Thermoelectric Generators

Feasibility in Automotive Engines

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DEN318 Third Year Project (Mech)

December 2016

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Abstract

The ever increasing use of non-renewable energy sources means that every effort needs to be made to make machines and devices as efficient as possible. In this effort, we try using renewable energy sources or reuse and recover used energy from nonrenewable energy sources. This Literature Review engulfs the Thermoelectric effect and describes how it can be used to run Thermoelectric devices that use the Seebeck and Peltier effects to either heat or cool using an electric current or use a temperature difference to produce an electrical current. One such device is called the Automotive Thermoelectric generator. This generator is used as part of a waste heat recovery system to reuse wasted heat energy which would otherwise be lost to the environment to produce an electrical current that can be stored and used for making cars more efficient, lowering their fuel consumption, lowering their $C0_2$ emissions and helping sustain the environment. The Automotive Thermogenerators can without a doubt help with the efficiency but they do also have some drawbacks that need consideration. Development of the device is discussed in the light of modern automotive giants such as BMW and Ford. Issues concerning these devices and large scale use is discussed. How these devices developed to aid the Internal Combustion engines over the years and whether they are feasible or not.

Declaration

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Was composed by me and is based on my own work. Where the work of the others has been used, it is fully acknowledged in the text and in captions to table illustrations. This report has not been submitted for any other qualification.

Name Hussain Ahmed Dar

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Date . 16-12-2016

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1. Introduction

Thermoelectric devices are semiconductors joined together that can convert thermal energy into direct current (DC) or electrical energy. These devices can also be used to reverse this process and can thus also convert electrical energy to thermal energy. These thermoelectric devices may be used for heating, cooling and electrical power generation. In this literature review, the electrical power generation ability of thermoelectric devices are discussed.

A thermoelectric device used for power generation purposes is referred to as a Thermoelectric Generator (TEG). Thermoelectric generators use waste heat to produce electricity without the use of extra parts or turbine as in conventional thermal electricity generation. They work by exploiting a temperature gradient between their two sides. Basically, if a metal is heated at one end and cooled on the other, electrons at the hot end would have more energy than the ones at the cooler end. This means the hot electrons have more energy than the ones at the cool end and would thus, tend to move towards the cooler end. Eventually, the cold end will become more negatively charged and the hot end will become more positively charged. This phenomena where a temperature difference can create a voltage is know as the Thermoelectric effect. This effect however created a nominal amount of voltage. Hence, semiconductors were used because they can conduct with positive charges and a useful amount of voltage can be obtained from them using the thermoelectric effect. Certain metal alloys are used in TEG's because they have high electrical conductivity and low thermal conductivity.(Zhang and Zhao, 2015). TEG's are being produced in a variety of sizes commercially. The sizes range from a a few millimeters to several centimeters. The thermoelectric materials used in the vary as well, with TEG's that can function in high temperature environments emerging fairly recently. This is especially useful because a high temperature gradient optimal for a TEG.

TEG's have a wide variety of applications. In thermal powered electricity generation or other industries where large amounts of heat energy is wasted, TEG's are used to make these industries more efficient by using the wasted heat energy leaving the factories to generate useable electrical energy.

These devices are also used in Aerospace applications called Radioisotope Thermoelectric Generators (RTG). RTG’s are highly useful for these applications, specially when space probes go so far away from the sun that solar power generation is cannot be used to power them. RTG’s are also easy to use because the temperature in space is near absolute zero which takes care of the old side of the RTG. On the other hand the other side is heated using a radioactive isotope that produces heat as it decays over time.(Thenakedscientists.com, 2012).
Since RTG’s have no parts that can move and fall, they have been seen as a highly reliable source of electric power generation.(Solar System Exploration, 2013). According to NASA, “Thermocouples have been used in RTG’s for a total combined time of over 300 years, and not a single thermocouple has ever ceased producing power.”(Solar System Exploration, 2013). This proves how the Thermoelectric generators and Radioisotope Thermoelectric generators have been an ongoing success in aerospace applications for years and years now.

