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Research article

The Virent of Clean Technology: Waste Heat Recovery Using a Thermoelectric Generator (TEG)

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ABSTRACT

The rising demand for energy-efficient technologies has paved the way for significant interest in waste heat recovery studies. This heed is demonstrated by the rapid growth in the rate of publications related to technical articles about sustainable energy systems. The purpose of this study is to understand the basic concepts of thermoelectricity used in a thermoelectric generator and how waste heat from an exhaust system of a vehicle can be recovered through it. The advantages and limitations of such systems are outlined with attention directed towards generating electricity from the recovered waste heat. It would be beneficial not only for the environment but for the industries with high footprints of waste heat as well.

Keywords: Waste Heat Recovery, Thermoelectric Generators, Energy Conservation, Heat & Mass Transfer, Clean Technology

Introduction

Government-decreed developments in fuel utilization considering the remunerative approach and all the waste emissions from internal combustion engines (ICEs) are paving the way for upheaval in engine efficiency [1]. In ICEs, chemical energy is converted into mechanical energy via the combustion of the fuel in the presence of air. It results in thermal expansion of gases because of the ignition process taking place in the combustion chamber on fuel and water mixture. This expansion causes the piston to work that turns the crankshaft to produce torque. A fuel consumption diagram is shown in the figure below which explains how much fuel is utilized in producing the required work and how much is utilized in other aspects:

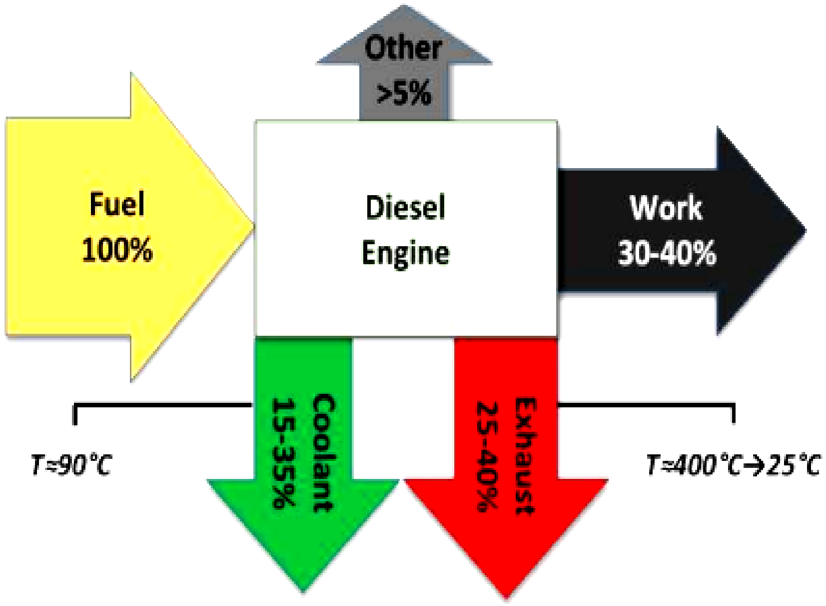

Figure 1: Energy balance diagram of diesel engine [2]

The above figure is self-explanatory, only 30-40% output is obtained in a novel diesel engine. The rest is being utilized by the coolant and the exhaust systems of the vehicle. This large portion of input taken up by the coolant and exhaust systems raises the equation of waste heat recovery. Other 5% losses are in defective combustion, losses during pumping, and friction and heat losses to the atmosphere via the engine oil.

In the past decade, there has been an augmented increase in fuel costs that paved the way for the consistently rising concern regarding global warming. Engineering industries are facing a challenge to minimize the ever-increasing greenhouse gas discharges and enhance the efficiency of their sites. This is where the use of waste heat recovery systems comes out as a solution to decrease the consumption of fuel, lessen damaging emissions and boost production efficiency [3].

Waste heat recovery techniques consist of detaining and conveying the waste heat to the system to be used as an additional energy source for further processes [4]. The waste heat after recovery can be utilized in generating electrical or mechanical power [5].

