Engineering
In
Electrical & Electronics Engineering

Submitted by

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2019-2020

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Certificate

Certified that the project work entitled **“Automotive Waste Heat Harvesting For Electricity Generation”** carried out by Mr. Akash Rawat, 1CR16EE007; Mr. Anshu Kumar 1CR16EE011; Mr. Mainak Mukherjee,1CR16EE040; Mr. Anubhav Goswami,1CR15EE010 are bonafied students of CMR Institute of Technology, Bengaluru, in partial fulfillment for the award of Bachelor of Engineering in Electrical & Electronics Engineering of the Visvesvaraya Technological University, Belgaum, during the year 2019-2020. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the Report deposited in the departmental library.

The project report has been approved as it satisfies the academic requirements in respect of Project work prescribed for the said Degree.

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DECLARATION

We, [Mr. Akash Rawat **(1CR16EE007),** Mr. Anshu Kumar **(1CR16EE011),** Mr. Mainak Mukherjee **(1CR16EE040),** Mr. Anubhav Goswami**(1CR15EE010)],** hereby declare that the report entitled **"Automotive Waste Heat Harvesting For Electricity Generation"** has been carried out by us under the guidance of **Ms. Anju Das,** Assistant Professor, Department of Electrical & Electronics Engineering, CMR Institute of Technology, Bengaluru, in partial fulfillment of the requirement for the degree of **BACHELOR OF ENGINEERING in ELECTRICAL & ELECTRONICS ENGINEERING**, of Visveswaraya Technological University, Belgaum during the academic year 2019-20. The work done in this report is original and it has not been submitted for any other degree in any university.

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Abstract

Majority of the vehicles commercially available today and on the roads today use internal combustion engines(ICE) for the power source. Such engines utilize only small share of the fuel primary energy converted to kinetic energy, however majority of fuel primary energy is wasted while dissipated in the ambient air as waste heat or as hot exhaust gas. A remarkable potential for improving the efficiency of the ICE systems lies in the recovery of the energy wasted today. This paper presents an overview of the state of the art of current research of exhaust waste heat recovery systems utilizing thermoelectric generators (TEGs). Such systems provide the direct heat-to-electric energy conversion and allow building the exhaust energy recovery systems without adding moving parts to the vehicles. The review will present the overview related particularly to vehicle engines exhaust energy recovery systems, introducing the key para meters, components and factors that determine the performance of such systems.

Acknowledgement

The satisfaction and euphoria that accompany the successful completion of any task would be incomplete without the mention of people, who are responsible for the completion of the project and who made it possible, because success is outcome of hard work and perseverance, but stead fast of all is encouraging guidance. So with gratitude we acknowledge all those whose guidance and encouragement served us to motivate towards the success of the project work.

We take great pleasure in expressing our sincere thanks to ***Dr. Sanjay Jain****,* ***Principal, CMR Institute of Technology, Bengaluru*** *for providing an excellent academic environment in the college and for his continuous motivation towards a dynamic career.*

We would like to convey our sincere gratitude to ***Dr. K Chitra****,* ***Head of Electrical and Electronics Engineering Department, CMR Institute of Technology, Bengaluru*** *for her invaluable guidance and encouragement and for providing good facilities to carry out this project work.*

We would like to express our deep sense of gratitude to ***Ms. Anju Das, Assistant Professor, Electrical and Electronics Engineering, CMR Institute of Technology, Bengaluru*** *for his/her exemplary guidance, valuable suggestions, expert advice and encouragement to pursue this project work.*

We are thankful to all the faculties and laboratory staffs of ***Electrical and Electronics Engineering Department, CMR Institute of Technology, Bengaluru*** *for helping us in all possible manners during the entire period.*

Finally, we acknowledge the people who mean a lot to us, our parents, for their inspiration, unconditional love, support, and faith for carrying out this work to the finishing line. We want to give special thanks to all our friends who went through hard times together, cheered us on, helped us a lot, and celebrated each accomplishment.

Lastly, to the ***Almighty****, for showering His Blessings and to many more, whom we didn't mention here.*

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LIST OF ABBREVIATIONS AND SYMBOLS

TEG-Thermoelectric generator

HEV-Hybrid engine vehicles

I.C.-Internal Combustion

TE-Thermoelectric

BTR-Best temperature range.

SiGe-Silicon germanium

Bi2Te3- Bismuth telluride

CoSb3-Cobalt triantimonide

PbTe-Lead telluride

DNA-Deoxyribo acid

PCR-Polymerase chain reaction

NOx-Oxides of nitrogen

(x=1or 2 or 3)

WHR-Waste heat recovery

EGP-Exhaust gas pipe

EGR-Exhaust gas recirculator

BMW-Bavarian motor works

GMC-General motor company

GM-General motor

AETEG-Automotive Exhaust Thermoelectric Generator

ATEG-Automotive Thermoelectric Generator

CHAPTER 1

INTRODUCTION

While recent developments in electric vehicle deployment have brought numerous non-petrol and hybrid vehicles to the markets, the major share of transportation, especially for heavy vehicles are still carried out by rather inefficient internal combustion engines (ICE). It has been estimated that as little as 12% of fuel primary energy could be utilized by an ICE vehicle in average. Unused energy is in this case dissipated as heat in exhaust gases (temperatures 300...700ºC) and engine coolant (temperatures 60...100ºC). The engine power levels refer to quite high heat flux within the waste heat, therefore capturing even some part of this may provide quite healthy amount of power regeneration. Typical applications for waste heat harvesting proposed include thermoelectric generators (TEGs), organic Rankine cycle (ORC), six stroke engines, turbocharging, exhaust gas recirculation and many other.

In this paper the literature review of TEG-based solutions for automotive waste heat harvesting has been presented. While not yet present on the commercial vehicles today, the thermoelectric waste heat energy recovery systems have been shown to be beneficial for a variety of ICEs and vehicles ranging from motorcycles to heavy cargo trucks .TEG based systems provide a solid-state energy conversion system with least moving parts and complexity, making them one of the more feasible and reliable options for waste heat recovery. On the other hand, the TEGs provide rather low overall efficiency ratings.

To achieve a noteworthy benefit from added TEG energy recovery system, many aspects of performance and operation of TEGs needs to be taken into account when designing such systems. This paper aims to summarize the general outlines of the exhaust energy recovery systems buildup, presented in Fig. 1.

Basically, the domestic heating boilers but also stationary ICE power production Systems would follow the same principles considering building combustion exhaust energy recovery systems for vehicles. Most engines operate with an efficiency rate of about 30%, with most of the wasted energy lost as heat. There is an increased need to identify alternative energy sources and enhance the efficiency of engines in order to reduce the consumption of fuel. The purpose of this project is to examine whether lost energy can be recovered in the form of electricity to power the electrical components of a vehicle. Thermoelectric Power generator will be analyzed as possible solutions to recover this lost energy in order to improve the overall engine efficiency.

Study on automobiles gasoline powered internal combustion engine shows that only approximate 25% - 35% of the fuel energy is used to drive the engine, whereas 40% of the fuel energy is wasted in exhaust gas, 30% in engine coolant and 5% in friction and parasitic losses. If the waste heat can recover, not only the every Ringgit spends for fuel is become more valuable, but also can reduce the fuel consumption due to less fuel require to generate electric for vehicle.

1.1 TECHNOLOGY BACKGROUND

The basic theory and operation of thermoelectric based systems have been developed for many years. Thermoelectric power generation is based on a phenomenon called

"Seebeck effect" discovered by Thomas Seebeck in 1821. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators. Fig.1 shows a schematic diagram illustrating components and arrangement of a conventional thermoelectric power generator. As shown in figure, it is composed of two ceramic plates (substrates) that serve as a foundation, providing mechanical integrity, and electrical insulation for n-type (heavily doped to create excess electrons) and p-type 00(heavily doped to create excess holes) semiconductor thermoelements.

In thermoelectric materials, electrons and holes operate as both charge carriers and energy carriers. The ceramic plates are commonly made from alumina (Al2O3), but when large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllium and aluminum nitride) are desired. The semiconductor thermoelements (e.g. silicon-germanium SiGe, lead telluride PbTe based alloys) that are sandwiched between the ceramic plates are connected thermally in parallel and electrically in series to form a thermoelectric device (module). More than one pair of semiconductors are normally assembled together to form a thermoelectric module and within the module a pair of thermoelements is called a thermocouple. The junctions connecting the thermoelements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips. The potential of a material for thermoelectric applications is determined in large part to a measure of the material's dimensionless figure of merit (ZT). Semiconductors have been primarily the materials of choice for thermoelectric applications. There are challenges in choosing suitable materials with sufficiently higher ZT for the applications.