Thermoelectric generators are also used in automotive engines usually referred to as Automotive Thermoelectric generators (ATEG). High temperature of waste exhaust systems are a potential area where a TEG could use the temperature gradient to generate electricity for the vehicle to reduce the load on the engine of the vehicle.(U.S. Department of Energy, 2016). A TEG is used in the exhaust to exploit the temperature gradient in the exhaust of a car and an electrical current is then stored or used by the car for various purposes that include giving the engine extra boost, powering the electrical components of the car and thus increasing the overall efficiency of the vehicle. In this Literature Review, the feasibility, efficiency and cost effectiveness of the Automotive Thermoelectric generator is being analysed.

2. Background Theory

A thermoelectric device essentially can be used in two ways. The first is heat pumping where electric current is supplied to the terminals and heat is transferred from one side to the other. The second is electrical power generation application of the module, in which heat is supplied to one side of the module and is cooled at the other. The result is an electric current generated at the terminals, which is achieved using a phenomenon called the Thermoelectric effect.

This Thermoelectric effect is used to either produce DC current from a temperature gradient or to pump heat when a DC current is applied to the terminals.

2.1 The Seebeck Effect

The Seebeck effect is when a current is produced, when heat is introduced to the junction of two different conducting materials. This effect was discovered by a scientist called Thomas Johann Seebeck in Berlin in 1821-1823. He found that temperature differences in a circuit with dissimilar metals could deflect a compass magnet. At first, he believed that this happened due to magnetism induced by the temperature difference but later Danish physicist Hans Christian Orsted found out that a thermoelectric force induced the current according to Ampere's law.(Electrical4u.com, 2011). Conclusively, he deduced that a temperature difference would induce a potential difference and thus electrical power is produced. This is the Seebeck effect.(Thermoelectrics.caltech.edu, 2016).

Figure 2.0 Thomas Johann Seebeck,
(Thermoelectrics.caltech.edu, 2016)

The Seebeck coefficient is a property of a material that gauges how well a material undergoes the Seebeck effect. The Seebeck coefficient is the ratio of the current generated (or potential difference) to the temperature difference in the temperature gradient.

2.2 The Peltier Effect

In contrast to the Seebeck effect, the Peltier effect is the phenomenon where an electrical current passing through dissimilar conductors cause a temperature difference at the ends. This was found by a French physicist called Jean Charles Athanase Peltier in 1834.(Encyclopedia Britannica, 1998). Better results of this effect are achieved using semiconductors. This effect can be used to transfer heat from one medium to another.

In a Peltier effect device, the electrodes with good electrical conductivity are used while semiconductor material is used between the electrodes creates two junctions. Electrical current is applied to the electrodes and thus thermal energy flows in the direction of flow of electrons. These devices are usually used for cooling purposes, especially in refrigerators and in computers to cool down the systems when conventional cooling methods are not that effective. (SearchNetworking, 2008). In 1838, Lenz described that depending on the direction of the current, thermal energy could be removed from a junction to freeze water and by reversing the current, the ice could be melted. The thermal energy increase or decrease is proportional to the current. This proportionality constant is known as Peltier Coefficient. (Thermoelectrics.caltech.edu, 2016)

Figure 2.1 Jean Charles Athanase Peltier
(Thermoelectrics.caltech.edu, 2016)

2.3 Thermoelectric Materials

Thermoelectric materials are the materials that have properties that are optimal for the thermoelectric effect. The materials need to have a high efficiency in their output voltage and the energy used to generate the output.