To conduct a waste heat recovery experiment using thermoelectric generators (TEGs), one must understand the following thermoelectric principles:

- Seebeck effect
- Working of the Peltier module

From 1821 to 1823, Thomas Johann Seebeck observed that two different metals having different temperature junctions deflect a magnetic compass. At first, he thought that this phenomenon is occurring due to magnetism induced by temperature differences concerning the Earth's magnetic field. Later, he realized that the deflection was governed by Ampere's Law as a result of 'Thermoelectric Force' which in turn induced current. Specifically, the temperature difference produces a potential (voltage) that can drive the current in a closed circuit [6]. Thirteen years after the Seebeck effect (1821), the Peltier effect was discovered; which is the liberation of heat at one of the junctions of a thermocouple and heat fixation at the other end, when an electric current is flowing through the circuit [7]

Literature Review

The efficiency of the internal combustion engine (ICE) to convert chemical energy into mechanical energy is not that great. This low efficient system results in the dissipation of heat in exhaust and coolant. One way to minimize or eliminate this dissipation of heat as waste energy is to make the engine more efficient. Another way is to utilize the waste heat for some other work so it doesn't go to waste [8]. Internal combustion engines of the present era are about 25% efficient [9] under certain driving conditions. Under different driving conditions, these efficiency rates can go anywhere from 20% to 45%. The rest is dissipated as heat in coolant and exhaust systems which can be reused through waste heat recovery systems such as a thermoelectric generator (TEG) [8]. Peyghambarzadeh et al. [10] used a water-based nanofluid coolant with five different concentrations ranging from 0.1 to 1 Vol% of Al_2O_3. The fluid was found to increase the efficiency of heat transfer up to 45% when compared with pure water. Leong et al. [11] used copper-based nanoparticles in ethylene glycol and water mixture that caused a 3.8% enhancement in the transfer of heat in the radiator. Jafari et al. [12] took a similar approach but with SiO_2 and concluded that it caused enhancement in heat transfer and radically reduced fuel consumption.

Zadsar and Gorji-Bandpy [13] experimented on an OM314 diesel engine, they used a twisted tape in the exhaust of the engine to increase the waste heat recovery. In addition to that, Lee and Bae [14] used the design of experiment (DOE) technique and formed a HEX with fins. They concluded that the fins must be placed in the path of the exhaust gases for better heat transfer. They also experimented with using different fins thicknesses and also altered the number of fins. A thermoelectric generator (TEG) can always become more efficient. Therefore, a lot of researchers are trying to find a way to increase the efficiency of TEGs. In recent years, for increasing the efficiency of about 5 to 8% [15], p-n junctions of new materials such as BiTe (Bismuth Telluride), ZnBe (zinc-beryllium) have been used. Karri et al. [16] researched multiple cases of waste heat recovery using TEGs. Chau [17] concluded that using a TEG in waste heat recovery from an exhaust system doesn't affect the performance of the engine, while Yu and Chau [18] explained that using a TEG setup for waste heat recovery can cause loss of kinetic energy of waste gases and increase pumping.

When thermoelectric generators are integrated into the heat exchangers to recover waste heat, M. H. Zaher et al. [19] showed that the output of power increases with the exhaust gas flow rate. Their experiment also concluded that axial conduction between a series of TEGs rows harms the overall efficiency.

Niu et al. [20] set up a very low-cost TEG with the simplest of configurations equipped with Bi_2Te_3 which has high commercial availability concerning the respective thermoelectric module (TEM). The foreseeable maximum power generation output was 150-200 W. Hsiao et al. [21] applied a model based on pure mathematics of a thermoelectric module (TEM) directing in the applications of waste heat recovery from an automobile engine to conclude their analysis. Zhou [22] introduced a TEG based on two stages, analyzing its output power and efficiency for a comparison between more conventional TEGs. Chen et al. [23] came up with a whole new model of thermoelectric generator (TEG) that utilizes a multi-element procedure for increasing efficiency.

Xiaolong Gou did a study to optimize thermoelectric power generation in waste heat recovery considering low-temperature output [24]. X. Lui et al. [25] have done a thorough thermal field simulation using the k-Ɛ turbulence model. T. Y. Kim et al. [26] performed several numerical simulations to study heat transfer efficiency through direct contact.

Design and Methodology

Design Approach

A waste heat recovery system was designed for the exhaust system of a bike (Atlas CD 70, compression ratio 9.3:1). A circular sheet of mild steel (304 grade) was mounted on the muffler of the bike. Peltier modules in series were attached on the steel sheet where the steel sheet acted as a conducting source between the Peltier modules and the muffler of the bike. An aluminum heat sink was used to protect the modules from overheating. Two booster circuits were used to increase the output voltage received from the temperature difference. The engine on the bike providing the heat is 4-Stroke OHC Air-Cooled.

Four Peltier modules were connected in series to use the maximum hot area of muffler surface.

