22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024

ISBN: 978-84-09-60656-6

Harnessing Waste Heat from Automotive Exhaust to Generate Electricity for Improved System Efficiency

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Abstract. In this study, we investigated a method of harnessing waste heat from automotive exhaust because it is one source of energy that is prevalent throughout the planet, especially in the combustion of fossil fuels. With the ever-decreasing reserves of oil, and the increasing negative impact of non-renewable energy sources, it is critically important that any novel means of energy generation be researched. We used a thermo-electric generator (TEG) device that utilizes a temperature differential across the device to generate electricity through a Seebeck effect. By sandwiching a string of semiconductors placed in series between two temperature conductive plates, we were able to créate a temperature differential which resulted in electricity generation. By placing the device on the exhaust pipe of a car, we measured the generated voltage while driving the car on the road. The results show that it is feasible to improve the method and enhance the device efficiency to recover waste heat from automotive exhaust efficiently.

Key words. Seebeck Effect, Thermoelectric Generator, Heat Energy Recapturing, Sustainability

1. Introduction

Presently, the idea of global energy shortages is far from a distant concern as the human population continues to increase. With more energy needed to secure the livelihood of more people, energy demand as a whole will increase. Despite the increase in energy demand, the amount of nonrenewable energy sources continues to diminish through use. Although the reliance on nonrenewable energy sources such as crude oil has decreased, they are still heavily dependent on, with the U.S.'s energy consumption in 2022 being 36% petroleum, 33% natural gas, and 10% coal [1]. The high dependency on these sources is due to the fact that countless modes of transportation, infrastructure, and products are based on the continuous use of nonrenewable resources. Most transportation relies upon internal combustion engines (ICE), and as a result, targeting this sector of energy consumption would be greatly beneficial in combating the reliance on fossil fuels.

With ICE vehicles being the primary form of transport throughout both the US and global sectors, being able to recapture lost energies and efficiencies is highly beneficial. Within an internal combustion (IC) engine, more than 62% of energy is lost simply as heat, primarily in the form of combustion gases [2]. Since ICE vehicles make up about 28% of U.S. energy consumption (approx. 27 quadrillion Btu yearly), it can be calculated that 17% of U.S. energy is wasted as heat from transportation vehicles yearly [3].

With a notable amount of energy being emitted via automotive exhaust heat, recapturing that same energy would prove to be beneficial in helping mitigate energy waste. Thermo-electric generator (TEG) modules [4-5] could become a staple of increasing vehicle energy efficiency by maximizing the amount of energy gained from fossil fuels while ICE vehicles remain in widespread use. Although thermo-electric generators themselves are not the most efficient, they are still capable of harnessing some amount of energy from waste heat sources like vehicle exhaust.

TEG modules tend to be only about 6% efficient, but being able to collect that much energy would recapture roughly 1 quadrillion Btu per year. This would help mitigate some of the energy consumption from vehicles in particular, as the energy from TEGs could be used for charging the car's battery, which would decrease the load on the alternator, increasing gas mileage and reduce atmosphere warming. Although electric vehicles (EVs) are becoming more prevalent, the transition to widespread EV use won't be immediate. The use of technologies to further increase the efficiency of ICE vehicles, such as TEGs, could become an important stopgap while the world waits for a fully electric future. A specific application of TEGs in ICE vehicles is in the commercial trucking industry, which has large rigs operating for long distances and for long periods. As a result, the exhaust system would be hot enough to generate electricity from TEGs reliably, as driving conditions would be fairly consistent compared to consumer-grade vehicles. Due to resource availability, this paper will highlight the exploration of the use of TEGs on a consumer-targeted vehicle.

This paper will outline the design of a TEG unit that can be placed on a car exhaust to capture heat energy passively. It is intended for the unit to be designed modularly, allowing for low installation costs and adaptability to many different vehicles. The main cost of manufacturing the unit is the TEGs [6], at about $25 each ($100 for all 4). As such, the unit has a substantial initial cost. However, since there are no moving parts, it is extremely reliable and durable when properly installed. As a result, it is capable of recapturing heat energy for a considerable amount of time and providing a worthwhile return on investment.

