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Future Impact of Thermoelectric Devices for Producing Electricity by Harnessing Waste Heat from IC Engine Exhaust

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ABSTRACT

Thermoelectric devices convert temperature gradient to electric voltage, and vice-versa. With the rising awareness about global warming and the scarcity of fossil fuels, these devices recently drew worldwide attention. Thermoelectric devices have emerged as promising power generating source from waste heat without burning any extra fuel. Due to this green feature and distinct advantages, the thermoelectric technology is instrumental in designing simple, compact and environment friendly system for harnessing waste heat emitted by automobile exhaust. The project is based on an array of thermoelectric modules which convert thermal energy into electricity for the purpose of charging small batteries etc. During this research, an assembly of thermoelectric modules is tested at various RPMs of the engine and several temperature gradients with a goal of proving its effectiveness in producing current for electrical parts running in an automobile. The research data proved that their current conversion efficiency is technically and economically practical for small applications.

Keywords: Thermoelectric generator, thermoelectric material, application of thermoelectric phenomenon

INTRODUCTION

In the last few decades, immense efforts have been made to explore, design and develop alternative technologies in order to fulfil the ever increasing energy requirements. Green technologies which include wind turbines, photovoltaic cells and biomass have started to play an important role in contributing towards the energy and environment issues arising in this world. These technologies have a clean style of power generation, which, to some extent, contributes to lessen the environment related issues. Thermoelectric devices are one of these technologies. They are composed of thermoelectric materials. Thermoelectric materials are a group of electronic materials which convert temperature gradients into electrical potential and vice versa [1]. Thermoelectric devices can be used to heat or cool, depending on the direction of the current [2]. These devices have a vast application in areas where heat energy has to be converted into electrical power. They offer better usability, safety, environment friendliness and simple working phenomenon. Thermoelectric devices produce electricity in the presence of temperature gradient. When connected to an electricity source, a temperature gradient is created by these devices by keeping one side as cold side and the other as hot side. Being composed in the solid state they are not complex but smooth in shape, noise free and work without any moving mechanical part or any working fluid. The waste heat emitted into the environment by various industries can be used to generate electricity by TEG (thermoelectric generators). These generators can obtain heat form chimneys or pipes carrying waste hot gases. They can even operate on heat obtained from vehicle's exhaust pipes [3]. NASA military appliances make use of it where other electricity sources are not available. Space industry is interested in using it along with solar power in space crafts and satellites. These devices were used in our research project for production of electrical energy from waste heat emitted from the exhaust pipe of an IC engine in order to test its working and viability for future automobile industry.

The benefits of installing TEG in an automobile exhaust lines are:

- Utilization of waste heat energy passing into atmosphere.
- Reduction in heat emissions into atmosphere.
- Production of additional electricity for components such as AC, headlights, horn, and audio system with no extra load on engine.

WORKING PRINCIPLE OF THERMOELECTRIC DEVICES

Thermoelectric devices work on the following principles:

Seed beck Effect

If in a circuit (shown in Fig. 3), two different conductors (or semi-conductors) 'a' and 'b' are connected in series and their junctures 1 and 2 are at different temperature T_h and T_c respectively, they will produce a potential difference between y and z [4]. The voltage generated 'V' due to Seebeck effect can be shown by the following equation:

$$\mathbf{V = \alpha \Delta T} \tag{1}$$

Here 'α' is known as Seebeck coefficient and 'ΔT' is the difference between the heated juncture and open juncture. The Seebeck effect is invertible as shown by Peltier effect.

Peltier Effect

The Peltier effect is the opposite of the Seebeck effect. In Fig. 3, if an electromotive force is added at y and z, electric current 'I' is produced in the circuit. This current produces heat in the conductors. When one connector of the conductor absorbs heat, the other releases the heat. The experiments show that the heat rate of absorption or release 'q' is in direct proportion to electric current 'I' as shown in the formula given below:

$$\mathbf{q = \pi_{ab} I} \tag{2}$$

Where, π_{ab} is Peltier coefficient.

