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Energy Harvesting System Using Thermoelectric Generators and Heat Pipes: A Review

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ABSTRACT

Environmental Protection issues and the global energy crisis worldwide have caused energy recovery techniques to come into play. One of the potential areas for this energy recovery is engine exhaust as huge amount of energy is lost in form of heat through exhaust gases. With appropriate recovery methods executed, considerable increase in efficiency of engine is obtained. For this aim, thermoelectric generators is proposed as the optimum solution as its solid state working doesn't have any moving parts or gas emissions and directly converts exhaust heat into electricity. Another promising technique to recover waste heat is usage of heat pipes. Heat pipes being excellent thermal conductors combine phase transition of fluid (typically water) to achieve efficient heat transfer. The present study focuses on various advancements achieved in the heat recovery from engine exhaust using thermoelectric generators and heat pipes and their combinations. The results of various researches depict the enormous potential of such technologies in saving non renewable energy sources and reducing environmental degradation.

Keywords: *Exhaust Gases; Heat Pipes; Heat Recovery; Thermoelectric Generators.*

1.0 Introduction

1.1 Engine exhaust heat

Due to globalization spreading across the world, consumption of fossil fuels increased deliberately, thus causing devastating effects on ozone layer and environment. Thus technologies reducing these consumptions and improving the overall efficiency of the system have gained much attention in the past few years. Automobile Manufacturers are putting strong efforts in recovering waste heat to reduce carbon footprints and greenhouse gas emissions and improving the overall efficiency of vehicle. Though intensive research is being done on recovering heat energy through regenerative braking in a vehicle, few researchers have focused on recovering engine exhaust heat.A significant fraction of fuel energy is rejected through the exhaust as waste heat, limiting the maximum efficiency of the engine to 42% [1].In a vehicle, almost 40% of the fuel energy produced in the engine is taken up by the exhaust gases, approximately 30% is transferredto the engine coolant, 5% is wasted as radiation and friction losses, and rest 25% is utilized for vehicle mobility and accessories[2].

Fig 1: Energy Distribution for an IC Engine [3]

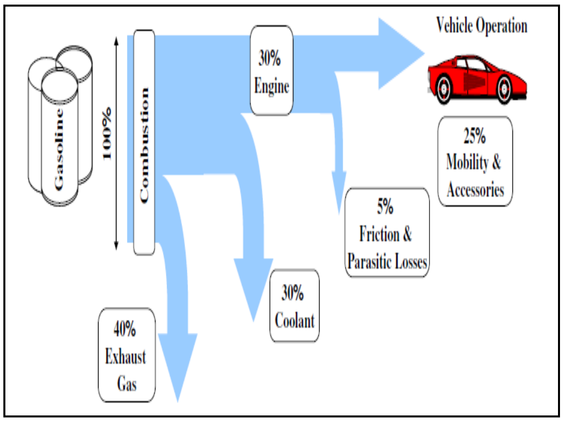

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Figure 1 shows the energy distribution of an IC engine in a vehicle. There are two possible areas of recovering engine exhaust heat viz. (i) Exhaust Gases and (ii) Engine Coolant. While Engine coolant can possess a maximum of 90 °C temperature, the maximum temperature of exhaust gases is over 700°C. Also, the energy possessed by exhaust gases of a vehicle, is of the same order of magnitude of mechanical power produced by the engine. Mechanical power produced is readily available, while utilizing the waste heat is a tough task [4].

Therefore recovering exhaust gas heat is most viable decision to make. Due to exhaust gases having high temperatures, most vehicle recover waste heat from the exhaust gases for electric power generation [5].

The waste heat recovery system is significant for increasing the overall efficiency of the vehicle and to reduce the fuel consumption by the engine.It would be possible to reduce the fuel consumption by about 10%, if 6% of the exhaust heat energy is transformed into electrical energy[6]. Increased efficiency and lower fuel consumption by improving the fuel economy leads to the production of fewer emissions from the exhaust which further leads to the reduction of greenhouse gas emissions.