With the experimentation of harnessing energy from waste heat in automotive exhaust systems, ICE vehicles would become more efficient, environment friendly by reducing the amount of heat reléase in the atmosphere, and optimized in utilizing fossil fuels. Although EVs may become more popular in time, fossil fuels will still be used as a staple of transportation energy until then. In the meantime, devices such as TEGs can help mitigate some of the energy issues that are experienced in the present so that the future of little to no energy waste arrives faster.

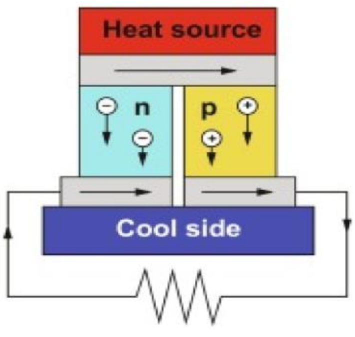

Fig. 1. Diagram of a TEG using Seebeck effect [4].

2. Seeback Effect of a Thermo-Electric Generator (TEG) System

The core functioning principle of a thermo-electric generator (TEG) is the Seebeck effect. Thomas Seebeck [4-5] discovered that applying a temperature differential to two disimilar electrical conductors or semiconductors resulted in the generation of an electromotive force. Specifically, electric charges move from the hot side to the cold side, producing an electromotive forcé proportional to the temperature differential multiplied by a coefficient according to the equation below:

$$\nabla V = S \nabla T \quad (1)$$

where V is the volt, S is the proportionality constant, T is the temperature and ∇ denotes the gradient operator. The basic configuration of the hot and cold side plates, as well as the semiconductors can be seen in Figure 1 [4].

3. Model Descriptions and Methods

In order to size the heat sink for this application, the amount of wattage that needed to be dissipated had to be determined first. In order to do this, the system was modeled as a thermal circuit, as seen in Figure 2.

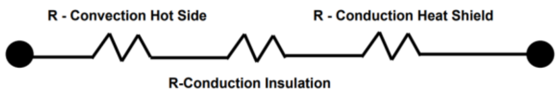

Fig. 2. Thermal circuit of a heat recapture system.

As seen in the model shown in Fig. 1, the convection between the pipe and the TEG, the conduction done by the insulation, and the conduction done by the heat shield through different resistances. The resistances as shown in Fig. 2 can be calculated as:

$$R_{Conv,\ hot\ side} = \frac{1}{hA} \quad (2)$$

$$R_{Cond,\ insulation} = \frac{L}{kA} \quad (3)$$

$$R_{Cond,\ heat\ Shield} = \frac{L}{kA} \quad (4)$$

In order to determine how many total watts that the entire system needed to dissipate, the amount of heat dissipation was needed from these three aspects in addition to how much each TEG must dissipate. The total resistance is shown in equation (5).

$$R_{Total} = R_{Conv,\ hot\ side} + R_{Cond,\ insulation} + R_{Cond,\ heat\ Shield} \quad (5)$$

In order to complete these calculations, the properties of each material utilized were shown in Table I.

Table I. - Material Properties.

Material	**Type of Variable**	**Quantity (W/(m*k)**
Air	Convection Coefficient(h)	100
Insulation	Conduction Coefficient(k)	237
Heat Shield	Conduction Coefficient(k)	7

With the physical properties known, the total resistance can be calculated using equation (5). Then calculate the total heat that these three materials actually need to dissipate using equations (6)-(7).

$$R_{Total} = \frac{1}{\left(100\frac{W}{m^2.k}\right)\left(0.002m^2\right)} + \frac{0.015m}{\left(237\frac{W}{m.k}\right)\left(0.002m^2\right)} + \frac{0.0032m}{\left(7\frac{W}{m.k}\right)\left(0.0129m^2\right)} = 5.06\ \frac{k}{W} \quad (6)$$

$$q_{dissipate} = \frac{573k - 293k}{R_{total}} = \frac{280k}{5.06\left(k/W\right)} = 55.26W \quad (7)$$

Lastly, the material dissipation was added to equation (7) what the TEG must dissipate multiplied by the number of TEG's as shown in equation (8).

$$q_{Total} = q_{dissipate} + 4 \cdot q_{TEG} = 55.26W + 4 \cdot 188W = 807.27W \quad (8)$$

We then chose to oversize our heat sink by nearly one and a half times what was needed. This was done to ensure that it could be reduced to a smaller one if necessary.