> **Mild Steel Wrapping:** Mild steel wrapping was used, specifically SAE 304 grade as it was easily available in the local market. Mild steel is also cheaper as compared to aluminum or copper sheets and also easy to shape it in the circular form of wrapping as shown in the figure below:

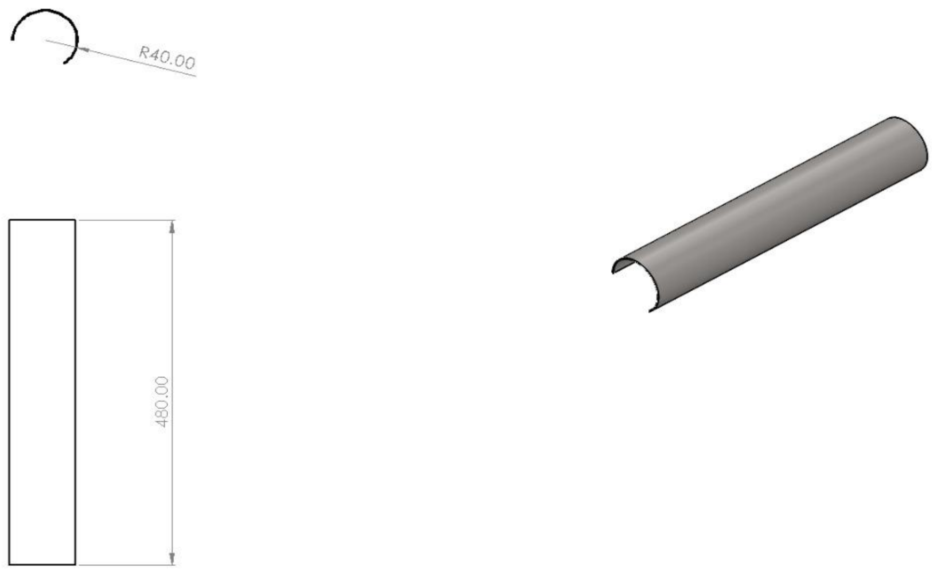

Figure 2: 3D model and dimensions of mild steel wrapping

Aluminum Heat Sink: Aluminum was used for the heat sink because copper heat sinks are expensive and for the application under consideration, an aluminum heat sink could easily dispose of any extra heat beyond the required temperature difference. The dimensions and computer-aided design of the heat sink are as follows:

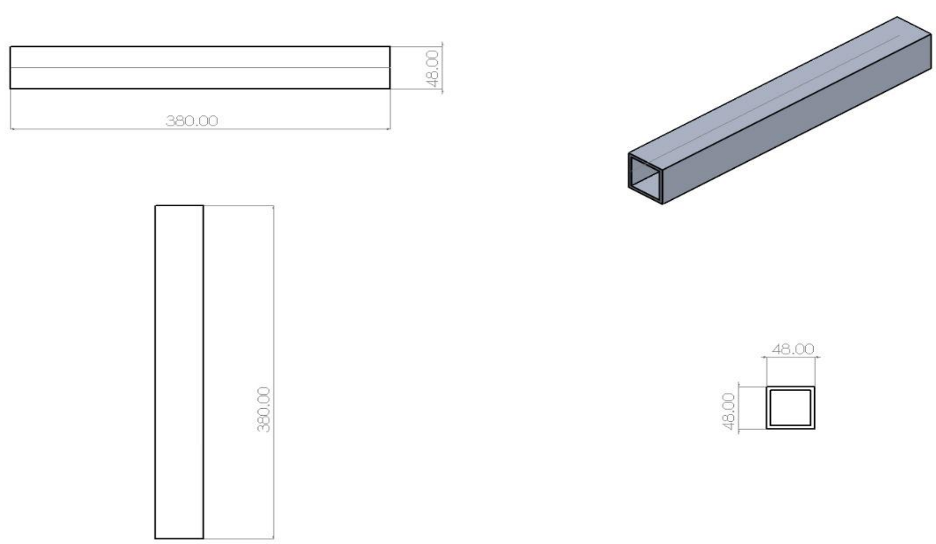

Figure 3: 3D model and dimensions of the aluminum heat sink

Application of Booster Circuits: Booster circuits were added to compensate for low output potential. Two of them were added to get the required voltage result. Booster circuits increase the voltage by decreasing the current flow thus inducing resistance in the circuit. The specifications of both used booster circuits with step up values and voltage drops are as follows:

Table 1: Boosters used in the design

Mini Booster		L6009 Booster	
Step Up Value	3V to 5V	Step Up Value	5V to 30V
Voltage Drop	0.2 – 0.7	Voltage Drop	0.7 – 1.0

Computer Aided Design of Waste Heat Recovery System: Following is the computer-aided design of all the parts that were talked about individually:

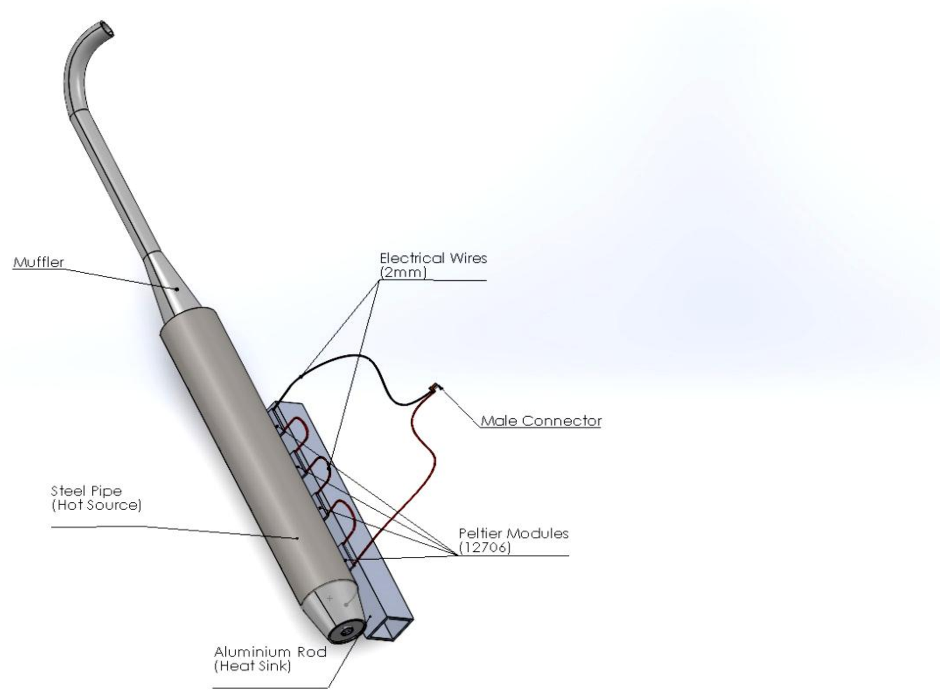

Figure 4: Waste heat recovery system assembly on the muffler of the vehicle

There are various methodologies to approach the concept of waste heat recovery but the one we will be taking is through an exhaust system of a vehicle. The heat from the exhaust system of a motorcycle, specifically the muffler will act as the heat source. The heat will vary depending on the working conditions of the vehicle under consideration. The heat will be carried to one of the junctions of the Peltier module through conduction. A steel sheet will act as a bridge to transfer heat from the muffler to the junction. The other side of the Peltier module will be cooled directly by the air of the atmosphere.

An aluminum heat sink will be placed on the cold side of the Peltier to absorb the heat so the temperature on both sides does not become similar. When the temperatures are maintained at both ends, the temperature difference will allow the Peltier to give an output of a certain voltage which can be altered by the booster circuits installed in the system.

Type of Engine Exhaust System for Heat Supply

The engine running on the Atlas Honda CD70 motorcycle is 4-Stroke OHC Air Cooled. It provides heat to the muffler; heat is conducted onto the mild steel wrapping. The design of the muffler was created on the CAD software, SOLIDWORKS. The dimensions were measured at university premises and the maximum outer diameter of the design was measured to be 77 mm.

The outside and inside area of the muffler accumulates to be 272.512 cm^2.

