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Automotive Waste Heat Harvesting for Electricity Generation using Thermoelectric Generator A Review

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Abstract - *To meet the increasing world demand for energy, the rate of depletion of non-renewable energy sources must be reduced while developing alternative renewable sources. This can be achieved by increasing the overall thermal efficiency of conventional power plants. One way to do this is by waste heat recovery. Most of the techniques currently available recover waste heat in the form of thermal energy which is then converted to electricity. Thermoelectric is the science dealing with both low- temperature and high-temperature thermal to electrical energy conversion systems. By using principle of thermoelectric automotive thermoelectric generator is implemented to recover waste heat from automobile. A remarkable potential for improving the efficiency of the ICE systems lies in the recovery of the energy wasted today. This paper presents a review 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 parameters, components and factors that determine the performance of such systems.*

Key Words: Internal combustion engine, Waste heat recovery, Automotive component, Thermoelectric generator, Thermoelectricity.

1. INTRODUCTION

Today majority of vehicle available on roads which uses internal combustion engine as power source such engine utilize only small amount of fuel and converted in to kinetic energy. However majority of fuel energy is wasted and dissipated in environment as waste heat or gas. This paper present an review in waste heat harvesting from automobile and generation of electricity using thermoelectric generator. such model provide direct heat to electric energy and allowing the exhaust energy recovery system without adding moving part to the vehicle, while now recent development in electrical vehicle deployment numerous non petrol and hybrid vehicle are available but for exportation especially heavy vehicle are carried by internal combustion engine. It has been observed and estimated that only 12% of fuel primary energy could be utilized by Internal combustion engine and 88% of energy is dissipated in the form of heat in exhaust gas. The temperature of exhaust gas is near about 300-700^{0}c and coolant used in engine has temperature 60-100^{0}c. Many application for waste heat harvesting proposed include thermoelectric generator, six stroke generator, turbo charging, exhaust gas recirculation and many other gas are available. In this paper the review of thermoelectric generator based solution for automotive waste heat harvesting is introducing which is not yet present on commercial vehicle today TEG based system provide solid state energy conversion system with least moving part and complexicity making them reliable option for waste heat recovery. The view point of energy utilization and environmental protection. Thermoelectric generator has attracted one of the power generation method to recover waste heat of the power plant because their heat source is not limited to size, heat is directly conversion in to electricity. The structure is simple and excellent. We can carry out power generation of thermoelectric generation system using exhaust gas of an internal combustion engine. This paper report the result effect of element length, installation of fins and exhaust gas flow rate on power output and efficiency of conversion of thermoelectric generation system using exhaust gas of an internal combustion plant. This paper gives study of recovery of this energy can be beneficial in reducing power costs and atmospheric pollution and also reducing depletion rate of non-renewable energy resources. The advantage of such conversion are very attractive and when converting low grade heat energy in to electricity by thermoelectric generator. These generators have no moving part and can run thousands of hours and here thermoelectric principle is used for energy conversion.

1.1 THERMOELECTRIC GENERATOR

Thermoelectric generator is solid state device. It consists of arrays of P and N types semiconductor materials. P and N type material are joined thermally in parallel and electrically in series. Following fig shows thermoelectric converter consist of no of alternate p and n type semiconductor element connected in series with metallic connector and sandwiched between two ceramic plates forming module of TEG [2].

Fig-1: Thermoelectric module

The ceramic plates are electrically insulating and thermally conductive. When temperature difference is maintained across module then electrical power will be delivered to an load compare with all thermo chemical device. Thermoelectric generators have advantage of simplicity and absence of moving part and silent in operation, environmental friendliness.

1.2 THERMOELECTRIC MATERIAL

Thermoelectric material should have large seebeck coefficient ( ) to maximize electrical potential and low thermal conductivity (k) to retain heat at junction and low electrical resistance i.e. high electrical conductivity to minimize ohmic losses. A thermoelectric module uses a bismuth telluride based alloy, it contain 98 couple of p -n semiconductor material. It require heat flux of about 8 w/cm2 with temperature difference of 2000c. This module convert 5 % of thermal energy in to electrical energy generally 14 watt of electrical power and to provide uniform temperature distribution across it the face of module should be aluminum because aluminum is the thermal spreader between two faces of module, heat sources and heat sink. Thermoelectric module works very efficiently due to their solid state construction example of thermoelectric materials are as follows:

1) Bismuth telluride (Bi_2Te_3)

2) Lead telluride (Pb_2Te_3)

3) Silicon germanium (SiGe)

4) Bismuth antimony (Bi-Sb).

Ceramic plates are usually made from alumina, semiconducting material of thermoelectric element are usually silicon germanium. The hot side and cold side plates are usually connected using highly conductive material like copper.