4. TEG System Design

The TEG device will consist of four individual TEG modules (TGPR-10W-4V-40S) wired in series. The module specifications are shown in Table II.

Table II. - TGPR-10W-4V-40S Specifications [6].

Max Power Output (W)	10
Output Voltage (V)	4
Max Operating Temperature (℃)	330
Max Efficiency Temp (℃)	225
Conversion Rate (%)	6.4

Individually, each module can output up to 4V at a temperature differential of 270℃, with a maximum current of 2.5 Amps. Placing four of these modules in series will provide a maximum of 16V. The TEG modules will be sandwiched by a heat sink on the cold side, and a heat transfer block on the hot side. The heat sink is intended to dissipate heat from the cold side of the TEG units, using the air flow from vehicle motion to increase heat dissipation. The heat transfer block will be in direct contact with the exhaust pipe, transferring as much heat as possible to the hot side of the TEG modules. Thermal paste was used to increase the efficiency of heat transfer on the hot and cold sides of the TEG. A heat shield and carbon insulation was used to minimize heat transfer from the hot to the cold side to ensure the highest system efficiency. The wires from the TEG modules were connected to a charge controller that will send the generated voltage to a 12V battery. Any electric auxiliary systems can be wired to the charge controller to get power from the battery. A section view of the system is shown in Figure 3.

To secure the system to the vehicle exhaust, U-bolts were used, with custom-made steel support brackets to constrain the U-bolts and hold the entire system rigidly. Additionally, clamps were added to ensure proper connection between the heat sink, TEGs, and heat transfer block.

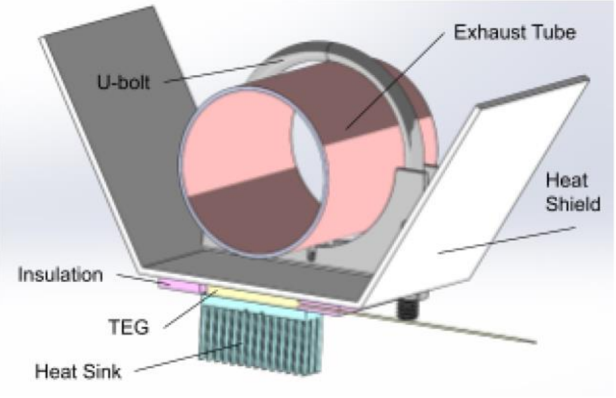

Fig. 3. System design with TEG section view.

5. Exhaust Temperature Benchmarking

To conduct real-world testing, a student's 2005 GMC Canyon was chosen to be the test vehicle. In order to understand the exhaust pipe temperatures, the truck's exhaust system was instrumented with thermocouples. Collecting this information was important as it would allow us to locate the ideal spot for the TEG assembly to maximize hot side temperature while staying within the maximum temperature range for the TEG modules. Thermocouples were placed before the catalytic converter, after the catalytic converter, before the muffler, and after the muffler. The test was run on a day when the ambient air temperature was 24.45°C. Exhaust temperatures measured under different conditions are shown in Table III.

Table III. - Exhaust temperatures measured.

Probe	Idle Temp (℃)	7.3 Miles City Driving (℃)	8.9 Miles Highway Driving (℃)
Pre- Catalytic Converter	137.5	358.9	395.3
Post- Catalytic Converter	71.2	308.2	381.8
Pre- Muffler	55.5	256.5	335.3
Post- Muffler	47.2	179.1	217.7

The TEG modules used on this assembly have a maximum operating temperature of 330℃ continuously [6]. From the collected data, it was concluded that placing the assembly after the catalytic converter would be ideal.