1.2 Thermoelectric generators

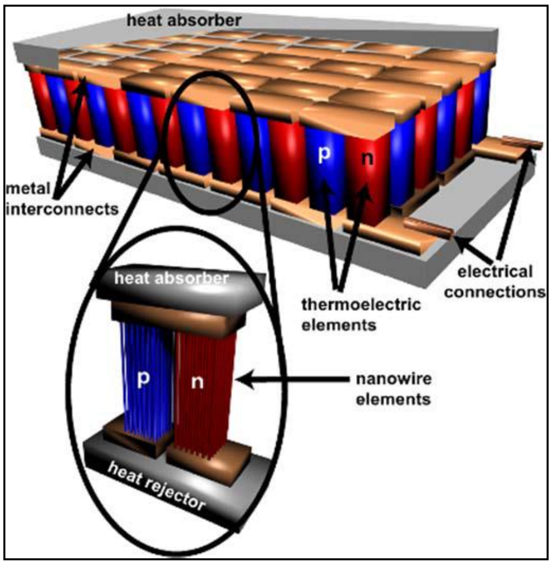
Waste heat from exhaust can be captured using different energy harvesting materials. Among various available heat recovery technologies, thermoelectric generators have gained much popularity[7]. Thermoelectric modules being compact and reliable, directly convert heat into electricity without producing harmful emissions. Also the modules operate in solid state and do not have any moving part or chemical reaction occurring at its surface.

A thermoelectric module works on the principle that when a temperature difference is maintained between two dissimilar materials, a potential difference is generated which is the Seebeck effect.

It is desired to have the hot side surface temperature of a TEG to be as high as possible, so as to maximize the Seebeck Effect [8].

A TEG consists of n-type and p-type semiconductors, arranged in couples, which can directly convert heat energy into electrical energy and can be considered as a useful device to execute the green technology practices[9,10,11].

Fig 2: Construction of a TEG



A figure of merit ZT is a dimensionless parameter taken into account to determine the performance of a thermoelectric material gives the heat absorbed in per area of the joint per second,

$$ZT = (\alpha^2/K)\sigma T \qquad (1)$$

Where, α stands for the Seebeck coefficient, σ represents the electrical conductivity, K is the thermal conductivity and T is the temperature[12,13].With the advancements in thermoelectric materials with large ZT lead to the application of the thermoelectric devices in various fields [15].

1.2.1 Limitation

With the application of new, cheap and effective materials possessing higher Z values, the usage of TEMs have significantly increases in the Automotive Industry.

But thermoelectric modules have high material cost and can withstand a maximum of 250 °C and thus posse'ssmall thermal efficiency.

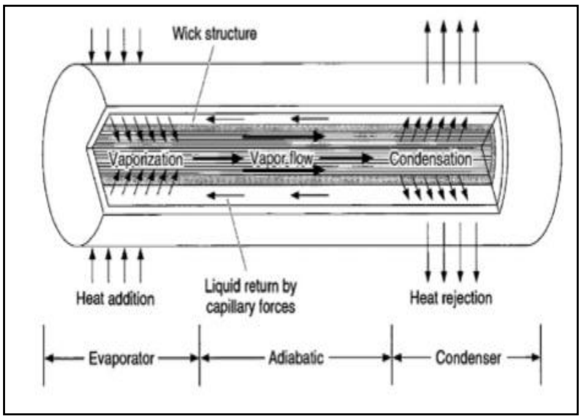
Rather than the core materials of the module, the linkages between the parts have a limitation of inability to work at higher temperatures. Though some manufacturers are trying to develop thermoelectric modules capable of sustaining high temperatures, still there are no modules available commercially which are compatible with the temperature of Exhaust Gases.

Thus there is requirement of a medium, which transfers heat energy from the exhaust gases to the modules efficiently and at compatible temperatures.

1.3 Usage of heat pipes

Heat pipe is a type of heat exchanger which combines the principles of both thermal conductivity and phase transition so as to get efficient heat transfer between two interfaces. Due to its simple working principle, heat pipes have dominated other traditional heat exchangers in the industries. A heat pipe is constructed of a sealed metallic pipe, containing small quantity of phase-changing fluid (typically water) filled at vacuum pressure, and the rest volume of the pipe consists either of a mix of thermal fluid vapor and non-phase-changing gas (typically air) or just thermal fluid vapor. The fluid rests at bottom (the evaporator region) due to gravity, where it is heated and changes its phase under the action of latent heat absorbed through heat conducted from the walls of the heat pipe. The vaporized fluid flows through the heat pipe system and condenses at the condenser region, transferring heat through the condenser region to the heat sink. Due to condensation process, the low temperature fluid droplets fall back at the evaporator region under the gravity or capillary action, completing one cycle of the process. The fluid is again evaporated and the cycle repeats. The heat pipes employment provides certain benefits such as compactness, economical, less weights due to lesser parts, effectiveness.