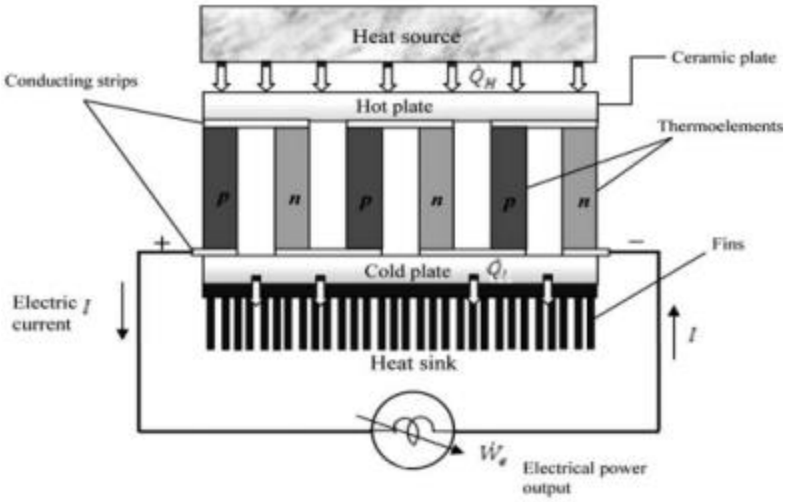


Fig.1 Components and arrangement of a typical single-stage thermoelectric power generator.

1.2 THERMOELECTRIC MATERIALS

Thermoelectric (TE) effect has been known for almost 200 years (discovered by Estonian-German physicist Thomas Seebeck in 1822) and is widely implemented in thermocouples for temperature measurement. A Seebeck coefficient Į is used to specify the electromotive force (emf) produced within the material per unit of temperature difference ǻT between the hot side of the material (Th) and cold side of the material (Tc) applied. Every material provides some TE effect but good TE materials provide significant Seebeck coefficient value. The p-type TE materials provide positive emf while n-type provide negative polarity. In practical assemblies, the TE material is built up as pylons (also referred to as legs), combining alternatively n- and p-type materials. As Seebeck coefficient is rather low, series connection between several tens TE legs is feasible for higher voltage output (used in commercial modules), see Fig. 2.

However, not all heat flux can be converted to electric power. Majority of heat power is carried through the material by heat conduction (Fourier heat) from hot to cold end of the material. A good thermoelectric material therefore has low heat conductivity Ȝ that will not allow the heat to pass without conversion to electricity. The TE materials are typically semiconductors with rather high electric resistivity ȡ. When the TE couple is loaded with current, the current passes through the material and again produces heat, of which major share is passed through the material.

The TE material resistance is the main reason for the high TEG source resistance. All three parameters listed above (Į, Ȝ, ȡ) affect the productivity of the TE material. One of the best figures to characterize the TE material efficiency is dimensionless figure of merit ZT, which combines the Seebeck effect, heat conductivity and electrical resistivity The ZT value can be used to assess the energy conversion efficiency from heat to electricity. This will always remain lower than ideal Carnot heat engine efficiency and can be expressed as The research for different semiconductor TE materials has yielded several advances recently that provide several options for building rather efficient direct heat-to-electric converters. Several materials are known with quite high values of ZT; however, different material properties provide variance in the ZT.

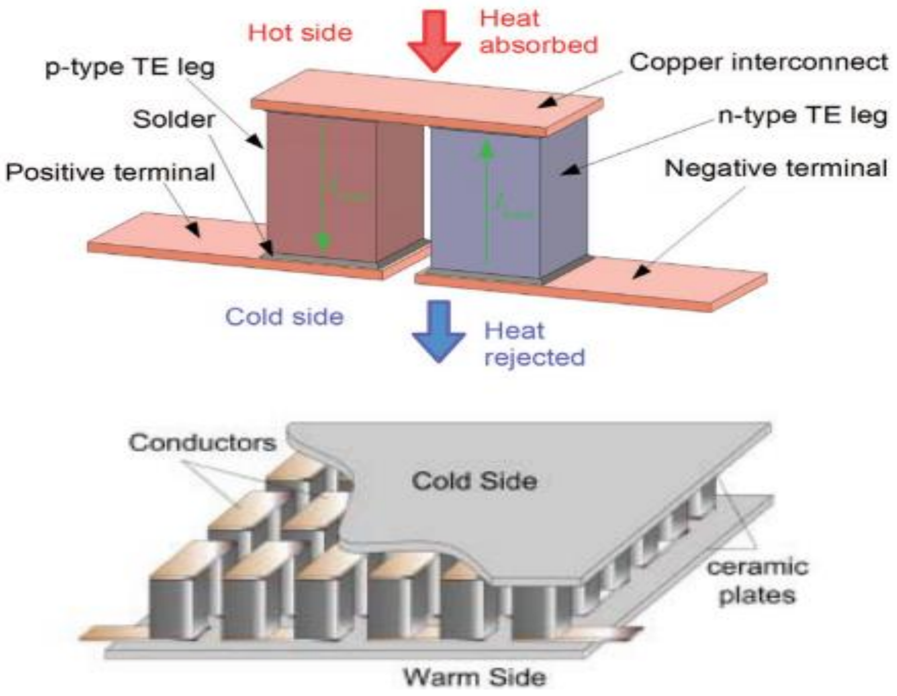


Fig. 2. Thermoelectric couple (top), and 18-couple TE module (bottom).

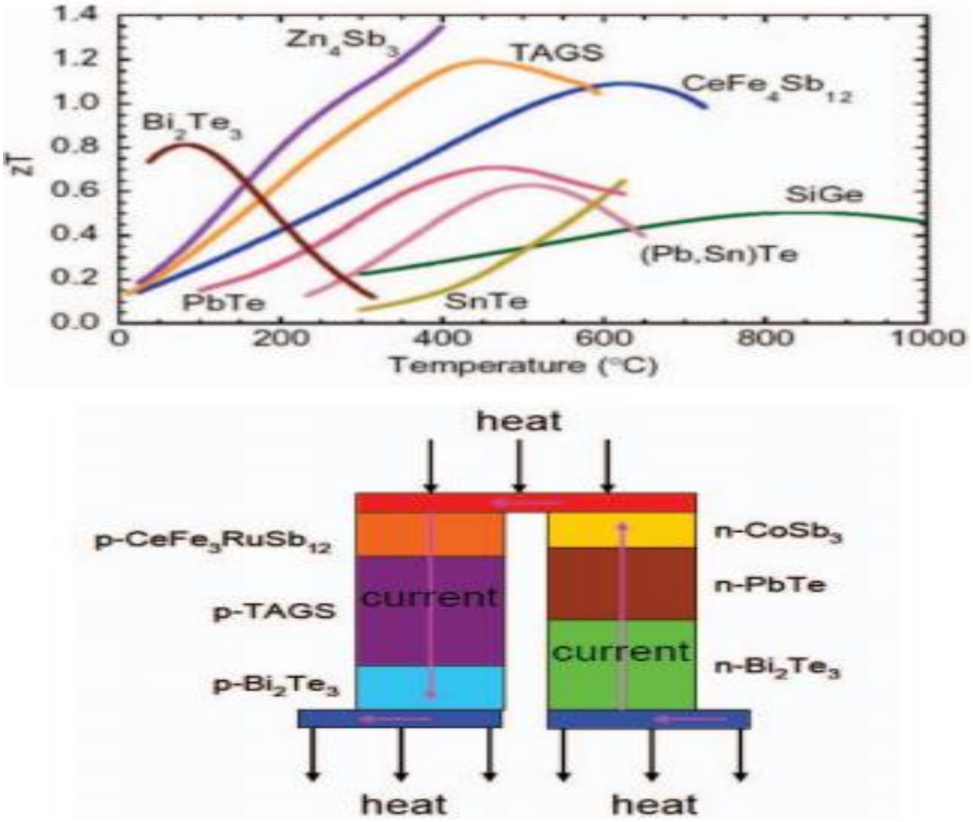


Fig. 3. Figure of merit (ZT) for different materials (top) and example of segmented TE couple (bottom).

They have limits to operating temperature [9] (Fig. 3). The heat flux through the material and resulting temperature difference for a particular application can be optimized with the material geometry used for TE module legs. To achieve higher efficiency in energy conversion and wider operating range segmented TE couples can be used (Fig. 3). Returning to formula (1) and (3) above, the electric power output of a thermoelectric unit is higher with greater temperature difference *ǻT* applied between the ends of the material and applying materials with high *ZT* for the temperature range.

Commercially available materials today are providing *ZT* value close to 1, which can be considered feasible in a range of applications. For lower temperature ranges the bismuth-tellure (BiTe) built modules provide the best effect (see Fig. 3). Discussed in the section about the heat exchangers, the hot side of the heat exchanger is likely to have temperature even over 300°C [12]. In these areas, BiTe modules reach their limits and are no longer feasible, as other materials provide high *ZT* values and high temperature withstand (see Fig. 3).

Commercially available materials today are providing *ZT* value close to 1, which can be considered feasible in a range of applications. For lower temperature ranges the bismuth-tellure (BiTe) built modules provide the best effect (see Fig. 3). Discussed in the section about the heat exchangers A sample of theoretical efficiency values for TEGs having this *ZT* value are presented in Fig. 4, for different temperature difference *ǻT* values in relation to TEG cold side temperature *Tc*. It can be seen that for highest efficiency values, the *Tc* should be kept as low as possible regardless of temperature difference.

This also provides a starting point for the automotive applications to use as much high-temperature exhaust as possible for achieving greater temperature difference.