1.3 WORKING OF THERMOELETRIC GENERATOR

Thermoelectric generators are based on three thermoelectric effect that are seebeck effect, peltier effect and Thomson effect. Seebeck effect is used for power generation and peltier effect is used for heating and cooling purpose.

1.3.1: Seebeck effect

In 1823 Thomson Johan seebeck invented seebeck effect it states that " an electrical potential is generated in an open circuit formed by two dissimilar conductor when their junction are maintained at different temperature" the magnitude of voltage generated is propotional to temperature difference and depended on type of conducting material it shown in following fig.

The p type thermoelectric material provides positive emf while n type material provides negative polarity emf combining both alternating n type and p type material forming thermoelectric module. As when seebeck coefficient is low then series connection between several tons legs is feasible for higher output voltage, here not all heat flux can be converted to electrical power. Majority of heat power is carried through material by conduction from hot side to cold side material. The faster hot molecules will diffuse towards the cold side then cold molecules there will be not build up of molecules of higher density at cold send, the density gradient will causes the molecules to diffuse back to hot end. In the steady state the effect of density gradient will exactly contract the effect of temperature so no net flow of molecules. If molecules are build up of charge at cold end will also provide a repulsive electrostatic effect and therefore electric potential to push the charge back to hot end. The electrical potential produced by temperature difference is known as seebeck effect and the proportionality constant is called as seebeck coefficient it can be defined as open circuit voltage produce between two point on conductor when uniform temperature difference of 1k is applied between those points. A single p-n conductor can produce a seebeck voltage of 40 mv ,heat source can be used as natural gas of automobile with increasing temperature difference between two point (ΔT).The voltage difference (ΔV) improve the seebeck coefficient ( ) is determined as follows

$$= \frac{\Delta V}{\Delta T}$$

And parameter ZT is a figure of merits which combine all three parameter listed above which affect the productivity of thermoelectric material. The ZT value can be used to assess the energy conversion efficiency from heat to electricity

$$ZT = (\alpha^2/k).\sigma T$$

where ,

α - Seebeck coefficient,
π - Peltier coefficient, β - Thomson coefficient,

σ - Electrical conductivity,
x - Conductor length, kI - Thermal conductivity T - Temperature,
I - Electric current ,

E - Electrical potential ,

T - Temperature difference ,

The high quality of thermoelectric material used to obtain seebeck coefficient to increase electric potential and low thermal conductor to reduce heat dissipation at joint and low electrical resistance to maintain and output voltage under environment and temperature voltage regulator circuit has been connect to TEG in output port.

1.3.2: Peltier effect

Thermoelectric heating and cooling are based on peltier effect i.e. current is passes through two dissimilar conductors there will be rise or fall of temperature at junction depending on direction of current". Electron moves from p type to n type material absorbing thermal energy from cold junction, electron dump their extra energy at hot junction as they flow from n type to p type material through electric connector.

1.3.2: Thomson effect

Heat is absorbed or produced when current flow in material with certain temperature gradient this known as Thomson effect. It states that "heat can be liberated or absorbed in single homogeneous conductor when electric current flows in presence of temp gradient.

2. HEAT EXCHANGER

The effect of important parameter of heat exchanger like radius of the shell, no of tubes, length of the heat exchanger, pressure drop is investigated and final model of the heat exchanger is proposed. Two heat exchangers are used: one heat exchanger is used to generate saturated vapor from the liquid working fluid and the second heat exchanger is used to generate super-heated vapor from that saturated vapor. Exhaust Gas Heat Recovery System for I.C. Output energy from I.C engine is about 30 to 40% of the total heat and residual parts of the heat waste in the form of cooling, friction in bearing & exhaust gas of the engine. Waste heat losses from equipment in the form of efficiencies reduction and from thermodynamics limitations on equipment and process. It means about 60 to 70% energy losses as a waste heat through the engine, 30 to 40% in the form of exhaust gas, 30 to 40% waste energy in the form of cooling system. Temperature of exhaust gases immediately leaving the engine may have temperature in the range of 450-600^{0}C. This temperature is low through recovery of exhaust gas and change into useful work and low temperature of exhaust gas in the environment.

Efforts can be made to design more energy efficient through engine with better heat transfer and lower exhaust temperature. 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. The amount of electric power produced remains very low at 4 W considering the total energy available in the hot gas .Rectangular heat exchangers with flat surfaces have been proposed in many variants. The designs include flat-plate designs, where the hot exhaust just passes through the parallel plates of a wider exhaust pipe section. It can be seen that adding pipe structure or the fins in different positions inside the heat exchanger would provide better heat capture characteristics. 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. Following fig shows the hexagonal heat exchanger and pipe structure of heat exchanger respectively [3].