2.3.1 Seebeck Coefficient

The Seebeck Coefficient of a thermoelectric material is the Voltage buildup when a small temperature gradient is applied to a material. The seebeck coefficient is defined by:

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

2.3.2 Efficiency of a Thermoelectric Material

The efficiency of a thermoelectric device is measured as the ratio of the energy output to the load connected to the terminals to the heat absorbed at the junction of the two different thermoelectric materials.

$$\eta = \frac{Output\ ot\ the\ Load}{Heat\ absorbed\ at\ the\ junction} = \frac{E}{\Delta T}$$

The efficiency of a thermoelectric material is directly related to the Figure of Merit, a bulk property (does not change with scale) of the material. The Figure of Merit is defined by the ratio of the product of the Seebeck coefficient and the temperature, to the product of the thermal conductivity and the electrical resistivity.

$$zT = \frac{S^2 T}{\kappa_t \rho}$$

Where S is the Seebeck coefficient, T is the temperature, κ is the thermal conductivity of the material and ρ is the electrical resistivity.

Actual thermoelectric devices have two thermoelectric materials and is discussed in detail later on. To account for the efficiency differences of the materials ,maximum efficiency (η_{max}) is used.

The maximum efficiency of a thermoelectric device is given by

$$\eta_{max} = \frac{T_H - T_c}{T_H} \frac{\sqrt{1+zT} - 1}{\sqrt{1+zT} + \frac{T_c}{T_h}}$$

T_H being the temperature at the hot side of the device and T_c being the temperature at the side being cooled.

3. Automotive Thermoelectric Generators

3.1 Working Process of a Thermoelectric Module

A Thermoelectric module works by exploiting a temperature gradient between the two sides of the generator. Using the principles of the Thermoelectric effect this creates a potential difference between the two terminals of the module. On ends of the module there are conductors that are in contact with a heat source and a heat sink . The heat source is provided at the junction of the two different conductors. This is where the Seebeck effect comes into play. The heat provided at the junction of the two different conductors creates a current at the terminals of the module.But the two different conductors cannot be metal, because the the direction of the current produced by the conductors would oppose each other. So instead, semiconductors used that are doped to change their electrical properties to conduct electricity using positively charged particles (and others with negatively charged particle) to conduct electricity.This means that when introduced to a temperature gradient, the particles that diffuse from the two semiconductors will have an opposite charge. Creating a potential difference across the terminals.

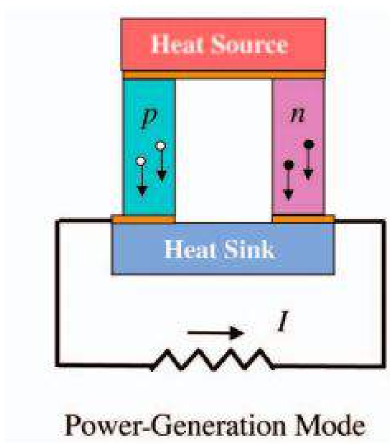


Figure 3.1

(Tritt and Subramanian, 2006)

3.2 Automotive Thermoelectric Generator (ATEG)

Internal Combustion (IC) engines driving the cars in today's world are not very efficient. Large amounts of energy from the fuel is wasted as heat energy from the car's exhaust and its radiator. Governments in various countries around the globe have been making efforts to regulate the Carbon Dioxide ($C0_2$) emissions in vehicles in order to sustain the environment. These emissions are proportional to the fuel consumption of IC engines and thus, car manufacturers in modern day strive to bring these emissions and fuel consumption to a maximum.