Heat source in this case cannot be the only TE module in contact with exhaust gas due to low heat transfer rate. Instead, special design of heat exchangers has to be applied to harvest the heat from hot gas and pass it then to the TEG module.

CHAPTER 2

LITERATURE REVIEW

2.1 Concept

Seebeck Effect:-

Seebeck found that if you placed a temperature gradient across the junctions of two dissimilar conductors, electrical current would flow. The effect is shown below in the Fig.4

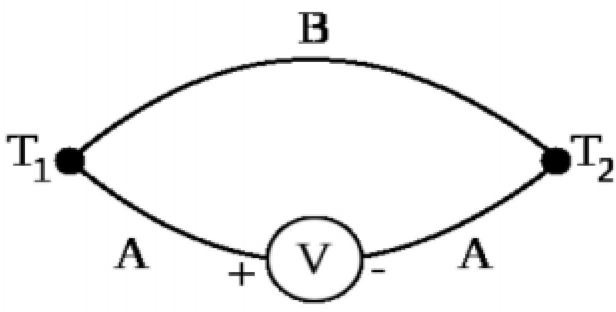


Fig.4 Seeback effect

Peltier Effect:-

Peltier, on the other hand, learned that passing current through two dissimilar electrical conductors, caused heat to be either emitted or absorbed at the junction of the materials. See Fig.5

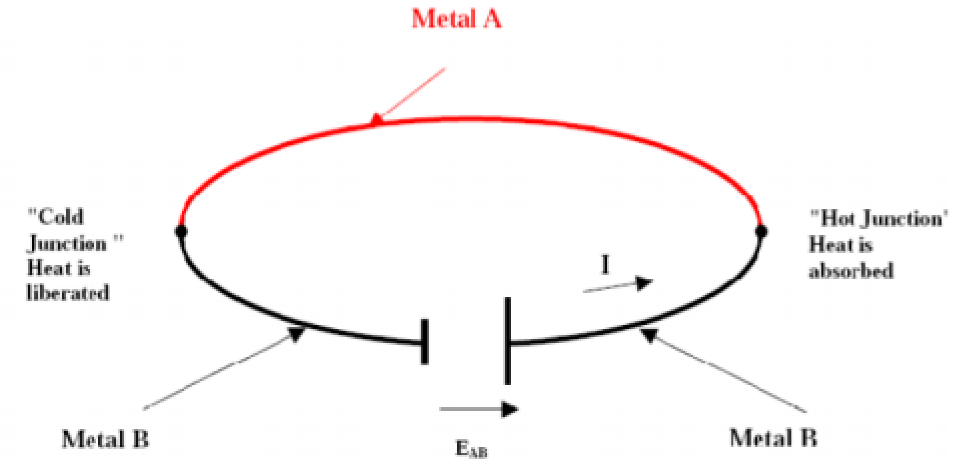


Fig.5 Peltier effect

Thermoelectric Effect:-

The phenomenon involving an inter-conversion of heat and electrical energy may be termed as thermoelectric effect. The effect is shown in Fig.6

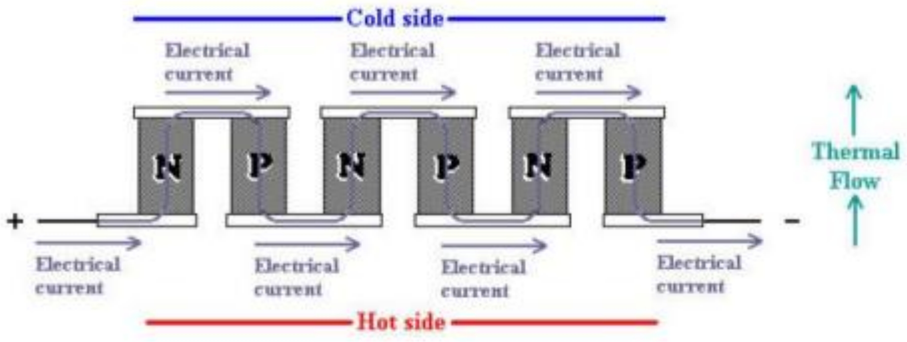


Fig.6 Thermoelectric effect

2.2 Construction

Thermoelectric generator is a device that converts thermal energy directly into electrical energy. The TEG structure is “sandwich like”, with thermoelectric materials which are “sandwiched” by two heat exchanger plates at its ends respectively. One of the two exchangers is at high temperature, and hence, it is called the hot side of the TEG; while the other side is at lower temperature and is called the cold side of the TEG. There are electrical-insulatethermal-conductive layers between the metal heat exchangers and the TE material of TEG. The two ends of n- and p-type legs are electrically connected by metal .The structure of TEG is as shown in fig.7

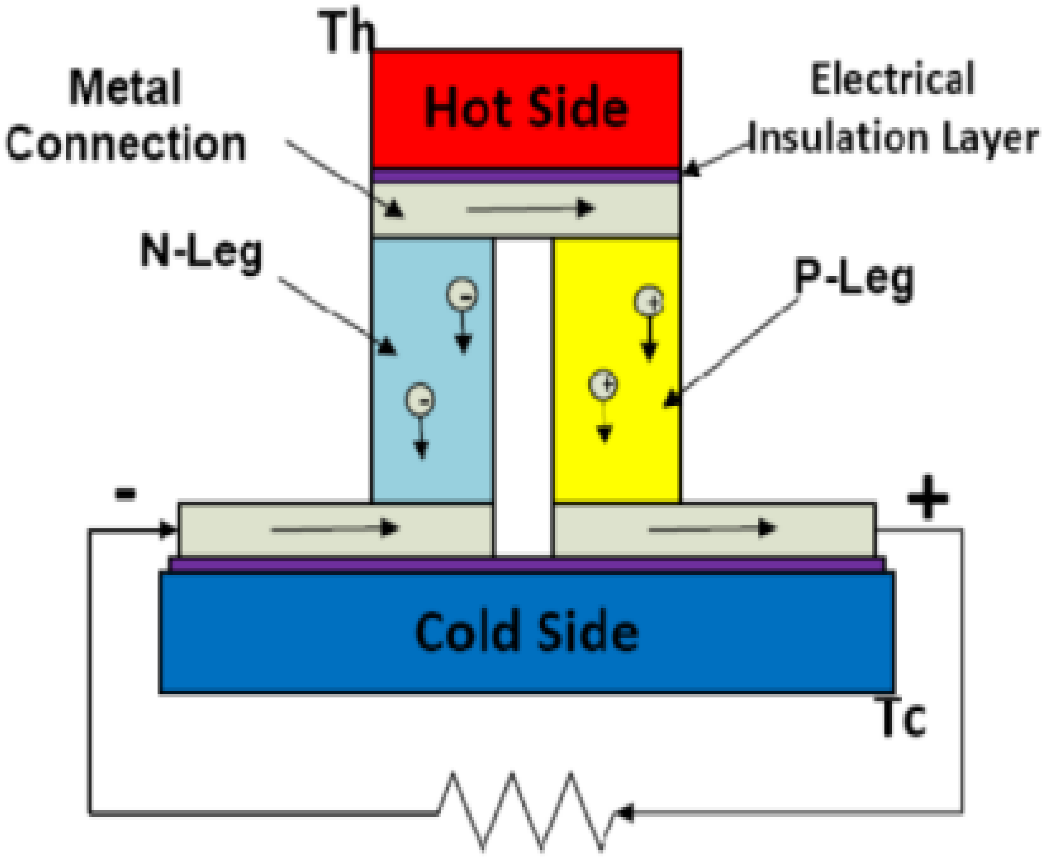
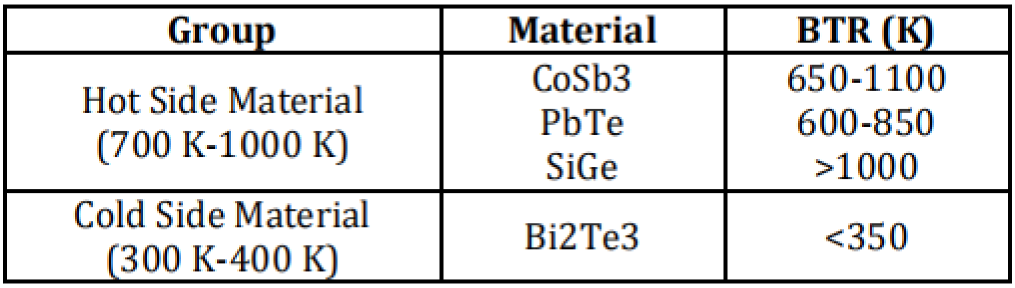