Fig 3: Working of a Heat Pipe



Now a days, heat pipes and thermoelectric modules are being used in combination to recover waste heat and transform the heat energy into electrical energy. Heat Pipes provides privilege to get controlled temperature of heat energy at the hotter surface of the modules while recovering maximum heat from the exhaust gases. This aids in employing the modules anywhere while making them work under operating temperature limits.

2.0 Energy Harvesting System

Gonclaves et al., 2010[16] used a combination of heat pipes with TEG for exhaust gases. The investigation with advanced thermoelectric generators showcased an efficiency of 5% heat recovery (transformed to electricity) of available (electric) energy for a hybrid car. As a consequence of which, the engine with an efficiency of 33% could achieve an extra mechanical power, resulting in 38% efficiency, and a saving of 5% in fuel. As per the system design, recovery of a significant part of the exhaust heat was achieved when the engine was at medium load/speed conditions, whereas at full power only one third was achieved.

Yu et al., 2014[17] investigated the startup time for TEG under different conditions. The experiments revealed that the start-up current significantly affects the durations to reach 40% and 80% of steady-state power, and the start-up durations showcased a difference of up to 70% to attain 40% of steady-state power, and 32% to attain a level of 80% of steady-state power. Corresponding to 60, 80 and 100 km/h speed, the temperature difference was 77.3, 105.5 and 132.0 °C respectively, across the leg; and the electrical potentials observed were 15.4, 20.5 and 25.0 mV, respectively. When 5, 15, 25 and 35 °C were taken as ambient temperatures, the temperature differences observed were 111.8, 108.8, 106.0 and 102.5 °C, respectively; and the subsequent electrical potentials were 21.9, 21.2, 20.7 and 20.0 mV, respectively.

Yang et al., 2011[18] worked on various materials to make heat pipes less in weight and more efficient. Lightweight materials can be used to reduce the weight of conventional copper heat pipes, however there is a problem of corrosion observed in lightweight materials.With a density of around 1800 kg/m^3, magnesium alloy is usually the most appropriate for present conditions and the thermal conductivity varies from 80 to 130 W/(m-K) but the magnesium alloys react with most of the liquids. Further work was conducted on different wick structures like the sintering and mixed mesh, which helps to enhance the heat flux in the boiling process.

Much lower temperature change can be achieved in adiabatic section due to reduction in the pressure drop inside the heat pipe.

Wang et al., 2012[10] designed the heat sink to enhance the ability of TEG. By lowering the length of heat sink under 14.5 mm, the power density of thermoelectric generatorwas further improved. In the initial stage of optimization, optimal fin-to-fin spacing of the heat sink was calculated using an analytical method.

As per the result, after the first-stage of optimization, higher performance of thermoelectric generators could be achieved.

The compromise programming method was used in the second stage of optimization, in which a compromise between the TEG performance and the heat sink performance was obtained when the heat sink volume is fixed.

It was also observed that the TEG output power density was improved by 88.70% and the heat sink efficiency was reduced by only 20.93%, at the compromise point when compared to the base case.

Bass et al., 1992[19]presented an exhaust based thermoelectric generator for installation on diesel trucks. 72 modules were installed to generate power in the experimental set up.

A hexagonal cross section generator was designed in which a square TEG of 0.5 cm thickness and sideof 5.3 cm was used with aluminum radiator based cold plates.

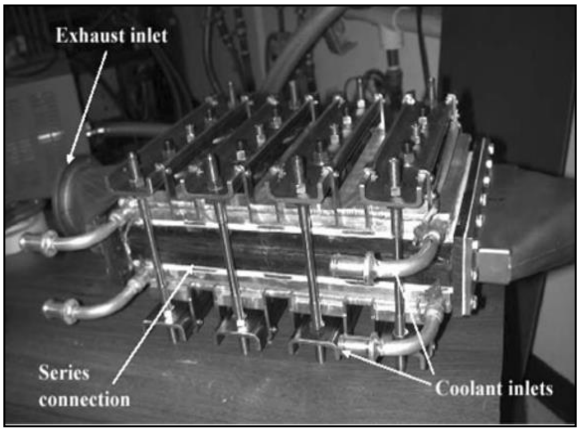
Bass et al., 1995[20] presented that boundary layer formation on the gas side causes a reduction in the generated power as exhaust gas velocity decreases due to the enlargement in the flow cross-section.

To ensure the full turbulence of exhaust gases, swirl fins were installed in the hot box.In the fin geometry, a discontinuity was introduced, by adding 0.953 cm gaps at 3.81 cm intervals.