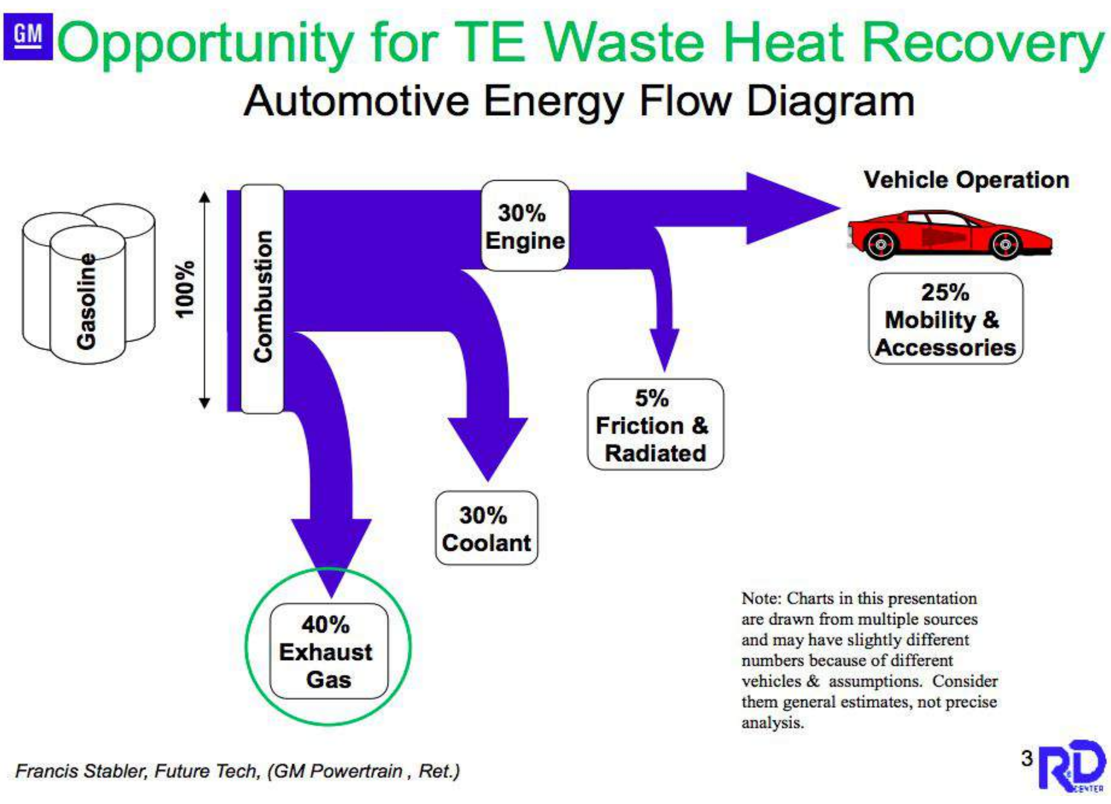


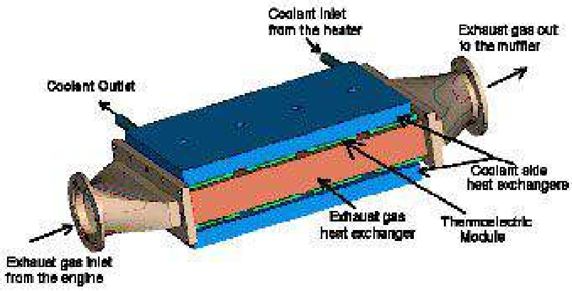
Figure 3.2

(General Motors and Future Tech LLC, 2011)

Automotive Thermoelectric generators serve the purpose of lowering the fuel consumption of a car by using waste heat in a car to create useable electrical energy and reducing the load on the alternator of the car. Using the Seebeck effect, an ATEG can recover heat energy and produce useful energy to lower the fuel consumption and emissions of a car. An ATEG is made up of p-type and n-type semiconductor material as in a thermoelectric module and are electrically joined in series and thermally in parallel. They work on the same principle as a thermoelectric module and create electricity from a temperature difference. Exhaust pipes tend to get very hot when an engine is working, making it the ideal place to exploit a temperature difference for heat recovery. An ATEG can typically perform at any temperature difference with a normal efficiency of 5% which can increase with the temperature difference.(Orr et al., 2015).

“The thermoelectric figure of merit (ZT) can be used to compare the efficiencies of different TEG’s operating at the same temperatures. The higher the ZT, the better the TEG. The ZT of thermoelectric has improved over time but presently the best commercially available TEGs have a ZT of approximately 1.”(Orr et al., 2015).