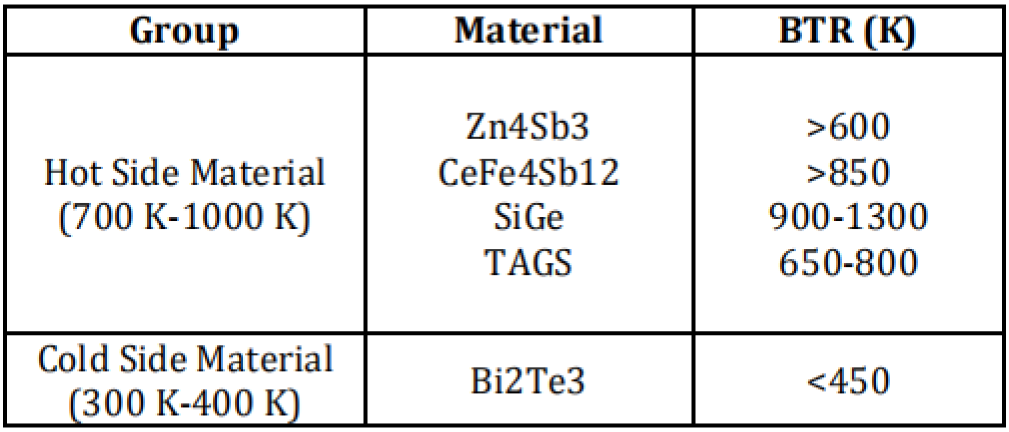
Fig.7 Simplified illustration of TEGs

Metals have been the main materials used in building TEGs, Despite metals' merit of high ratio of electrical to thermal conductivity, modern TE materials includes 26 main semiconductors. The performances of TEGs are largely affected by the materials used. Hence, the selection and combination of TE materials is important for the design of a good TEG. It is necessary to examine and compare the various TE materials. TEGs mainly have segmented structures. Within a segmented structure, each material should be used in their best temperature range (BTR).



Group	Material	BTR (K)
Hot Side Material (700 K-1000 K)	CoSb3 PbTe SiGe	650-1100 600-850 >1000
Cold Side Material (300 K-400 K)	Bi2Te3	<350

N-type material groups by best temperature range



Group	Material	BTR (K)
Hot Side Material (700 K-1000 K)	Zn4Sb3 CeFe4Sb12 SiGe TAGS	>600 >850 900-1300 650-800
Cold Side Material (300 K-400 K)	Bi2Te3	<450

P-type material groups by best temperature range

In modern TEGs, two or more types of materials are usually used in one leg, to increase the efficiency of the TEG. This approach of increasing TE couple efficiency is called as segmentation. It is a thumb rule that, the compatibility factors of materials within the same leg cannot differ by a factor of 2 or more. If this rule is violated, the maximum efficiency can be decreased by segmentation. Thus, the compatibility factor, is one of the important considerations while selecting TE materials. The value of u which maximizes the reduced efficiency is called as compatibility factor. It is denoted as, and can be expressed as,

$$s = \frac{\sqrt{(1+zT)}-1}{\sigma T}$$

Where,

Z-Figure of merit (µV/K),

T –average temperature (T2+T1)/2 in the device(K),

σ -Seebeck coefficient (V/K),

u- current density (A/m3),

S-Compatibility factor (1/V)

It is clear that *s* depends on temperature of materials which is derived from other temperature dependent properties like σ, κ, and ρ. It means that cannot be changed with device geometry or the alteration of electrical or thermal currents.

2.3 Working Principle

TEG consists of one hot side and one cold side. The hot side with higher temperature, will drive electrons in the n-type leg toward the cold side with lower temperature, which cross the metallic interconnect, and pass into the p-type leg, thus developing a current through the circuit as sown in Fig.8. Holes in the p-type leg will then follow in the direction of the current. The current can then be used to power a load.

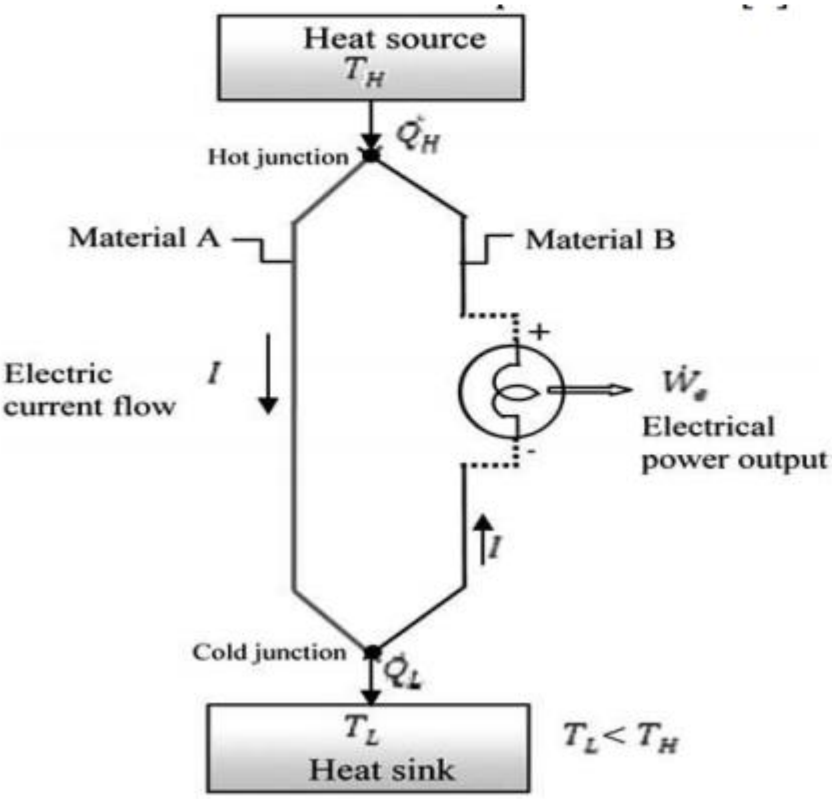


Fig.8 Principle of thermoelectric generator

If temperature difference is kept constant, then the diffusion of charge carriers will form a constant heat current, hence a constant electrical current. If the rate of diffusion carriers were equal, there would be no net change in charge within the TE leg.

In Automobile:-

The main focus of energy conversion is on three conversion locations mainly exhaust gas pipe (EGP), exhaust gas recirculation (EGR) cooler, and retarder. The most significant factors for the waste heat quality are power density and temperature range. The EGP is the target of the most automobile waste heat recovery related research. The exhaust system contains a large portion of the total waste heat in vehicle. The gas flow in exhaust gas pipe is relatively stable. Fig.9 shows that TEG utilizing the exhaust gas heat for operation. With exhaust temperatures of 973 K or more, the temperature difference between exhaust gas on the hot side and coolant on the cold side is close to 373 K.

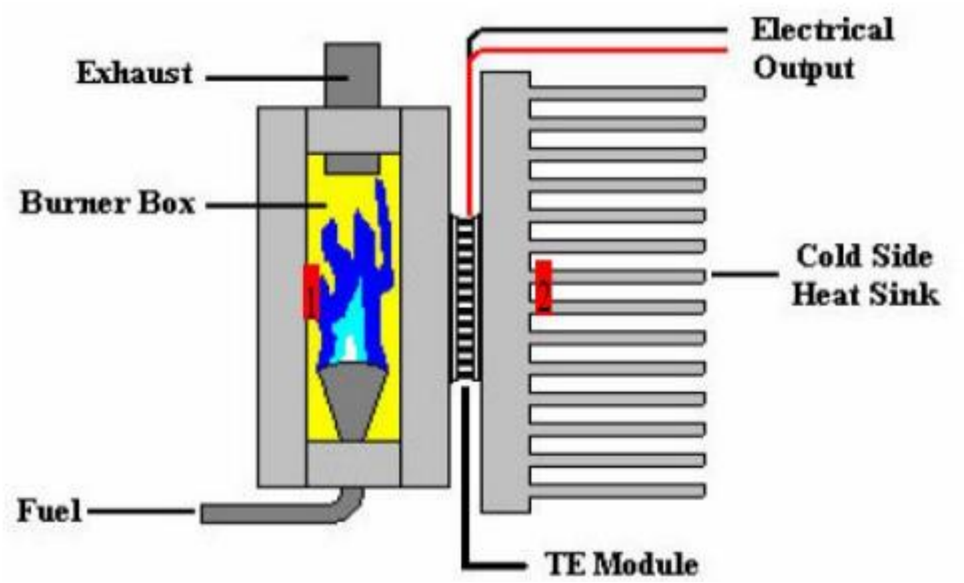


Fig.9 TEG utilizing the exhaust gas heat

This temperature difference is capable of generating 100-500W of electricity. In the water coolant based system, though the temperature is lower, it may be high enough to produce significant electricity for use in the vehicle when TEGs are attached. The main advantage of EGR gas is large temperature difference. Since EGR gas comes directly from the cylinders, its temperature is in the range of 820 K-1050 K, which is similar to that in exhaust manifold. Considerable amount of heat. In the power plants and other industries there are lots of flue gases produced having significant amount heat. In the chimneys the temperature of flue gases would be a round 373K which is the hot junction & the ambient air is cold junction having temperature 308 K. So there is temperature difference of 353 K. Applying the same technique to this it will gives output of 4.583 mV for one thermocouple loop so by adding these in series in large number we can generate large amount of electricity