6. Bench Testing of the Device Prior to Install on the Vehicle

Before testing the assembly on the vehicle, bench testing was needed to verify performance. The TEG assembly, as described in the system design section, shown in Fig. 3, was placed onto a 24in section of steel exhaust pipe. A heat gun was used to provide a heat source to the system as a stand-in for the internal combustion engine. The assembly was instrumented with thermocouples so data could be gathered while running the tests. These thermocouples were placed on the exhaust pipe, TEG hot side, TEG cold side, and heat sink. A volt meter was used to measure the voltage from the TEGs. The goal of conducting bench test was to measure the generated voltage as a result of the temperature difference between the hot and cold sides of the TEG modules. The test bench can be seen in Figure 4. The initial system design lacked a heat transfer block, and the results quickly showed that the hot side of the TEGs would not get significant heat from the exhaust. As a result, the design was modified with the addition of a steel heat transfer block to contact the exhaust and TEG hot side directly.

Multiple bench tests were conducted with results taken over a sixty-minute run time. The results of the final bench test are shown in Table IV, with TEG hot and cold side temperatures displayed, as well as temperature differential and generated voltage.

7. Test Bench Limitations

As can be seen from Table IV, the test bench was not able to reach the desired maximum temperature differential of 270℃. This was due to the heat source being unable to replicate the heat coming from an internal combustion engine exhaust properly. Since our heat sink was intended for higher heat dissipation, it dissipated too much heat and started to cool down the exhaust pipe when cooled with compressed air. Due to these limitations, it was decided to move on to vehicle testing despite not acquiring the desired result on bench test. It should be noted that extrapolating the data shows a voltage near 16V at the maximum desired temperature differential.

8. Actual Vehicle Test with Device Installed

To conduct the vehicle tests, the assembly was fastened to a location after the catalytic converter. Thermocouples were attached in the same location as on the bench test so the data could be directly compared. The driving test was broken into three stages to assess the TEG assemblies' performance under different conditions. Thermocouple and volt meter measurements were taken periodically. The first part of the test consisted of idling, the second test consisted of residential and city driving, and the third part consisted of highway driving at an ambient temperature of 11.11℃. The combined data from these tests is shown in Table V. To note, issues with the TEG setup for on-vehicle testing required using pipe and heat sink temperatures.

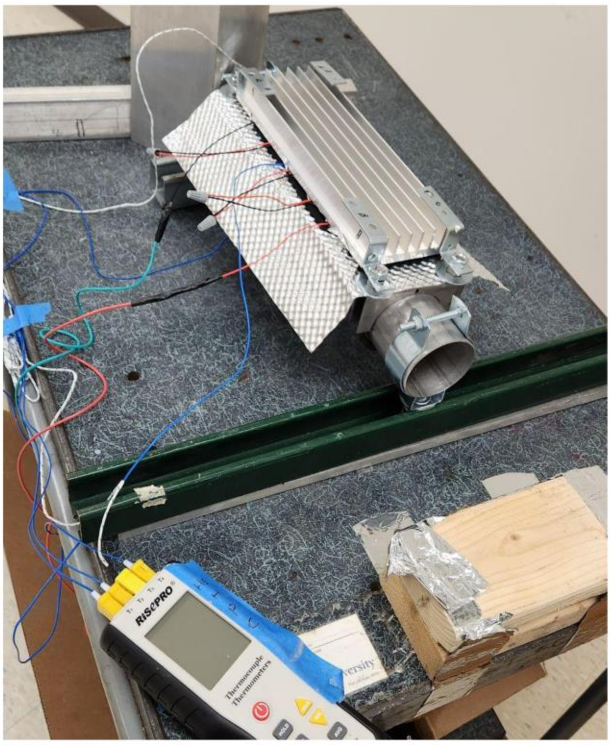

Fig. 4. Bench test layout (heat gun not pictured).

Table IV. - Bench test data.

Hot Side (℃)	**Cold Side (℃)**	**Temp Differential (℃)**	**Voltage (V)**
28.89	23.61	5.28	0.39
31.72	22.22	9.50	0.63
36.28	21.89	14.39	0.92
44.28	24.78	19.50	1.14
52.00	27.72	24.28	1.33
56.50	27.39	29.11	1.48
60.72	23.89	36.83	1.54
66.06	23.22	42.83	1.67
68.22	23.28	44.94	1.74
70.39	22.89	47.50	1.80
72.28	22.72	49.56	1.85
73.78	22.11	51.67	1.89
76.11	20.78	55.33	1.98
79.28	21.00	58.28	2.07
84.00	21.61	62.39	2.22
88.50	21.78	66.72	2.43

From this test, the TEG device generated an average of 6.1 volts at a hot side/cold side temperature differential of 81.1℃ with a maximum of 7.2V at 110.9℃. The data was graphed with a line of best fit, as shown in Figure V.