The car’s exhaust is sandwiched in between two thermoelectric modules that produce electricity using temperature gradients. The exhaust itself acts as a heat exchanger for the hot side of the module while another heat exchanger is used for the cold side of the modules. This side of the ATEG is powered by coolant to keep this side of the ATEG cold. Hot exhaust gases created from burning of fuel in the engines run through the exhaust and keep one side of the thermoelectric modules hot while coolant from the radiator runs the cold side heat exchanger keeping the other side cold. The modules use this



Schematic of a TEG incorporated with a special heat exchanger installed in an exhaust system. Courtesy of Dr. Bassem Ramadan.

temperature difference to produce useable electrical power to reduce the load on the alternator. This system is also referred to as the waste heat recovery system.
(Kettering University News, 2009)

For now heat exchangers can be 5-10% efficient but research in new thermoelectric materials that will aid the thermoelectric modules will improve the efficiency of this system. (Kettering University News, 2009).

As compared to other heat recovery systems, ATEGs have some properties that give it the edge of other systems. This system has no parts or moving bodies. This means that it is small, scalable, silent and durable. They have no chemical reactions and moving parts, this means they have little wear and corrosion issues. (Orr et al., 2015).

The fuel economy of the engine is basically reduced by replacing normal load parts with ones that can be electrically powered by an ATEG. These parts include electrical oil pumps, electrical water pumps and starter generator motors. (U.S. Department of Energy, 2016).

Many large automotive manufacturers have referred to this technology for making their vehicles efficient. These include BMW, Ford, GM, Honda and Renault. Their ATEG's are quite similar in design and usage.

3.3 Development of the ATEG

BMW claims to have made considerable progress in the Automotive Thermoelectric generators. They have developed two different systems to help make their cars as efficient as possible. The first is a usual waste heat recovery system from the exhaust while the second one is called the exhaust gas recirculation system. The first step taken by the engineers was to integrate a TEG in the exhaust system to produce electrical power to aid the engine by decreasing the load from the engine and giving it some power to make the engine consume less fuel. The first such system came up in 2008 developing 200 watts of power that could be used. (Media, 2011). With rapid developments in new materials that could be used for TEGs, these systems are capable of developing 600 watts and developers insight that this should reach 1000 watts soon as more efforts are put in the research of this technology. (Media, 2011).

BMW's alternate development was integrating the TEG with the radiator of the exhaust gas circulation system. This breakthrough has led to an extra 250 watts of power generation in the system decreasing the $C0_2$ emissions and fuel consumption by 2%. (Media, 2011).

BMW says that the TEGs are an excellent counterpart for their Efficient Dynamics Brake Energy Regeneration system. They aid with keeping the seats warm in cold starts and most excitingly function at their best when the car is accelerating because as the engines get used more, it releases more exhaust gases that in turn increase the temperature in the exhaust pipe. A higher temperature gradient means the TEG works even better. (Media, 2011).Researchers claim that TEG based systems lead to a decrease in fuel consumption by a good 5%.

Ford's sustainability plans include the thermoelectric technology for the purpose of decreasing emissions emitted by their system and increasing fuel averages and output power. Ford has developed a feasibility report for the US government funding them for this project that states how the TEG is capable of producing a peak 500 watts for their system using the exhaust heat recovery TEG systems. According to them, thermoelectric technologies will remain limited in the near future until important fundamental issues are resolved. Loads of research and investment is still required in areas of cost, performance, heat management, systems integration, manufacturing and durability of these technologies. (Overview of Ford's Thermoelectric Technologies, 2011).

General motors (GM) have also used in their cars the Peltier effect devices to overcome the fuel consumption issues related to cold starts. Fuel economy is drastically reduced due to cold engine oil and transmission fluids. Engines use more fuel than usual until coolant temperature reaches predetermined calibration. Increased heating of the engine coolant can improve fuel consumption by 0.2% to 1%. (General Motors and Future Tech LLC, 2011)