CHAPTER 3

PROPOSED MODEL

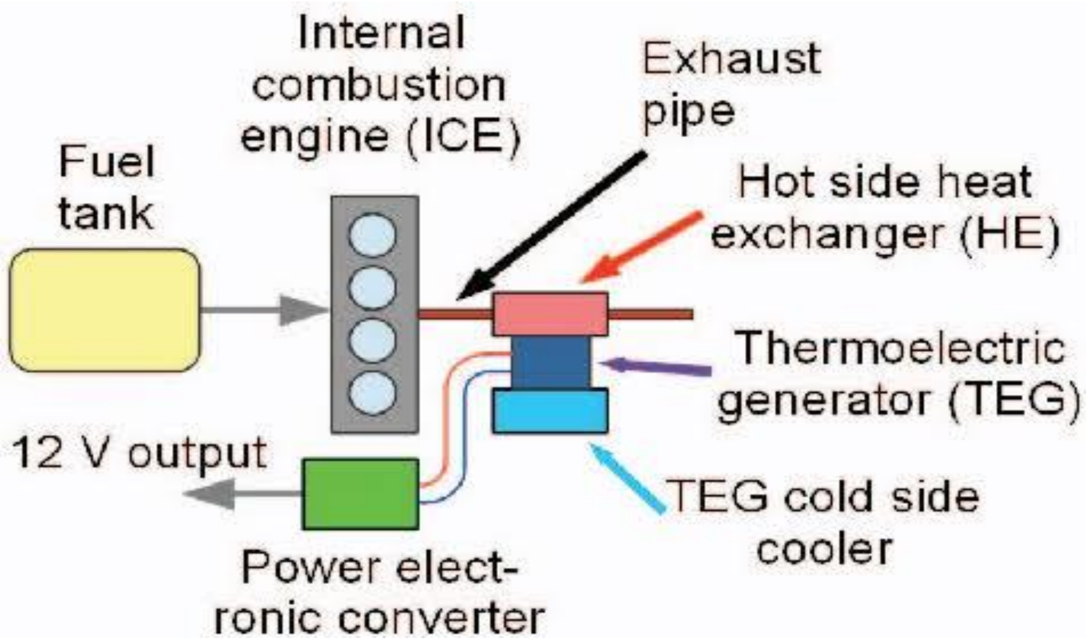


Fig.10 Proposed Model

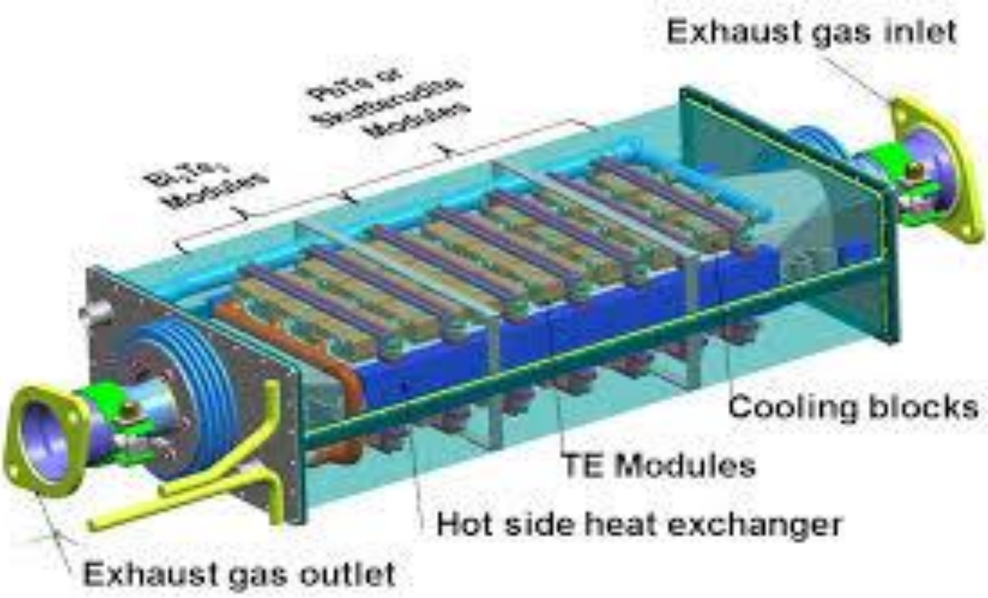


Fig.11 Thermoelectric Generator

An ICE used as automotive power source utilizes typically diesel or then petrol fuel. A general reference to energy utilization distribution is presented in Table I . In general it can be seen that exhaust products carry roughly 40% of the energy used in the engine and coolant carries another 30% . For an engine with 50 kW mechanical power utilized this means 67 kW of power wasted in exhaust alone. Harvesting less than 2% of this power could provide electric supply of 1 kW, sufficient for the devices in the vehicle supplied by alternator.

The mechanical energy output can be rather variable due to driving cycle characteristics and this means also variation in the efficiency of the engine While the engine load and rotation speed are low (for example when idling) the amount of exhaust from combustion is also low. Considering other heat transfer in the engine (especially coolant) the temperature of the exhaust in this case is also quite low.

When the engine is running at considerable load and higher rotation speeds, both the amount of exhaust as well as exhaust temperature are higher. Such variations in engine exhaust output provide additional design challenges for the TE heat harvesting systems. For example, it would need consideration which levels of engine exhaust output the TEG system would be optimized for. It is likely that the power needed for cooling liquid or air circulation could be even higher than TEG output for unoptimal operation. This affects the selection and design of heat exchanger, TEG, cooling and power converter units. For the initial exhaust parameters selection, values described in the literature of the exhaust for common vehicle engines have been listed in Table II.

The simplest heat exchanger to be heated by the hot exhaust gas is the exhaust pipe itself. Use of exhaust pipe for thermoelectric hot side heat supply, presented in provides a rather trivial, small in volume set-up. Air cooling used in this case does not provide high heat dissipation capability and it is likely that the cold side of the TEG module will heat up also as a result of heat conductivity through the module. As a result, the amount of electric power produced remains very low at 4 W considering the total energy available in the hot gas. An example of heat-pipe supplied TEG system is presented in , where heat is transferred with 10 heat pipes from inside the exhaust pipe.

This design could be considered as one of the smaller ones; however the temperature difference provided is also quite low for efficient production. Another research with heat pipes on both hot and cold side is presented in . Having a more complex and efficient heat exchanger will require large surface areas that become in contact with hot gases. For this, additional space and volume around the exhaust system of the vehicle is required and it can be challenging in case of many vehicles.

In general, 3 locations for energy harvesting system have been proposed behind the exhaust manifold, between manifold and catalyst converter, right after the catalyst converter and in the end of . For the operation of the catalyst converter, the preferred location is after the catalyst converter, where the exhaust temperatures still remain rather high , but the catalyst converter operation is not affected. As the locations differ by the distance from the engine so do also the parameters of exhaust gases that are passing these regions . It has to be taken into account also that the heat exchanger would cause the pressure drop in the heat exchanger, but the decrease of temperature of the gas could also lead to volume decrease of the exhaust exiting the heat exchanger. The pressure drop has been indicated to vary from 45 to 10 000 Pa and beyond. It is considered quite

significant factor in several papers and even it is claimed to require mechanical energy from camshaft to push out the gases. This cannot be agreed with, as the pressure of the exhaust is high(300…500 kPa) compared to normal pressure of 101.6 kPa. The pressure drop in the heat exchanger on the other hand tends to have value more close to average air pressure normal fluctuation. There seems to be a tendency between the HE efficiency and pressure drop, namely more efficient heat exchangers seem to exhibit higher pressure drop values . It could thus be estimated, that an efficient HE can be designed and implemented on a vehicle that does not provide a pressure drop significant enough to harm the combustion efficiency. While the exhaust side heat exchanger is supplying the hot side of TE modules, the cold side of these modules needs to be actively cooled to guarantee the needed temperature difference for TE module to work efficiently. The common proposals for cold TE module side cooling are use of air or then liquid cooling. In the latter case both independent configurations as well as engine coolant system based solutions are presented . In general, for the higher power solutions presented, the coolant circulation is used.

Some research on engine coolant heat utilization has been done to observe the low-temperature heat harvesting. The system with heat pipes used air-cooling on the cold side, as the engine coolant liquid was supplying heat to the hot side. In this case the hot side reaches even over 100ºC at idle condition, when the air cooling is not that effective and remains at over 90ºC during driving. At the same time, the cold side provides temperatures of T_c=45 ºC while driving but in idling the T_c would be 20ºC higher than this. This system provided efficiency of 2.1% and output of 75 W while driving at 80 km/h. However, also collecting the coolant heat can have limits, due to efficiency of modern diesel engines. It has been estimated that in winter conditions the low-power engines would even have trouble reaching their normal operating temperature at 70ºC.The TE module as a power source can be described as a simple voltage source with remarkable source resistance

The emf of the source is proportional to the Seebeck coefficient times temperature difference according to . The TEG module source resistance is due to the TE material proprietary resistance and compared to typical electric conductors has rather large value. Considering the source resistance constant, it can be estimated that the output power of the TE module is at maximum if the external load resistance is equal to the source resistance value.