Thomson Effect

Thomson states that heat power (Q_T) is absorbed or evolved along the length of a material rod if its ends are at different temperatures. This heat is proportional to the flow of current and to the temperature gradient along the rod. He also explains Peltier heat 'Q_p' in the following formula.

$$\mathbf{Q_p = \pi I} \tag{3}$$

Here 'Q_p' is Peltier heat and 'I' is the junction current. This formula also shows the direct relation between the Seebeck and Peltier effects, namely $\pi = \alpha T$, where T is the temperature of the junction. The amount of Thomson heat released or absorbed is directly related to the temperature gradient provided [5].

Basic Principles of Thermoelectric Generator

The p-type and an n-type thermoelectric components were connected with metallic electrodes at the hot-end, which is called thermoelectric couple or temperature difference couple. As shown in Fig. 2, the open-end of the thermoelectric couple is connected with an external load whose resistance is R_L. When the electric current passes through the circuit, the electric power consumed by the load is I^2R_L. That is how a generator coverts thermal energy into electricity. [6]

MATERIALS AND METHODS

Selecting Standard for Thermoelectric Materials

In order to increase the efficiency of the thermoelectric generator, it is necessary to increase the optimum value Z of thermoelectricity leg.

$$\boldsymbol{Z} = \frac{\alpha^2{}_{pn}}{(\sqrt{k_p\rho_p} + \sqrt{k_n\rho_n})^2} \tag{3}$$

Optimum value Z is the standard of evaluating the quality of a certain materials in the research on thermoelectric materials.

$$\mathbf{Z} = \frac{\boldsymbol{\alpha^2}\mathbf{T}}{\boldsymbol{\rho}\mathbf{K}} = \frac{\boldsymbol{\alpha^2\sigma}}{\mathbf{k}} \tag{4}$$

In real practice, the dimensionless optimum value Z of electric material with single temperature difference is expressed by multiplying Z with absolute temperature.

$$\mathbf{ZT} = \frac{\boldsymbol{\alpha^2}\mathbf{T}}{\boldsymbol{\rho}\mathbf{K}} = \frac{\boldsymbol{\alpha^2\sigma}}{\mathbf{k}}\mathbf{T} \tag{5}$$

This equation makes it clear that to find materials with high optimum value, the method is to enhance the Seebeck coefficient and electrical conductivity along with reducing thermal conductivity of the material [7].

Major Thermoelectric Materials

Presently common thermoelectric materials are bismuth telluride (Bi_2Te_3) and its alloys, plumbous telluride (PbTe) and its alloys and silicon germanium (SiGe) alloys. A larger Seebeck effect can be produced by using p-n junctions between p-type and n-type semiconductor materials as compared to junction between different metals.

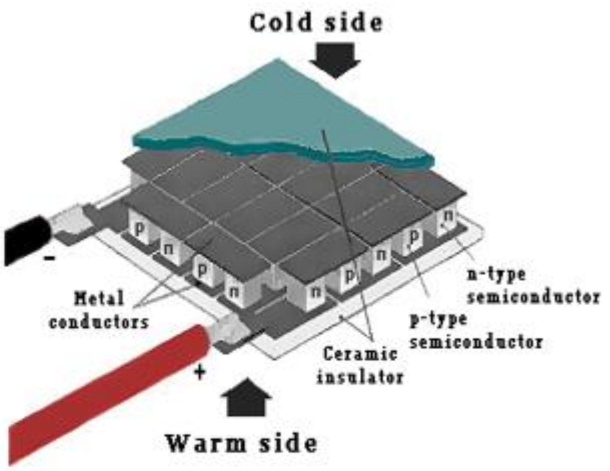

Fig. 1 Peltier thermoelectric module cut section [Innoveco Australia]