Thacher et al., 2007[21] used 16 HZ-20 thermoelectric modules in a GM Sierra pickup truck. Thecarbon steel hot box contained eight modules mounted on either side and all the modules were attached in an electrically series arrangement but were thermally in a parallel arrangement.

The results showed that at a temperature difference of 200°C between the two sides of the bismuth-telluride modules generates 19 W. An ETEG setup of 330 mm x 273 mm x 216 mm dimensions weighing 39.1 kg generated a maximum power of 255.1W. Figure 4 shows the experimental setup used in the GM Sierra pickup truck.

Fig 4: Experimental Set Up Used in Gm Sierra Pickup Truck [21]



Ikoma et al., 1998[22], performed experiments using SiGe based exhaust thermoelectric generator. The experimental setup constituted 72 SiGe-based modules and each of the module generated 1.2W at a temperature difference of 563K between the hot and cold surfaces.

The experimental setup 440 mm x180 mm x70 mm in dimensions were used. Modules were mounted between a hot box and two water-cooled jackets working under conditions of 60 km/h hill climb mode. The inner shell had a rectangular cross-section and the two smooth faces with which the hot side of the module came into contact. The proportion of area occupied by modules to the faces of the inner shell was only 55%. Maximum power generated by the setup was 35.6W.

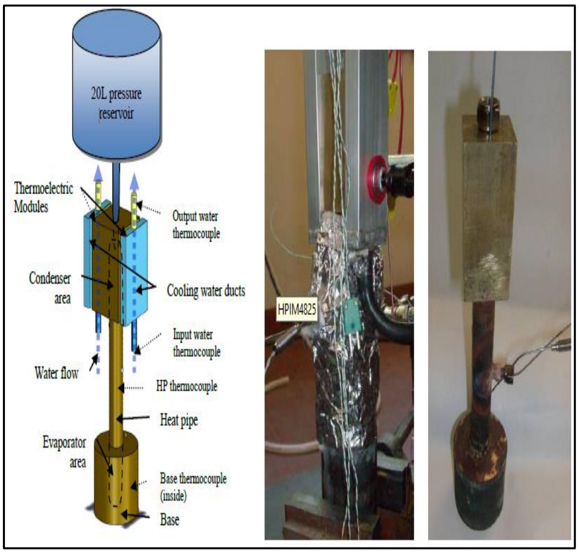
Martins et al., 2011 [4] incorporated heat pipes and TEG to design a model recovering waste heat from exhaust gases. Variable Conductance Heat Pipe was used to transfer heat from hot exhaust gases to the TEG modules at a temperature level compatible with the working of the modules.

The evaporator and condenser sections of the heat pipe were soldered to a cylindrical base to increase heat transfer area and an additional cylindrical tank of 20L having water was used to control the pressure inside heat pipe. Two blow torches were used to provide same heat of exhaust gases to the modules and other surface of modules were cooled by water flowing at a rate of 40 to 115L/s in the cooling ducts.

The results revealed the power generation of around 1kW at 1 bar absolute (atmospheric) pressure, and when the pressure was raised to 10 bar the power developed increased to 1.4kW. While using two different fluids for Heat Pipes; Water and Downtherm A, Martins et al., 2011[4] discovered that Downtherm A fluid possesses lower potential as compared to water.

However Downtherm A fluid could be useful where working temperatures are above 200°C since Downtherm A fluid works at lower pressures as compared to water. The experiment proved the capability of Heat pipes in dealing with very large power inputs and also showed the ability of these devices in recovering waste heat.

Fig 5: Experimental Set Up Dictating Usage of Heat Pipe and Cylindrical Tank with Thermoelectric Modules.[4]

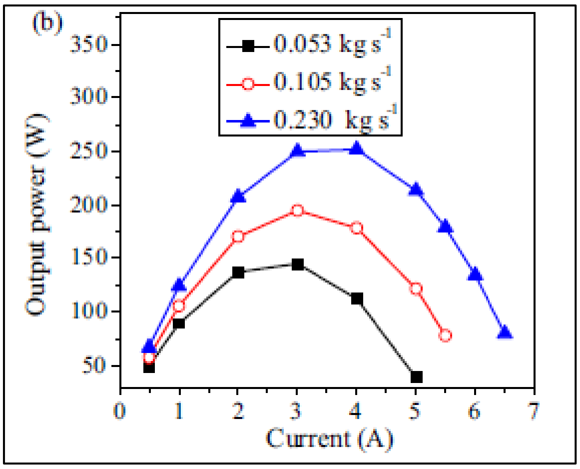


Du et al., 2015[10] developed a numerical model for thermoelectric generators coupled with both exhaust and cooling channels. The study carried out comprehensive design optimization of the cooling channels with both air and liquid as coolants.