TE module output characteristics presented in reveal close to linear relation between output voltage and current. The output power on the other hand is varying in quadratic manner with a distinctive maximum power point. Keeping in mind the low overall efficiency of the TE module the power of the TE module should be harvested at maximum power point for maximizing the benefit. The automotive TE applications see high variation in the dT values due to variable loading of the ICE. This means that the voltage in the output of the module will also vary and maximum power point keeps shifting.

For TEG modules in general the maximum power point tracking (MPPT) systems are suggested while methods for MPPT tracking are similar to ones used with photovoltaic supply: perturb and observe , incremental conductance, open circuit voltage ,short-circuit current and many more. The maximum power point is usually found within 5% accuracy . The MPPT systems can be integrated to the power electronic converter control systems, used for raising the voltage from TEG to automotive

12 V level. Several different converter topologies can be used for such conversion, most popular ones being boost and sepic topologies. These converters operate at high switching frequencies and the output voltage is set by a fast-acting controller using PWM modulation. In order to implement the MPPT functions, additional slow control loop is added . As the TEG and heat exchange system provide relatively high inertia and thus low output power variation rate, it is sufficient if the MPPT control is acting at only few times per seconds sample rate less than 10 Hz) . Pointed out in the first sections, a TEG is having higher electric output as the temperature difference is higher.

The heat exchangers can provide rather high surface temperatures (and resulting temperature difference) within the vicinity of the exhaust gas input, but the temperature would decrease as the exhaust passes through the heat exchanger. This question arises when high heat power levels are harvested from the exhaust gases using proper heat exchangers.

In such case the number of TE modules to be used for electric conversion will also be high. The type, assignment and connection of the TE modules depend also on their placement on the heat exchanger and the heat exchanger temperature profile . In automotive application such system can then provide significantly higher electric energy output than, for example, when connecting TE generator directly to battery .Care has to be taken also in connecting the modules in series and parallel before connecting the TEGs to the power electronic converter, due to location of distinct maximum power point for every operating temperature difference. While these seems to be the simplest connection schemes, different temperature properties of the TEGs can provide different working points; after connecting these modules directly none of the modules could reach their maximum power points. Analysis in reveals that the efficiency loss could be in series connection at 9% and in parallel connection at 12%.

CHAPTER 4

DESIGN PROCESSES

4.1 Automotive waste heat recovery systems using TEGs

Large multinational car companies like BMW , Ford , Renault and Honda have demonstrated their interest in exhaust heat recovery, developing systems that make use of TEGs. All of their designs are relatively similar. Typically the TEGs are placed on the exhaust pipe surface (shaped as a rectangle, hexagon, etc.) and they are cooled with cold blocks using engine coolant. Examples of a rectangular shaped and hexagonal shaped heat exchanger can be seen in Figs.12 and 13. This technology has not yet been installed in present production cars and is still in the concept stages. The BMW system uses a shell and tube heat exchanger. High temperature TEGs are used and the system is rated to produce 750 W from a number of 20 W rated TEGs. The Ford system heat exchanger uses many small parallel channels lined with thermoelectric material for the exhaust gases to pass. Liquid cooling is used in this case. This system is rated to produce a maximum of approximately 400 W with 4.6 kg of thermoelectric material. The Renault system is to be used on a diesel truck engine. It has dimensions of 10 cm × 50 cm × 31 cm. This system uses a counter fl flow heat exchanger arrangement using liquid cooling. A combination of high temperature TEGs at the high temperature end and low temperature. TEGs at the low temperature end were used. The modelled system is predicted to produce approximately 1 kW. The Honda system used a simple design of a thin flat rectangular box with TEGs placed on the top and bottom surfaces. Liquid cooling was used in this design.

The system consisted of 32 30 mm × 30 mm TEGs and produced a maximum of approximately 500 W. The claimed fuel consumption reduction is 3%. An image of the prototype from Honda can be seen in Fig. 14. Alternative heat exchanger designs have been explored such as a design by Dai metal. which used liquid metal exhaust heat exchanger with a solid state electromagnetic pump. The liquid metal transfers the heat from the exhaust gases to the hot side of the TEGs. The liquid metal used was a GaInSn alloy with a melting point of 10.3 °C. A total of 40 50 mm × 50 mm BiTe TEGs were used and the system managed to power a 120 W LED lighting array. Alternative heat exchangers on the cold side of the TEGs have been explored such a design by Hsuetal. which used finned air cooled aluminum heat sinks. This system used 24 BiTe TEGs and generated a maximum of 12.41 W with an average temperature difference of 30 °C.

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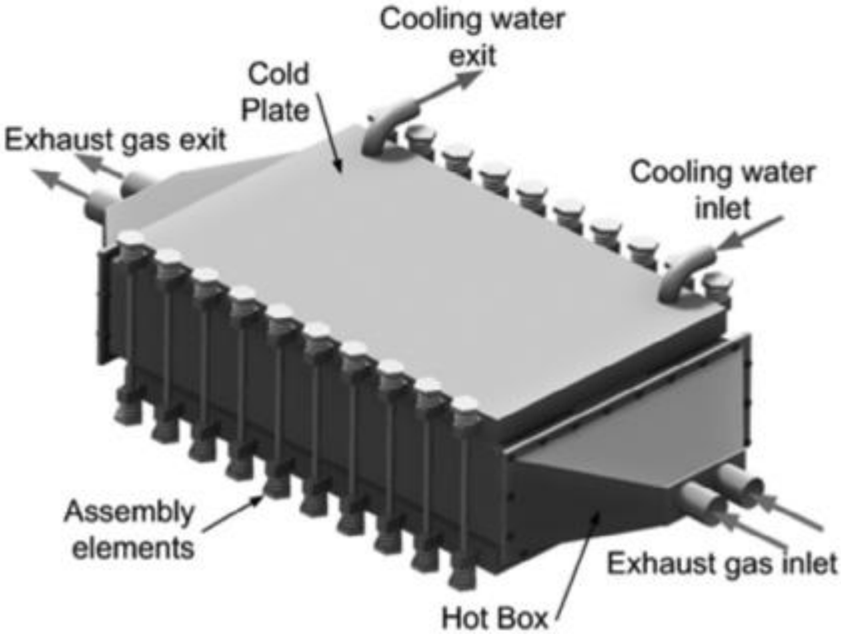

Fig.12. Rectangular exhaust heat exchanger

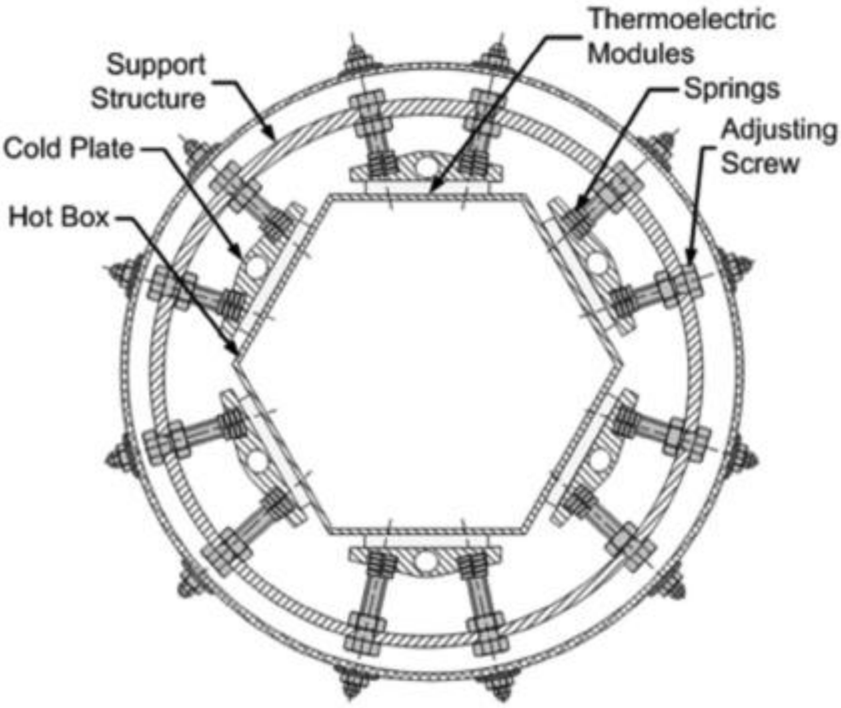

Fig. 13. Hexagonal exhaust heat exchanger.

4.2 Automotive waste heat recovery systems using TEGs and heat pipes.

A waste heat recovery system has been developed by Kim et al. and Baatar et al. to replace a traditional car radiator. This system is shown in Fig. 14. The aim was to replace the radiator without introducing an extra moving component. Only existing moving components like the water pump and fan were used. The use of heat pipes and TEGs allowed for heat transfer and power production without introducing extra moving parts. The system consisted of 72 TEGs of 40 mm by 40 mm size. 128 small diameter heat pipes were used. During idle conditions, the hot side was approximately 90 °C and the cold side was approximately 70 °C. During these conditions 28 W were produced. When run in the driving mode of 80 km/h, the hot side was approximately 90 °C and the cold side was approximately 45 °C. During these conditions 75 W were produced. Kim et al. has designed an exhaust heat recovery using both TEGs and heat pipes as demonstrated . In this system, the exhaust gases flow through an exhaust pipe with heat pipes protruding through.