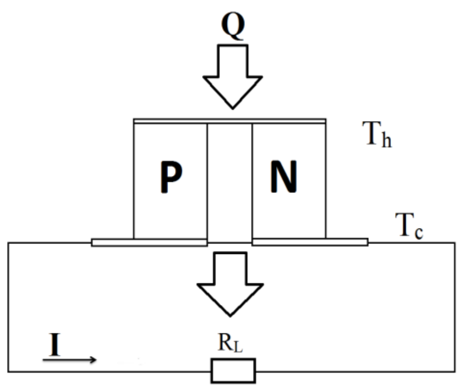

Fig.2 Thomson Effect

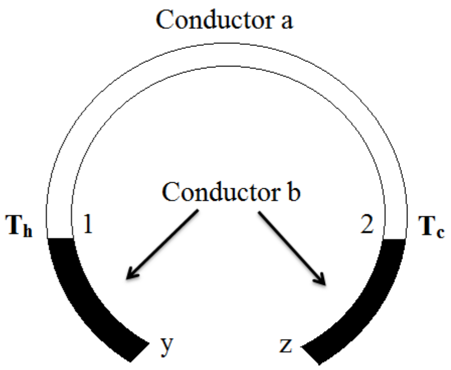

Fig.3 Seebeck Effect

Fig. 4 Bismuth Telluride thermoelectric device (TEC1-12706)

Fig. 5 Thermal fins [Electronics-cooling China]

Thermoelectric Module

Thermoelectric module has normally plate-like shape. It is prepared from a large number of semiconductors such as Bi_2Te_3 and PbTe . But this module is not flexible making it unfit for non-flat surfaces (e.g. circular tubes) used in waste heat recovery applications where the heat flow is perpendicular to the ceramic plates. [8] The semiconductors are highly doped by pollutants to increase their electric conductivity. Good semiconductors have electric conductivity in between 200µV/K - 300µV/K. [9] Semiconductors which can withstand high temperatures should be used in such circuits. Some of the high quality thermoelectric semiconductors are Bi_2Te_3, CaMnO, $Ca_3Co_4O_9$, Sb_2Te_3, and PbTe. Bi_2Te_3 based materials are known to have seebeck coefficient of −287 µV/K at 328K. However, one must realize that Seebeck Coefficient and electrical conductivity have a trade-off - a higher Seebeck coefficient results in decreased carrier concentration and electrical conductivity [10]. Bismuth telluride has also high electric conductivity of 1.1×10^5S·m/m^2 with its very low lattice thermal conductivity of 1.20 W/(m·K). An assembly comprising 200 modules with a gradient of 100K temperature produces 15 volts and has 4.2% efficiency. It is commercially available TEG[11]. $CaMnO_3$ shows metallic behaviour at temperatures higher than 400 K and its electrical resistivity is lower than 12 Ω-cm at 1000K in air [12]. We have $Ca_3Co_4O_9$ semiconductor for high temperature withstanding property. $Ca_3Co_4O_9$ has good thermo electric properties. It can bear temperatures up to 800ºC. [13] Its Seebeck property 206μV/K, Figure of merit ZT=0.23. Thermal conductivity is $1.2Wm^{-1}K^{-1}$. This conductivity value is for 880K. This TEG generates 4.2 % efficiency with 4.2 volts for 200 modules and 100K temperature difference.

Thermoelectric Shield

It is a material which protects the modules from being damaged by high temperatures. Mostly ceramic materials are used for this purpose. It should be thick [14].

Thermal Fin

It is used for increasing the thermal gradient value. It is also used to produce an impinging flow of hot air on the central region of the fin assembly, which then turns through 90º and exits outwards in both directions through the rectangular channels formed by the cooling fins [15]. When we increase the thermal gradient value, it increases the seebeck voltage generated by TEG. It is made by aluminium metal. When we include thermal fin, it increases the efficiency of the TEG [16].