With varying different parameters like coolant flow rate, coolant flow arrangement and Baffler length the Computational Fluid Dynamic analysis show higher output power generation with liquid cooling than air cooling.

This is due to negligible power required to pump liquid coolant recirculation as flow velocity is low for liquids in comparison with air.

Fig 6: Performance of TEG with Different Liquid Coolant Flow Rates



Kim et al., 2011(a)[5] in their research developed a system to replace radiators for Light-Duty vehicle’s internal combustion engine. The proposed system contained an aircooling unit constructed of heat pipes and heat sinks to cool the engine water coolant and in the study it was found that the cooling performance of a TEG is higher than the vehicle’s radiator. Additional benefits of such a system as described were to convert heat energy into electrical energy. The model used 128 Heat Pipes and 72 TEG’s and was tested under both idle and driving conditions.

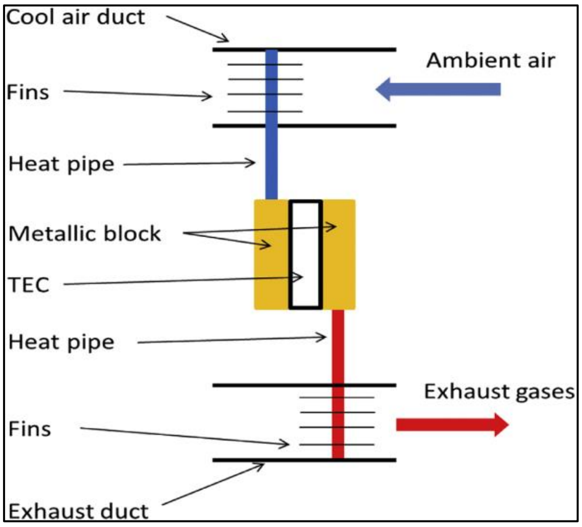
Maximum output power obtained from the proposed thermoelectric generator was 75 W in driving condition and in idle condition maximum power output observed was 28.5 W. 2.1% was the calculated thermoelectric module efficiency of the TEG and at a driving speed of 80km/h, 0.3% was the overall efficiency of electric power generation from the waste heat of the engine coolant.

Kim et al., 2011(b)[9] designed a thermoelectric generator system working in combination with heat pipes to produce electricity from a limited hot surface area. In the experiment exhaust gases were used as a heat source and the study revealed that the amount of electricity generated from the modules is directly proportional to their heated area. Thus the system so designed to obtain extended hot surface area with the help of 10 heat pipes, which acted as highly efficient heat transfer devices and transmitted heat to many modules. The maximum power developed by the system was 350 W when the evaporator surface of the Heat Pipe was heated to 170°C.

Espinosa et al., 2010[24] modeled two thermoelectric generators using engineering equation solver, one composed of Mg_2Si/Zn_4Sb_3 for high temperature applications and the other composed of Bi_2Te_3 for low temperature applications. The research used finite- difference method along with a strip-fins convective heat transfer coefficient and the results concluded various parameters of the TEG like connection, material, proportion, and size influence its maximum power output. The results of the model were validated against the experimental data available for a truck diesel engine.

Orr et al., 2014[25]developed a waste heat recovery system which consisted of a combination of 8 TEG's of 40*40mm size and 2-6mm diameter heat pipes for each heat sink. The system converted heat to electricity with a conversion efficiency of 1.43% which was 1/15th of the maximum carnot efficiency. The maximum power produced by the modules was found to be 6.03 W when charging a 12V battery.

Fig 7: Proposed Model For Usage of Heat Pipes and Teg [25]



Karri et al., 2010[26] developed a system that constituted of a TEG (Thermoelectric Generators) that was placed posterior to the catalytic converters and insulation was done on the interceding exhaust piping and according to the motor vehicle industry, it is advisable to avoid placing TEGs in the middle of the exhaust manifold and the catalytic converters as it can possible cause retardation in the rate of heating of catalytic converters, thereby leading to an increased pollutant release. The probable positions of TEG is further limited by the temperature limits.