The heat pipes absorb some of the heat and spread it through the aluminium block they are inserted into. The hot side of the TEGs are placed on the surface of the aluminium block. The rejected heat from the TEGs is removed by a water cooled heat sink placed on the other side of the TEGs. This system generated a maximum of 350 W using 112 40 mm × 40 mm TEGs. Goncalves et al., Brito et al. and Martins et al. developed a system that works in a similar way by using the heat pipe to extract the heat from the exhaust gases to the hot side of the TEGs and using a water heat sink to cool the other side of the TEGs. In this case a variable conductance heat pipe (VCHP) is used insteadof a standard heat pipe.

A VCHP operates in the same way as a standard heat pipe but can maintain a steady operating temperature. A VCHP contains non condensable gases inside. With increasing heat load, these gases are pushed up the heat pipe and into the expansion tank. This increases the length of the condensing section. Therefore with an increasing heat load, the operating temperature does not change because of the increasing condenser length removing more heat. Keeping a steady heat pipe operating temperature despite varying heat loads is useful when using TEGs because they can fail when operating over their rated maximum temperature. The actual system and schematic can be seen .Shown in Fig. 15 is a bench type proof of concept exhaust heat recovery system developed by Orr et al.This system used heat pipes on both sides of the TEG for transferring heat both to and from the TEG. This design demonstrated how the thermal resistance on the hot and cold sides of the TEG can be kept relatively low without having to introduce moving components. The system is air cooled using a fan to simulate air flow from a car moving at speed. A counter flow heat exchanger arrangement was used to maximize the rate of heat transfer. Exhaust gases were supplied from a small 50 cc gasoline engine. A total of 8 40 mm × 40 mm TEGs were used which generated approximately 6 W of power. A similar design is also demonstrated by Remelial but in this case for industrial waste heat recovery.

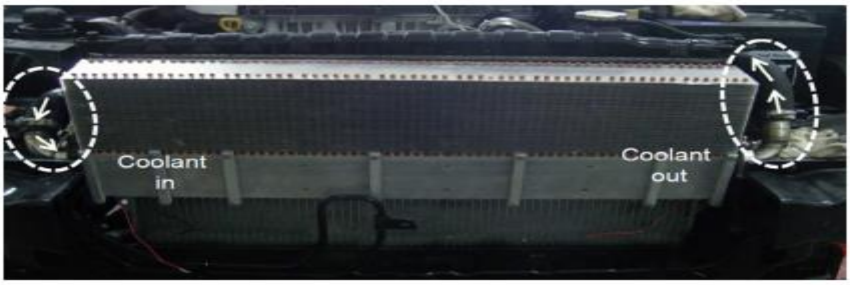

Fig. 14. Combined radiator and TEG waste heat recovery system.

Fig. 15. An exhaust heat recovery system using heat pipes to transfer heat both to and from the TEGs.

4.3 Heat Exchanger

The heat exchanger is an essential element of in AETEG which determines its overall performance. Since its primary function is to extract heat from flowing exhaust gas, an optimum design and sizing are critical for delivering the maximum power output. The efficiency of the TEG (ηTEG) which is given by,

$$\eta TEG = \eta HE \times \eta TE \times \varepsilon$$

where, ηHE is the heat exchanger efficiency, ηTE is the conversion efficiency of the cluster of TE modules and ε is the ratio of heat transfer from modules hot side to the cold side. An ideal heat exchanger should have low weight and high ηHE without causing severe backpressure to the flow of the exhaust gas. The back pressure will increase the parasitic losses in the vehicle.

Thermal efficiency (ηHE) of the heat exchanger mainly depends on three factors: (a) type, (b) internal geometrical shape and (c) materials of construction. The types of heat exchangers are classified according to the heat transfer mechanisms and the number of fluids.

Construction type and flow arrangements are some of the other parameters used for further classifications. In automotive TEG, the type of heat exchangers used are mostly indirect, contact type with direct heat transfer between different medium such as gas and solid in the hot side and solid and liquid in the cold side of the system. According to the construction type and geometrical shape classification, the heat exchangers used are mostly either box type or tubular with extended surfaces such as fins or heat pipes depending upon the space available for the integration into the vehicle [10, 11, 21].

The choice of the materials for the heat exchanger fabrication is determined by their thermal conductivity, density, and fabricability. Since most of the heat exchangers are with extended surfaces, its shell outer temperatures are significantly influenced by the thermal conductivity of the materials used. The density of the materials used decides the overall heat exchanger weight and the parasitic loss associated with it.

Materials which are easy to fabricate by multiple manufacturing routes could bring in design flexibility and result in reduction of overall AETEG cost. Stainless steel, aluminum and brass are some of the heat exchanger materials used so far and tested in both diesel and gasoline engines.

The heat transfer from the exhaust gas to the outer shell of the heat exchanger where the TE modules are placed occurs by the combination of the convection and conduction mechanisms. The thermal resistance (R) for the convective heat transfer is given by $R = 1/(h.A)$ where h is the heat transfer coefficient and A is the area of the heat transfer surface. Any internal arrangement which enhances the heat transfer area (A) increases the convective heat transfer which subsequently improves the hot side temperature (TH).

The thermal resistance for the convection mostly occurs in the boundary layer. Various kinds of fins with different shapes, dimensions, and arrangements are customarily set in the heat exchanger inside wall to enhance the turbulence resulting in the breakdown of the boundary layer. Figure 3 shows some of the most commonly used internal arrangements in box type heat exchangers. Fishbone and inclined plate fin arrangements are some of the shapes showing high heat transfer rate from the exhaust gas with acceptable level of back pressure [22, 23]. Serial plate arrangement with the plate's direction perpendicular to the gas inlet showed the highest back pressure. Such arrangement gave backpressure as high as 190 kPa in a shell of 280 × 110 × 30 mm with inlet and outlet of 40 mm diameter [23]. An open shell metal foam filled plate heat exchanger also showed a very high efficiency of heat recovery 83.5% [24]. However, the high tortuosity of the foam structure creates an unacceptable levels of back pressure. The temperature distribution in the heat exchanger along the exhaust flow direction usually tends to be lower in the downstream than the gas inlet region due to the heat loss to the TE module located close to the inlet [25]. Such nonuniformity in the temperature distribution reduces the power output of the modules placed beyond certain specified length in the downstream. Computational analysis carried out using different exhaust and coolant flow arrangements such as co-flow/parallel flow and counter flow suggest predicted a different overall power output [26]. However, it must be noted that a detailed experimental validation of these analyses only can confirm the preferred configuration that can maximize the overall power output.

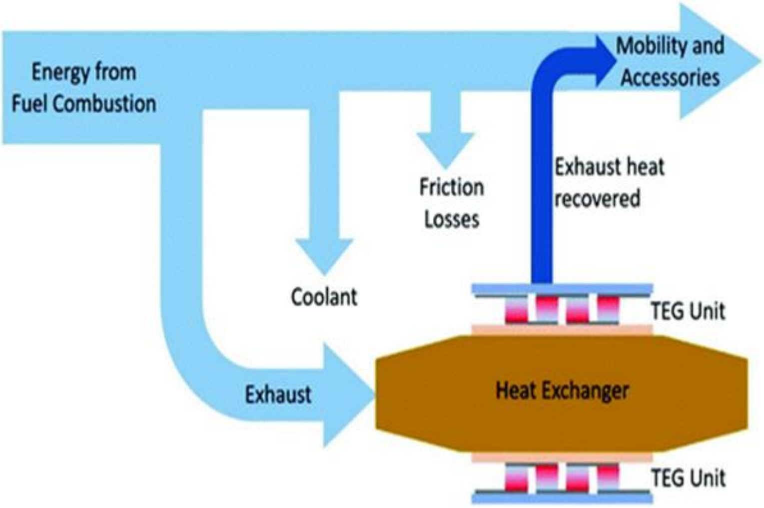

Fig 16. Proposed working model with Heat Exchanger

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

Research of the thermoelectric heat power harvesting for automotive applications has been carried out in cooperation with several vehicle manufacturers over the last decades. In the following, the most interesting results of the research have been described. Table III summarizes the achievements reported. The efficiencies presented include both TE-generator (TEG) individual performance indication and the heat recovery system total efficiency. The latter considers the energy within the exhaust gas as the input to the system and electric energy as the output. The reports present on the average quite conservative results of efficiency. The highest numbers are found for simulation case, reaching over 5%. If true, this would be a significant boost to the engine efficiency and could provide a significant fuel economy improvement. As the results indicate higher energy recovery efficiency for higher driving speeds, the improvement on the highway driving could be more noticeable. In more realistic numbers usable energy extracted by TEGs would be in range from 200...1000 W. While it does not match the ICE performance, it could provide supply to a growing number the electric and electronic systems in a vehicle. This way the alternator load could be reduced and engine mechanical output increased.