From this data, extrapolation along the line of best fit indicates that if the desired temperature differential is reached, there is a potential to obtain 15.12V with this device.

9. Vehicle Test Limitations

As the data clearly shows, the desired 16V to charge the 12V battery was not within scope. One reason for this was due to being unable to reach the peak hot side temperature. Since the heat sink chosen was oversized, it was dissipating too much heat, cooling down the exhaust pipe. This lowers the hot side temperature, decreasing the device's performance. While the data collected did not satisfy our initial requirements, it clearly shows that this device has the potential to generate significantly more than 6.1V.

Table V. - Actual vehicle road test data.

Ambient Temp (10 ℃)	**Pipe Side (℃)**	**Heat Sink (℃)**	**Voltage (V)**	**Temp Differential (℃)**
5 min	149.1	82.9	4.8	66.2
10 min	181.3	83.7	6.9	97.6
15 min	182.0	88.5	6.9	93.5
20 min	196.0	85.1	7.2	110.9
25 min	183.9	88.5	6.6	95.4
30 min	177.3	88.0	6.4	89.3
35 min	147.0	82.3	5.8	64.7
40 min	158.1	86.9	6.1	71.2
45 min	156.0	80.5	6.2	75.5
50 min	152.6	76.8	6.0	75.8
55 min	152.0	72.1	6.1	79.9
60 min	152.7	71.4	5.9	81.3
65 min	146.7	77.7	5.8	69.0
70 min	135.8	71.1	5.1	64.7
Mean	162.2	81.1	6.1	81.1

10. Safety Considerations

In order to generate the necessary energy for the desired TEG working point, it becomes unsafe to handle quickly as the exhaust warms up. While end-case usage does not require any interfacing with the device or exhaust, installation, and experimentation require careful consideration. To safely handle the equipment, heat-resistant PPE gloves must be worn after giving the exhaust time to cool adequately. Since the voltage and current produced by the TEG modules are low, little consideration is necessary for electrical safety aside from general procedures, as well as secure mounting of the battery and proper routing of wiring.

11. Conclusion

While the results from the bench and vehicle tests did not reach the desired 16V for the system, they show that the current design is a step forward in the right direction. With more time to optimize the design and testing, it should be possible to increase the TEG hot/cold side temperature differential, increasing the voltage output. An example in optimizing the design includes redesigning the heat transfer block to conduct more heat to the hot side of the TEG module, as well as a better clamping system to increase uniform contact between components. Additionally, the heat sink size can be optimized for the test vehicle. Alternatively, the TEG device can be used on hotter exhaust systems to increase the voltage output. During the road test, the results showed that the exhaust system on the test vehicle was only reaching maximum temperatures during highway driving. While this may not be ideal for consumer vehicle applications, there are many other applications where this device could recapture waste heat energy. One promising application for this technology is on the exhaust system of commercial semi trucks, which operate at much higher loads causing the exhaust system to be consistently hot for a prolonged period. With the benefits of this system, including ease of installation and high reliability, alongside the results from the testing outlined in this paper, it is logical to further research and development to make this technology not only more viable but also widespread.

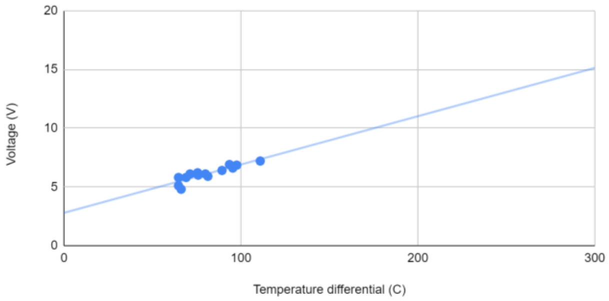

Fig. 5. Actual vehicle road test data shows voltage as a function of temperature differential.

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