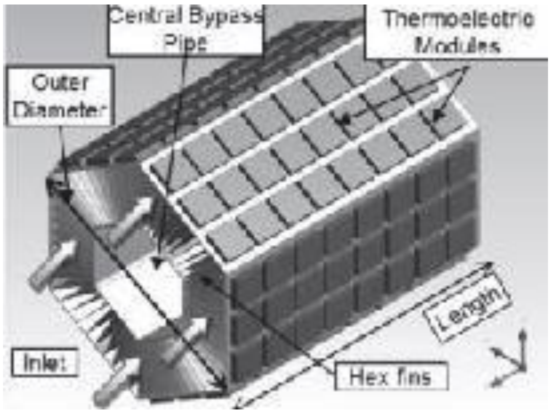

Fig 2(a): Hexagonal heat exchanger

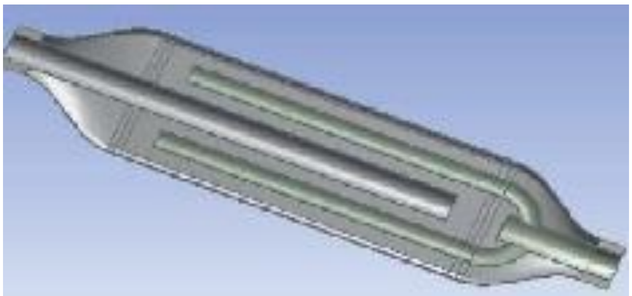

Fig 2(b): Pipe struture heat exchanger

3. INTERNAL COMBUSTION ENGINE

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 No.3.1 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 un optimal 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 shown in below table[3].

Table 1: Average Exhaust Temperature and Mass Flow Figure

Sr. No.	Type	TE (deg C)	mE (g/s)
1	Light duty	700 (500...900)	10...30
2	Heavy duty	512 (500...650)	20...40
3	Urban	300	5.7
4	Suburban	400	14.4
5	Max. perf.	500	80.1
6	Suv	400....7000	20...100

4. WORKING OF AUTOMOTIVE THERMO-ELECTRIC GENERATOR

As a thermoelectric generation system using the exhaust gas of an internal-combustion plant, a thermoelectric generation system in which many thermoelectric generation modules sandwiched by two square heat transfer tubes and electricity is generated by the difference in temperature between the exhaust gas and the cooling water flowing inside the heat transfer tubes respectively is postulated, and the power output and the conversion efficiency are obtained by test calculations. When the exhaust gas of an intimal combustion plant is used, the film resistance between the exhaust gas and the inner wall of the heat transfer tube is large and the difference in temperature effective to elements can not be applied with the shape of a commercial module though the heat drop between the exhaust gas and the cooling water is as much as 360 maximum. It is found that installation of fins in heat transfer tubes on the hot side and an increase of the thermoelectric element length are effective to solve this problem. As a result of this test calculation, it is indicated that electric power of 184 kW maximum can be recovered from the exhaust gas of an internal-combustion plant whose declared output is 10,000kW when the element length is 15.2 mm, the increase rate of the heat transfer area caused by installation of fins is 4 and the exhaust gas flow rate per tube is 1,212 Nm /h. In the future, the results obtained by this test calculation will be verified by making a mockup of a thermoelectric generator

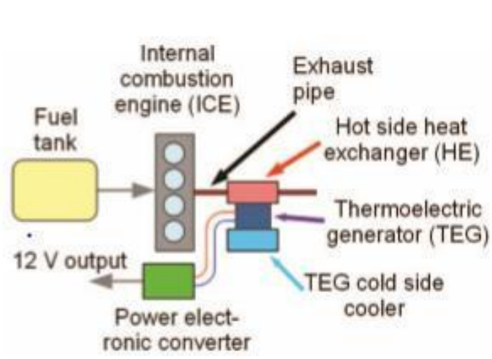

Fig-4: Operation of Automotive Thermoelectric Generator

5. SAMPLE APPLICATION

One possible application of TG WHRS is as a replacement to the alternator in a car. Electrical loads in motor vehicles can be categorised as continuous loads (ignition, fuel injection, etc.), long-time loads (lighting, heated rear window, etc.), short-time loads (turn signals, stop lamps, electric windows, etc.) and seasonal loads (air conditioners, seat heaters in winter). The alternator is the source of this power in addition to the power required to ensure adequate energy storage in the battery. The alternator is mechanically driven by the engine and operates at an average efficiency of about 50%. Tests carried out on a medium family sedan equipped with a 4 - cylinder 2.2 litre engine and 5-speed manual transmission shows that with no electrical load and full electrical load the alternator uses up to 2% and 5% respectively of the engine's output power without an alternator [2].

6. CONCLUSIONS

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 and connection of the TE modules depend also on their placement on the heat exchanger and the heat exchanger temperature profile[3].

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%.

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