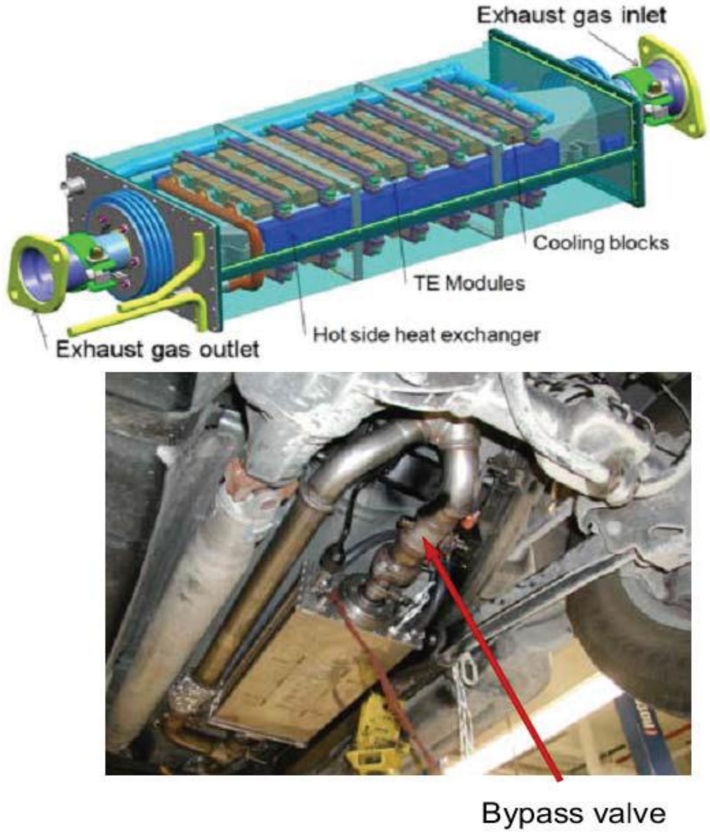

Fig 17. GM implementation of TEG system for exhaust energy recovery

5.2 DISCUSSIONS

The thermoelectric (TE) systems for waste heat recovery have currently rather low system efficiency, which prevents using them feasibly for the direct fuel energy conversion. However for the cases when the heat from a device is wasted in any case, as the exhaust heat from internal combustion engine, the TE systems could provide the benefit for improving the overall efficiency of the vehicle. The Rankine cycle based exhaust energy recovery systems can yield rather high performance with theoretical system efficiencies of up to 14% presented . In a system with both TEG and Rankine cycle turbine system, the TEG expected performance is only 10% of the Rankine cycle section theoretical output ; it is stated that during more common operating conditions the efficiency would be at remarkable 3 … 8%. At the same time, TEG systems have been reported to have efficiency ratings of 0.9 ... 5% for maximum conditions. The TEGs have however many advantages on the maintenance and reliability side, as TE modules does not contain any highpressure nor moving parts common to Rankine cycle systems.

TEGs are solid-state, silent, very small, completely scalable and durable . While the commercially available TE materials have already quite affordable prices, the overall TEG system cost is rather high due to numerous components needed in it. As the vehicle manufacturers struggle to find means to increase the fuel efficiency, it seems probable that the TEbased energy recovery systems would find their way into commercial ICE vehicles only when legislation would require this. Considering the latest trends in energy efficiency policies, such legislation updates are rather likely, but could in this case also provide increase to ICE vehicle and maintenance costs.

Waste heat recovery entails capturing and reusing the waste heat from internal combustion engine and using it for heating or generating mechanical or electrical work. It would also help to recognize the improvement in performance and emissions of the engine if these technologies were adopted by the automotive manufacturers. By using this thermoelectric system one can generate electricity from the high temperature difference and it is available at low cost. In heavy duty vehicles the smoke coming out of the exhaustion system will form the NOxgases which are major concern for the green house gases. But because of this the temperature will come down of exhaust gases so, the formation of the NOx gases will be minimal. If this concept of thermoelectric system is taken to the nano level or micro level then there will be ample amount of electricity can be generated which are just wasted into the atmosphere.

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If this concept of thermoelectric system is taken to the nano level or micro level then there will be ample amount of electricity can be generated which are just wasted into the atmosphere. The following figure shows the graph drawn between temperature difference and voltage under no load condition and with the cooling fan.

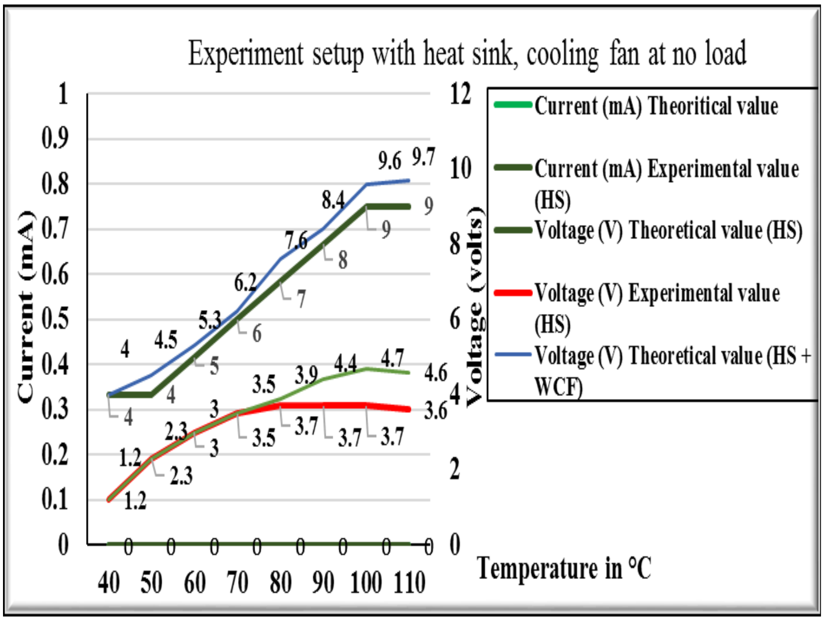

Fig. 18. Experimental setup with heat sink,cooling fan at no load

CHAPTER 6

CONCLUSIONS

Investigations have found that an appropriate way of improving the overall efficiency of the fuel use in a car is to recover some of the wasted heat. One of the prominent technology introduced for this waste heat recovery is TEG. TEG is having higher electric output as the temperature difference is higher. The heat exchangers can provide rather high surface temperatures (and resulting temperature difference) within the vicinity of the exhaust gas input, but the temperature would decrease as the exhaust passes through the heat exchanger. Automotive application such system can then provide significantly higher electric energy output than, for example, when connecting TE generator directly to battery.

- Both TEGs and heat pipes are solid state, passive, silent, scalable and durable
- Heat pipes can reduce the thermal resistance between the TEG and gases
- Heat pipes can reduce the pressure losses in the gas stream due to a reduced fin surface area.
- The use of heat pipes allows for more design flexibility because TEG placement is not limited to the exhaust pipe surface.
- Heat pipes can be used for temperature regulation of the TEGs.
- TEGs have limitations such as relatively low efficiency and maximum surface temperatures.
- Heat pipes have limitations such as maximum rates of heat transfer and working temperature ranges.
- A completely passive and solid state exhaust heat recovery system can be developed using both TEGs and heat pipes.

6.1 ADVANTAGES

- TEGs are solid-state device, which means that they have no moving parts during their operations.
- No moving parts so maintenance required is less frequently, no chlorofluorocarbons.
- Temperature control to within fractions of a degree can be maintained, flexible shape, very small size.
- TEGs can be used in environments that are smaller or more severe than conventional refrigeration.
- TEG has long life, and also it can be controllable by changing the input voltage/current.

6.2 APPLICATIONS

- One possible application of TG WHRS is as a replacement to the alternator in a car.

- Camping. A camping/car type electric cooler can typically reduce the temperature by up to 20 °C (36 °F) below the ambient temperature. The cooling effect of Peltier heat pumps can also be used to extract water from the air in dehumidifiers.

- Portable coolers.

- Cooling electronic components and small instruments.

REFERENCES

1. Pratiksha Pohekar, Pooja Alaspure, Pragati Punase, S.G. Tikhe, “Automotive Waste Heat Harvesting For Electricity Generation using Thermoelectric Generator A Review,” International Research Journal of Engineering and Technology(IRJET),vol. 05 issue 02,Feb 2018 .p.2395-0072.
2. Capel, E. M. Taib Ibrahim, Nursyarizal Mohd Nor, “Hybrid Energy from Exhaust System,” IEEE 7th International Power Engineering and Optimization Conference (PEOCO), 2013. pp. 134 – 138.
3. Haider, J. G. Ghojel, J. I. “Waste heat recovery from the exhaust of low power diesel engine by using thermoelectric generator,” International Conference on Thermoelectric (ICT). 2001, pp. 413 – 418.
4. Jaydeep. V. Joshi1 and N. M. Patel (2012), Thermoelectric system to generate electricity from waste heat of the flue gases, Advances in Applied Science Research.
5. Chan, C.W., Ling-Chin, J., Roskilly and A.P. (2013). A review of chemical heat pumps. Thermodynamic cycles and thermal energy storage technologies for low grade heat utilisation.p.1542-1546
6. Lauri Kütt, Matti Lehtonen (2015) IEEE 5th International conference on Power Engineering, Energy and electrical drives(POWERENG)