3.5 Thermoelectric Materials in Automotive TEGs

The British Supersonic Transport has been researching into new thermoelectric materials. Bismuth telluride, commonly used as a thermoelectric material, contains expensive tellurium and can only work at temperatures up to 250 °C, whereas thermoelectric generators can reach 500 °C. So BSST used a different family of thermoelectric materials. They experimented with blends of hafnium and zirconium that are capable to withstand higher temperatures.. This increased the generator efficiency by about 40%. General motors however developed another class of thermoelectrics called skutterudites, which are cheaper and perform better at high temperatures. The company's computer models show that in their test vehicle (Chevrolet Suburban), the device could generate 350 watts of power. This ment that they improved the fuel economy by 3 percent. (Anon, 2011)

A comparative study was made in a publication by the Clarkson University, that compared commercially available low zT bulk materials with high zT bulk materials. The study uses Bi_2Te_3 (p-type and n-type)to represent the low bulk materials and in contrast the B_4/B_9C (QW p-type) and Si/SiGe (QW n-type) as the high temperature bulk materials. And the results of the test are shown in the graphs below.

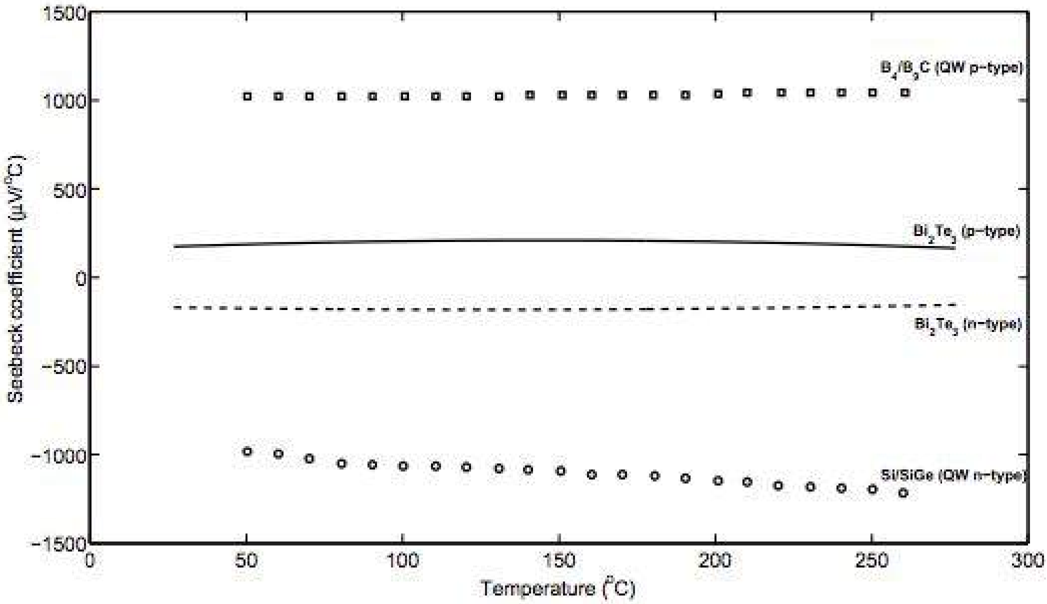


Figure 3.3 Materials Seebeck

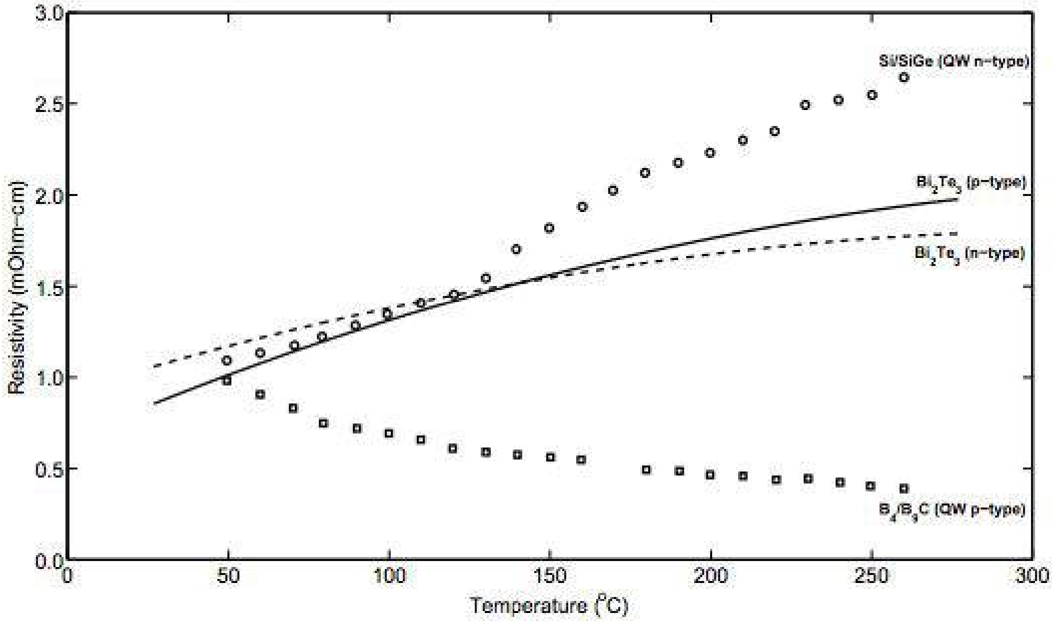


Figure 3.4 Material Electrical Resistivities

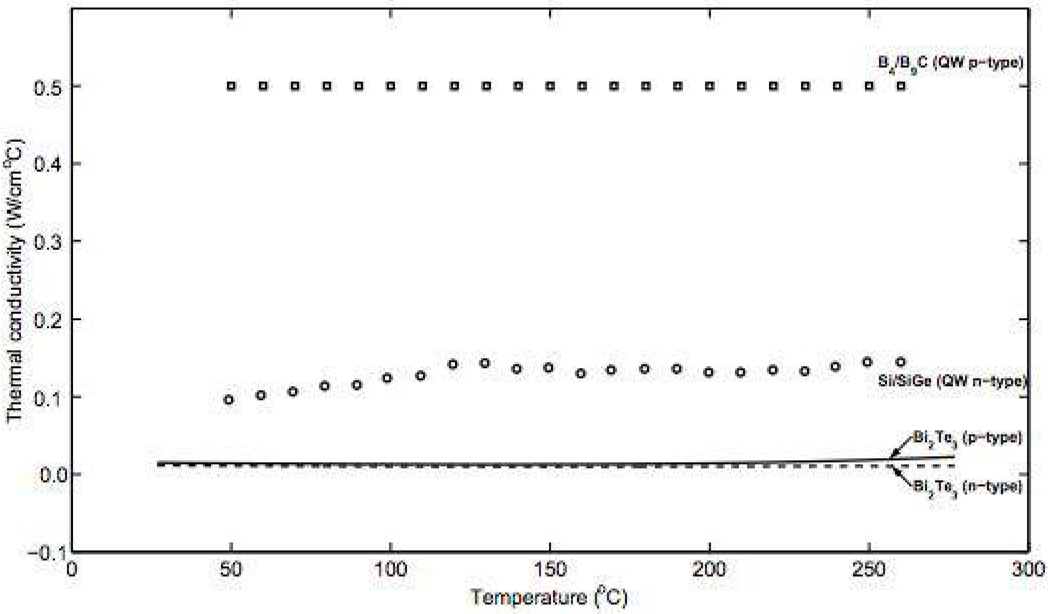


Figure 3.5 Materials Thermal Conductivity

3.4 Cost-effectiveness and issues with the ATEG

The automotive TEG is a recent technology and is still under deep research for it to be an even more productive and efficient system of waste recovery in automotive engines. The ATEG has an efficiency of about 5-10% that has capability and room for more advanced systems. Research in new materials will allow these systems to become more efficient. For now TEGs are capable of producing about 1 KW or 1000 watts of power to be used in the automotive systems.