Design of Thermoelectric Generator

The thermoelectric power generator is a solid state device that provides direct energy conversion from thermal energy due to temperature gradient into electrical energy based on the 'Seebeck effect'. Compact thermoelectric generator based on optimized thermal contact interface was designed and developed [17]. The thermoelectric generator assembly was constructed by using an array of 16 thermoelectric devices. These thermoelectric modules were made from bismuth telluride material. In terms of electrical design, the thermoelectric modules were connected in series. Each when connected in series generated current depending on the temperature difference between the hot and cold parts. The hot part was suspended for reducing heat sink [18]. Cold water was used for cooling the sink for obtaining maximum temperature difference across the module. Dimensions of each module were 40 mm in width, 40 mm in length and thickness of 4 mm. These thermoelectric modules were connected with thermoelectric couples connected electrically in series and thermally in parallel. This allowed the thermoelectric generator to be under direct influence of all gases emitted from the engine exhaust.

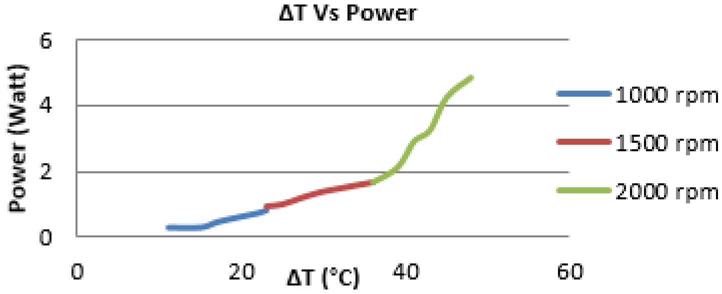

Fig. 6 Variation of power with temperature difference

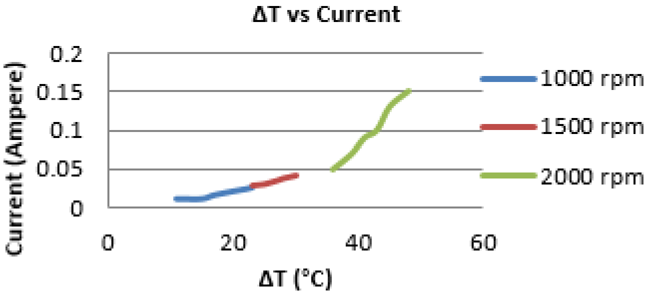

Fig. 7 Variation of current with temperature difference

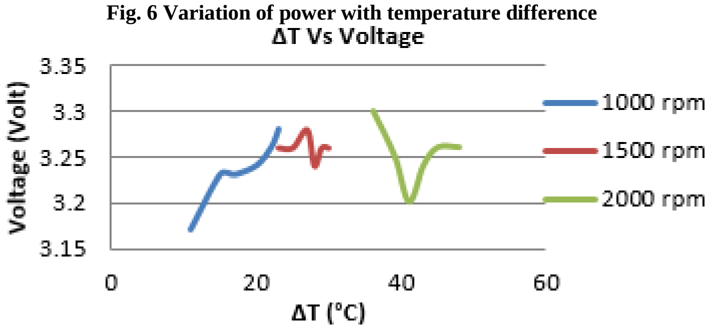

Fig. 8 Variation of voltage with temperature difference

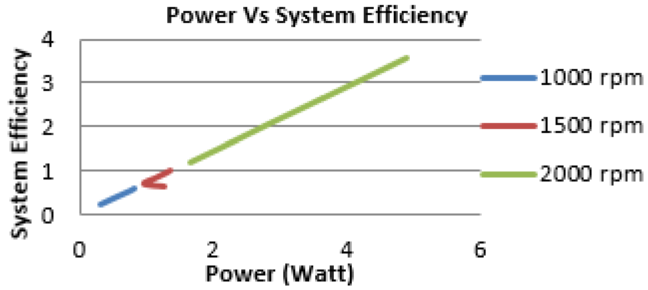

Fig. 9 Variation of system efficiency with power

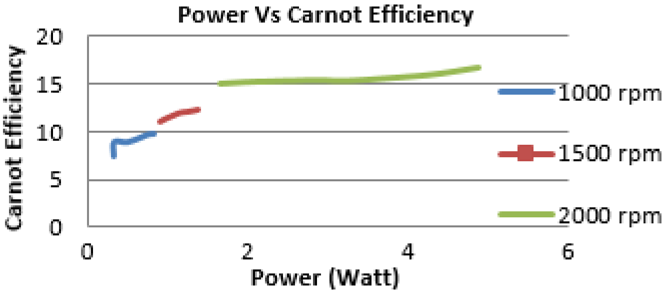

Fig.10 Variation of Carnot efficiency with power

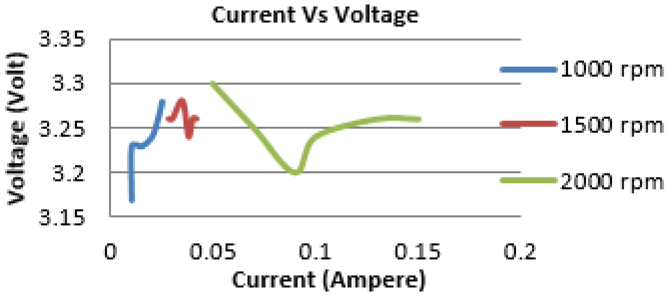

Fig. 11 Variation of voltage with current

RESULTS AND DISCUSSION

The TEG was fixed at the end of the exhaust pipeline of a four stroke petrol engine tested in a couple of experiments by running the engine at RPM of 1000, 1500 and 2000 with varying temperature gradients at 10 minutes' intervals. By finding the current and voltage using a multi meter, power was calculated using formula: P= V × I.

The results were encouraging with a reasonable amount of current produced by the thermoelectric generator. The trends are shown below by plotting graphs between parameters of current, voltage, rpm, power and overall system efficiency. The calculation shows that increase in temperature difference results in increased power generation. Since power produced is directly related to the temperature difference provided to the TEG, the power generation increases in the presence of higher temperature gradient.