The aim of Baatar and Kim, 2011[27] research was use a proposed TEG instead of a conventional radiator and also use basic parts of water cooling system of radiator and avoid the usage of additional mechanical devices and water pumps etc. The suggested thermoelectric system, extracts the heat from engine coolant, as the waste heat of coolant is used to generate electricity. Also, due to the air-cooling structure and additional cooling effects by heat conversion to electricity, the cooling performance as to the radiator can be considerable. The proposed engine coolant TEG has air-cooling structure contained a hot side block and a cold side block made of heat pipes and sinks. The hotter side block of TEG consists of the inlet and outlet ports of engine coolant to channel the water cooling system of a vehicle. Cooling plates and hot side block are attached like a sandwich. Also the hot side block can have Thermoelectric modules attached on both sides. The TEG which was fabricated has dimensions of about 80mm(W) * 250mm(H)*740mm(L). Experimental results depicted that the power output of the fabricated TEG observed was merely 75W at a driving condition of about 80 km/h, the overall efficiency of electric power generated from the utilization of waste heat from engine coolant is only about 0.4%, an estimation indicated that the waste heat through engine coolant was about 18kW during the driving condition for a 100 kW engine.

Chaudhry et al., 2012[28] presented that, a heat pipe can be regarded as a simple device having high thermal conductivity and is independent of any moving part which could transfer large amount of heat efficiently and effectively over large distances at a temperature which is invariable, without employing any external electricity. A heat pipe can be defined as a slender tube constituting a wick structure that is lined on the inner surface and some quantity of fluid like water at the saturated state. It constitutes of three sections, the evaporator section at first end, where absorption of heat and the vaporization of fluid takes place, a condenser section on the other end, where the condensation of vapor and rejection of heat occurs and the mid section is the adiabatic section, where an opposite flow of vapor and the liquid phases of the fluid can be observed, through the core and the wick respectively, to ensure that the cycle is complete without any significant heat transfer between the fluid and the surrounding medium.

Hsiao et al., 2009[29] fabricated a thermal resistance model to recover waste heat from the exhaust pipe. This model could be categorized into three parts, first being the hot side, second being the cold side and lastly TEG itself. Exhaust gas is the fluid that surrounds the hot side and ambient airsurrounds the cold side. The heat energy from exhaust gas is dependent on its temperature and according to observations, temperature increases with the increase in the engine speed. For the reduction of heat loss from ambient, the heater was implanted into a hollow block made of Teflon. Water, was circulated throughoutand acted as a coolant. At coolant temperature of 90°C, the maximum power output and thermal efficiency determined were 0.135W and 0.135%. Under the working condition as designed, a maximum power of 0.43W was generated at 0.35 A current, and the maximum power density was around 51.13 $mWcm^2$.

Weng and Huang (2013) [30] modeled a combination of heat exchanger and TEGs, make up the energy harvesting system. The heat exchanger is made up of a hexagonal pipe, radial fins, and a hollow center body, which is connected to a uniform exhaust pipe having an equal diameter on both ends of 62 mm. The hexagonal pipe has a length of L and a circle of diameter 140 mm which is inscribed. A divergent/convergent part, connects this to the exhaust pipe. The hollow center body is composed of two heads of length90 mm each shaped like a bullet, as well as a pipe of circular cross section of diameter 100 mm and length L and is supported by radial fins which are 1 mm thick, connected on inner side of the hexagonal pipe on the other end. Aluminum is used to make all the solid components. TEGs of length L_{TEG} (colored by red) were attached to the hexagonal pipe on the outer surface, beginning from the upstream edge.

Figure 8 shows the distribution and variation of the temperature difference between the hot and cold sides

of the TEG cuboid in a system in which L or denoted as L_{TEG} which is about180 mm and h_e is around 1800 W/m^2 K.

Figure 9 portrays the x-y and y-z cross-sectional temperature variation in the system in which L =L_{TEG}= 180 mm and h_e= 1800 W/m^2 K.

Figure 10 highlights the total power generation rate against the length of the heat exchanger when the length of the TEG cuboid (LTEG) is fixed at 50 mm.