Other waste or energy recovery systems like the Hybrid Regenerative Braking systems can store large amounts of kinetic energy from the already rotating wheels and brakes to electrical energy large enough to run alongside the petrol engine to run the car. These systems use the kinetic energy already on the tyres and wheels that would otherwise be wasted to be converted into electrical energy by the use of a motor and a battery. When the tyres need to brake the motor runs in the reverse direction and act as an electrical generator to store electrical power in a battery. This system has developed so much and is so brilliant and significant that it has been adapted not only by fuel saving car development projects all over the globe from Toyota to BMW to the all electric revolutionary Tesla to the high speed, super performance engines of Formula One. (HowStuffWorks, n.d.)

The issue with ATEG is that it can not yet make enough power o help aid the petrol engine to run but can merely operate electrical components for vehicles unlike the hybrid regenerative technology that can significantly aid the engine to better performance, efficiency and at times create enough power to run the vehicles on its own. As discussed the competitor technologies are capable of generating enough sustainable power.

In order for ATEGs to function, they need to be attached to the vehicle, adding extra weight and load on the vehicle. This means that the car is heavier and hence also requires more power to run as well. This means that part of the power generated by the ATEG is compensated for the additional weight incurred on the body of the car.

Developments and research in thermoelectric materials is vital in order for the ATEG to be able to generate enough power to help aid IC engines in actually helping the car to manoeuvre rather than just driving small electrical components in the car.

TEGs have some other drawbacks associated with them. They have a relatively low energy conversion efficiency rate. This technology has been researched but progressed at a slower rate compared to its competitive waste recovery or regenerative systems. This system requires a temperature gradient for the seebeck effect to take place, this however limits the applications in practical world to only nominal uses. Only situations where there is a considerable temperature difference present can this technology be used. Not only that a temperature gradient is required for TEGs or ATEGs to function but constant heat source is also required along side other specific requirements for them to function. (profile, 2010)

Thermoelectric devices are not a bad option for waste heat recovery system and other aerospace and refrigeration applications but there is less awareness and knowledge about this technology to the general world and customer of vehicles.(profile, 2010)

On the other hand TEGs are environmentally friendly and reliable source of energy. They have high reliability and durability due to the fact that they have no moving parts to worry about and hardly corrode or wear off over time. This has a beneficial impact on the automotive production.

In the long run, according to the U.S Department of Energy, billions of dollars can be saved in fuel savings in the United States alone over a span of one year. The table below illustrates how the U.S. can save using TEG devices in automotives applications alone. (U.S. Department of Energy, 2016)

The power of increasing fuel economy by 1% and 5%

	Segment	Type of Savings	Estimated Fuel Savings over 1 Year (Billion nominal US Dollars)
Auto/Light-duty trucks	Personal	1% Fuel Savings	\$5.0 B
Heavy-duty trucks	Commercial	1% Fuel Savings	\$1.4 B
Auto/Light-duty trucks	Personal	5% Fuel Savings	\$25 B
Heavy-duty trucks	Commercial	5% Fuel Savings	\$6.9B

Reference: Davis (2012), Transportation Energy Data Book, Table 1.17. EIA (2013), "Gasoline and Diesel Fuel Update" (http://www.eia.gov/petroleum/gasdiesel/ accessed March 2013)

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(U.S. Department of Energy, 2016)

5. Conclusion

As reviewed thermoelectric devices use the Thermoelectric effect for various application including industrial, aerospace and automotive. An in-depth review of automotive thermoelectric generators indicates that it is a useful technology that the automotive world is benefiting from. But still loads of investments and research needs to be put into this technology specially in the research of thermoelectric materials, as they are the variable that can increase or decrease the efficiency of these devices and likewise the efficiency of automotive vehicles.

However, output produced using this technology is not as high as it's other competitors that use waste energy recovery systems, especially the hybrid regenerative braking system that is capable of producing significantly higher outputs as compared to thermoelectric generators. There is no doubt that TEGs aid the IC engines to improve efficiency and lowers emissions and fuel consumption, but with limited generator efficiency.

Conclusively, if this technology is to be used at it's full potential, it might be able to improve its power outputs dramatically. On the other hand Automotive thermoelectric generators can also use the Peltier effect for heating and cooling purposes inside the car.

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