By taking values of current on Y-axis and Temperature Deference on X-axis, a graph is plotted which shows the increase in current as temperature difference increases. The graph plotted between Temperature Difference and Voltage shows clearly the increase of voltage with increased temperature gradient. The voltage produced was found to be directly in relation with the temperature difference. It increased as the temperature gradient increased. As power increases system efficiency also increases. This is shown by the graph when engine is run at different RPMs with gradual increase in RPMs. Increase in power also results in the increase in the Carnot efficiency of the engine as a result of using TEG at the exhaust. Carnot efficiency is regarded as the factor relating to mechanical efficiency of engine which is improved by the waste heat recovery done by the TEG. The following graphs show increase in voltage and current with increase in rpm of the engine from 1000 to 2000. The comparison shows different trends of current and voltage.

CONCLUSION

A detailed study on Thermoelectric Generator was carried out followed by a series of experimentation. These experiments will be fruitful for the further researchers working on the thermoelectric generators in order to generate electricity from waste heat in various methods. On the basis of data and observations during the experimentation, following conclusions were made:

- Potential difference was produced between two points of electric conductors if they were at different temperatures. The charge carriers migrated from the hot side to the cold side.
- Potential difference was proportional to the temperature difference and dependent on the material and its Seebeck coefficient.
- The maximum temperature difference tested was 48°C at 2000 rpm and it produced a thermal efficiency of 3.58% and an output power of 4.89 watts.
- Bismuth Telluride thermoelectric device (TEC1-12706) with ZT = 1 were used to conduct this research.
- The maximum temperature difference tested (48° C) was fairly modest, higher differences would result in higher efficiency. Typical thermoelectric devices require a temperature of approximately 500° C to achieve an efficiency of up to 15 %.

The development, validation and demonstration of TEG is the approach to meet the future energy demands. It will be helpful in order to maintain the green environment by enabling commercial feasibility. Automobile industry will be benefitted by this technology. It will be helpful in charging the batteries in automobiles without any extra cost. It will also provide enough electricity for lightening and other purposes if these assemblies are fitted in chimneys of large factories.

REFERENCES

[1] GJ Snyder and ES Toberer, Complex thermoelectric materials, *Nature Materials*, **2008**, 7, 105–114.