Fig 8: Temperature Distribution

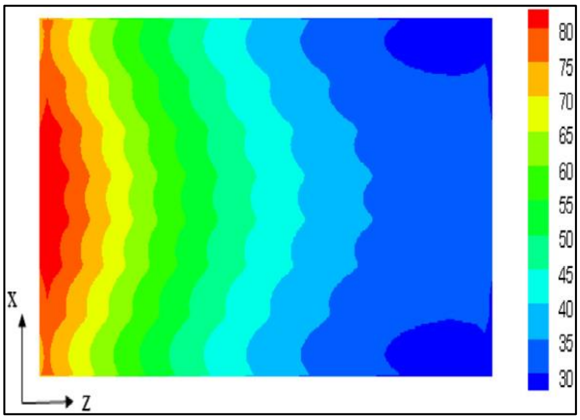


Fig 9: Cross sectional Temperature Distribution

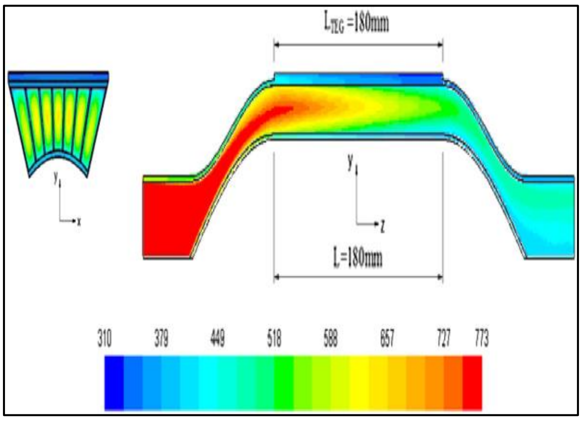
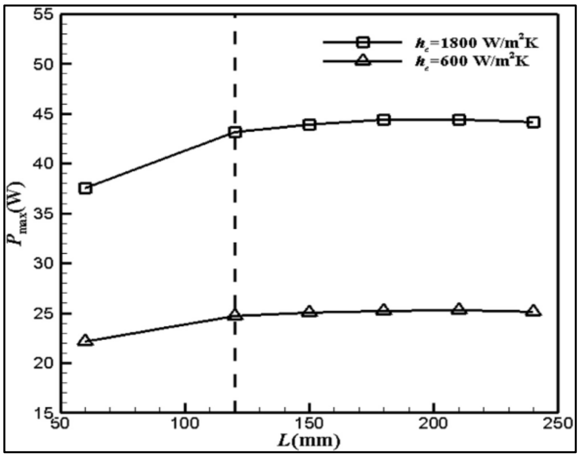


Fig 10: Total Power Generation V/S Length of Heat Exchanger



Baker et al.,2012 [31] designed a heat exchanger model to recover waste heat from Cummins 6.7-L diesel engine exhaust. The specified conditions for this analysis include a TEM which is 1 m in length and 30 cm wide, with exhaust duct of height 3.5 cm and coolant duct of height 1 cm. The total volume of TEM was 16.5 L with a coolant flow rate of 1 L/s, and exhaust flow rate of 270 L/s, coolant inlet temperature of 300 K, and exhaust valve outlet temperature of 800 K. The exhaust flow enthalpy flux of 122 kW was a result of the flow rate and temperature combination. The engine conditions for exhaust flow were typically exclusive for the Cummins engine running at a speed of 2000 rpm and having a torque load of 475 N-m. The results indicated that the use of 2 TEM's resulted in maximum power, one located to the above the turbo and the other located below the exhaust after-treatment devices. Using only one TEM, maximum power was observed with the TEM placed underneath the after-treatment device. Even though temperatures were higher on the side above, the downstream location generated the maximum power due to the condition that, for all cases, the temperature into was a greater than 500 K in the exhaust after-treatment system to maintain the activity of the catalyst.

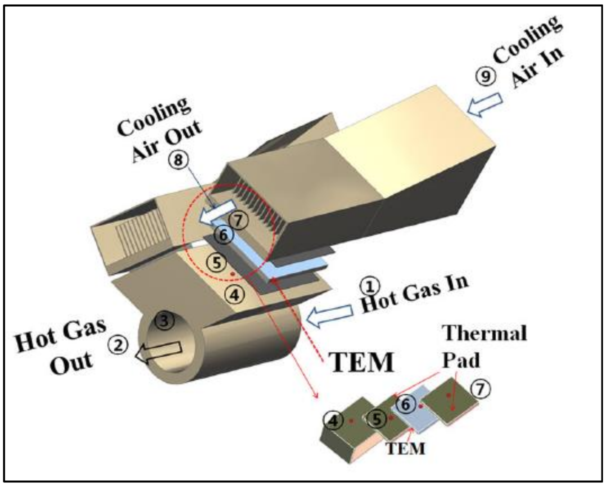
Liang et al., 2014[7] worked on two types of TEG i.e. single stage and two-stage TEG. A Two-stage TEG has different pairs of thermocouple on both sides of TEG: m pairs on top layer and n pairs on the bottom layer, connected together by a single wire. Thus the total number of pairs of thermocouple becomes (m+n). External resistance (RL) is kept same in both the cases. Based on Newton's cooling law, as well as Fourier's and Seebeck effect, following results are obtained. The maximum output power is 18.6% and conversion efficiency is 23.2%, higher than single stage TEG. Two-stage TEG gives best result when the heat source temperature is between 600K and 800K and the optimum ratio of m/n is between 0.8 and 0.9.

Niu et al., 2014[6] chose an in-line six cylinder turbocharged diesel engine for analyzing different operating parameters. Dynamometer is used for measuring power output. The shell of exhaust channel is made of stainless steel 310 and its 1mm thick. On the surface of exhaust channel, 20 TEG modules are placed and heat sink is cooling water. A TEG module includes 160 TEG units and they have same current flowing through them as they are electrically connected in series. They are thermally connected in parallel as they share same heat source and heat sink and heat transfers through them simultaneously. The dimensions of TEG module are 41*26*3.52 mm. The TEG units are insulated by placing ceramics on the top and bottom sides. Thermoelectric material used is Bismuth Telluride (Bi_2Te_3). Heat transfer and pressure drop can both be balanced by taking baffler angle as 30 °. If the number of exhaust channels are 3, highest TEG power is obtained. Also, the highest voltage of 56.1V is obtained when exhaust channel inlet/outlet area of cross section is the smallest i.e. 30*40 mm due to increase in flow velocity.

Orr et al., 2016[32] demonstrated the usage of heat pipes in the design flexibility of exhaust heat system as it overcome the limitation of placing TEGs on the exhaust pipe surface. Heat from exhaust gases is extracted by the fins in the exhaust duct. Then heat is transferred via heat pipes to TEG's hot side and gets converted into electricity. The other side of TEG is attached to the heat pipes which get cooled from the ambient air flowing in the duct in which fins are placed. There were a total of 8 TEGs of 62*62 mm in size. The diameter of the heat pipes was 8 mm and thickness was 1 mm for handling high temperature and pressure. Various testing were done for finding the maximum power output. At 2500rpm with no load, the exhaust gas temperature was 218 °C and mass flow rate was 0.0157 kg/s. The cooled air temperature was 31°C and mass flow rate 0.02 kg/s. Power output is 15.17 W. To increase the exhaust gas temperature and mass flow rate, a chassis dynamometer to put the car under load. This improved the power output to 20.36 W. Further increasing engine speed to 4000rpm, the power output reached 28.18 W. When a powerful fan is attached on cool side of TEG, the power output shoot to 37.85 W as it allowed the temperature change from 89 °C to 54°C.

Jang et al., 2015[8] investigated on TEG system models. TEGM1 was the convectional TEG module with a heat-conductive aluminum block. A Bi2Te3-based TEG was used with dimensions 60*60 mm. In this TEG system, TEMs with 200 p- and n-semiconductors pairs were tested. To create a single flow current direction, all modules were connected electrically in series. Thermal contact resistance between the TEM and hot/cold plate interfaces were reduced by applying adhesive thermal grease and thermal pads. The TEGM 1 heat exchanger system was brought in direct contact with the TEG system and the temperature profile was noted. The cold air temperature (T_c) and the hot gas temperature (T_h) influenced the temperature in the flow passage. For providing variable exhaust gas temperature between 200 °C - 500 °C, engine simulator was used. Also, the cold side temperature between 10 °C – 30 °C was maintained through forced convection by a fan. With the temperature difference of 39 °C – 53 °C, the emf obtained was 0.3 – 1.0 V. It was concluded that a large power output can be obtained by high temperature difference.

Fig 11: Conductive TEG Experimental System (TEGM 1) [8]



3.0 Conclusions

The study reveals the huge potential in recovering low grade energy from the exhaust gases of an internal combustion engine, which is otherwise dissipated in the environment. This recovery further increases the net work output and hence the efficiency of the engine. This research paper showed various existing methods of recovering heat but the most convenient as well as efficient system came out to be thermoelectric generator. TEG has a relatively low conversion efficiency and to maximize the energy conversion efficiency, TEG can be incorporated with heat pipe. Also with the usage of heat pipes, the temperatures on the hot surface of the TEG can be regulated and reduced to operating temperature limit range. Further, more power would be produced by using material with high ZT at higher temperatures on hot side and a material with high ZT at low temperatures on cold side. The HP-TEG (heat pipe thermoelectric generator) technology has advantages over TEG system because heat pipes can reduce the thermal resistance between the TEG and exhaust gases. A completely passive and solid state exhaust recovery system can be developed using both TEGs and heat pipes and also the future lies in such systems with the depletion of non renewable resources.

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