[2] Jatin Patel, Matik Patel, Jigar Patel and Himanshu Modi, Improvement in the COP of Thermoelectric Cooler, *International Journal of Scientific & Technology Research*, **2016,** 5(5), 73-76.

[3] TC Harman, PJ Taylor, MP Walsh and BE LaForge, Quantum Dot Super Lattice Thermoelectric Materials and Devices, *Science* ,**2002**, 297, (5590), 2229-2232.

[4] Subasinghe Kobbekaduwa, Modelling and Analysis of Thermoelectric Generation of Materials Using Matlab/Simulink, *International Journal of Energy and Power Engineering*, **2016**, 5(3), 97-104.

[5] R Venkatasubramanian, E Siivola, T Colpitts and B O'Quinn, Thin-Film Thermoelectric Devices with High Room-Temperature Figures of Merit, *Nature*, **2001**, 413, 597-602.

[6] Kuei-Fang Hsu, Sangeeta Lal, Tim Hogan, Mercouri and G Kanatzidis, $CsPb_3Bi_3Te_8$ and $CsPb_4Bi_3Te_9$: Low-Dimensional Compounds and the Homologous Series $CsPb_mBi_3Te_5 + m$, *Chemical Communications*, **2002**, 13, 1380-1381.

[7] K Kumaravel, P Balashanmugam and G Balasubramanian, Study and Performance Analysis of Charging Vehicle Battery using Bike Exhaust Gas, *Journal of Mechanical and Civil Engineering,* **2015,** 1(4), 143-157.
[8] HB Lee, HJ Yang, JH We, KJ Kim, KC Choi and BJ Cho, Thin Film Thermoelectric Module for Power Generation Applications using a Screen-Printing Method, *Journal of Electronic Matererials*, **2011**, 40(5), 615-619.
[9] Driss Kenfaui, Guillaume Bonnefont, Daniel Chateigner, Gilbert Fantozzi, Moussa Gomina and Jacques Guillaume Noudem, $Ca_3Co_4O_9$ Ceramics Consolidated by SPS Process: Optimisation of Mechanical and Thermoelectric Properties, *Materials Research Bulletin,* **2010,** 45, 1240–1249.
[10] Basel I Ismail and Wael H Ahmed, *Recent Patents on Electrical Engineering* **2009**, 2, 27-39.
[11] M Rezaei, WK Muzammil, MH Hassan, S Paria and M Hasanuzzaman, Technologies to Recover Exhaust Heat from Internal Combustion Engines, *Renewable and Sustainable Energy Reviews*, **2012,**16, 5649–5659.
[12] DY Chung, T Hogan, P Brazis, M Rocci-Lane, CR Kannewurf, M Bastea, C Uher and MG Kanatzidis, $CsBi_4Te_6$ A high-performance thermoelectric material for low-temperature applications, *Science,* **2000**, 287, 1024-1027.
[13] Ugur Erturun, Kaan Eremis, Karla Mossi, Effect of Various Leg Geometries on Thermo-Mechanical and Power Generation Performance of Thermoelectric Devices, *Applied Thermal Engineering*, **2014,** 73,126-139.
[14] Dongyi Zhou and Shi Chu-ping, Study on Thermoelectric Material and Thermoelectric Generator, *Journal of Chemical and Pharmaceutical Research*, **2015**, 7(3), 395-401.
[15] Z Duan and YS Muzychka, Experimental Investigation of Heat Transfer in Impingement Air Cooled Plate Fin Heat Sinks, *Journal of Electronic Packaging*, **2006**, 128, 412-418.
[16] FJ DiSalvo, Thermoelectric Cooling and Power Generation, *Science,* **1999**, 285, 703-706.
[17] Krishna Purhoit, PM Meena, Khushbo Singh, Sheetal Kumar Jain and Manish Dadhich, Review Paper on Optimizations of Thermoelectric System, *International Journal of Innovative Research in Engineering & Management,* **2016,** 3(4), 259-263.
[18] TM Tritt, Holey and Unholey Semiconductors, *Science*, **1999**, 283, 804-805.