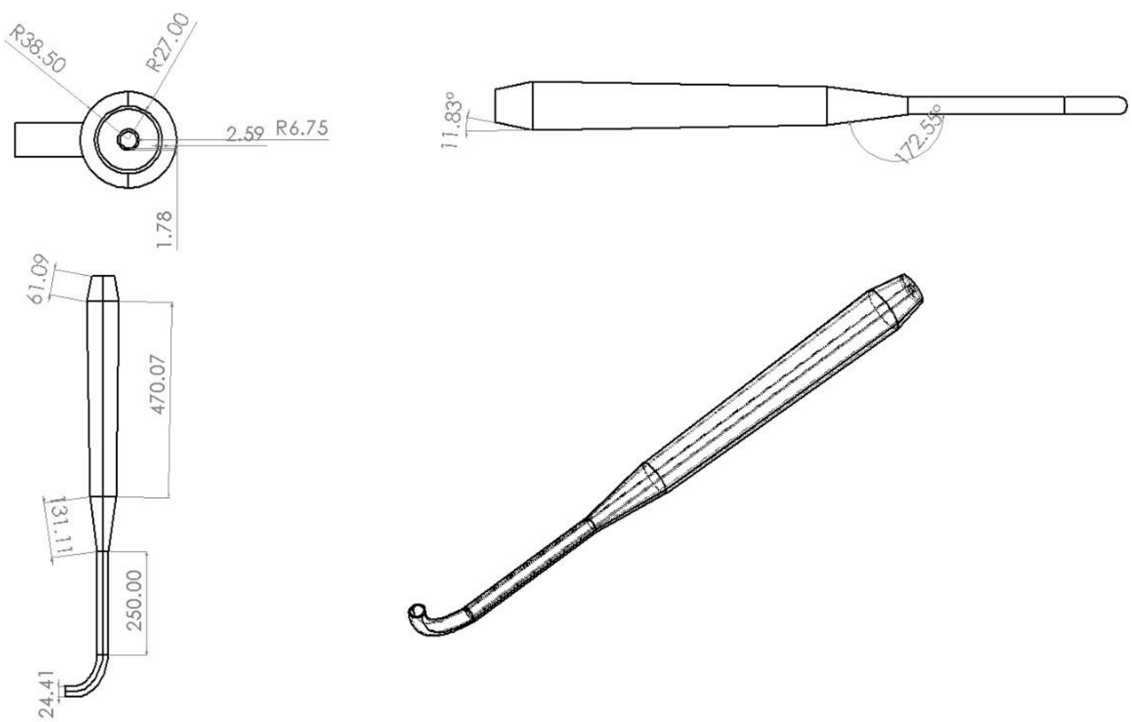

Figure 5: Dimensions of the muffler

The specifications of the CD70 engine providing heat to the muffler are as follows:

Table 2: OHC engine spec, OHC = Overhead Camshaft [27]

Technical Specifications of ATLAS Honda CD70 Engine			
Engine Type	OHC, Air Cooled, 4-Stroke Engine	Frame Type	Backbone Type Framing
Displacement Spec	~72 cm^3	Dimensions of the Engine	1897 x 751 x 1014 mm in (LxWxH)
Ratio of Compression	9.3:1	Capacity of Petrol	8.5 liters with 1 liter as reserve
Weight (Dry)	82 kg	Transmission	4-Speed Constant Mesh
Ground Clearance	136 mm	Clutch	Wet Plates (Multiple)

Measurement of Temperatures and Voltages

The temperatures at the hot and cold sides of the Peltier module are to be measured at different stages of the engine running times with the help of a 'Mini Infrared Thermometer'. For the measurement of the produced voltage at the end of the experimentation, a multimeter will be used to get an accurate reading. The multimeter to be used is present in the laboratory of Electronics in the Biomedical Engineering Department, University of Engineering & Technology Lahore.

Parameters

Following are the parameters of the proposed Waste Heat Recovery System:

Table 3: Input and output parameters of the WHR system

Parameters			
Input Parameters		**Output Parameters**	
The temperature at the cold junction	To be measured with the help of an Infrared Thermometer	Voltage/Current	To be measured with the help of a Multimeter
The temperature at the hot junction	To be measured with the help of an Infrared Thermometer	Boosted Voltage	To be measured with the help of a Multimeter

Results

To find out the voltage produced and amount of heat absorbed by the thermoelectric generator when the temperature of the flue gases at the core of the muffler is as follows:

Table 4: Problem statement data

Motorcycle running time	**The temperature of the flue gases at the core of the muffler**
After 30 minutes	110^{o}C

Proposed Simulations

The whole analysis will be conducted in four stages which are as follows:

- Steady-State Thermal analysis for the heat transfer from flue gases to the surface of the muffler through convection and radiation
- Steady-State Thermal analysis for the heat transfer from the surface of the muffler to the surface of the steel wrapping through conduction
- Thermal-Electric analysis for calculation of voltage produced and the heat absorbed by the Peltier module
- Design and Analysis on MATLAB for the increase in voltage through the booster circuits connected to the Waste Heat Recovery system.

Steady-State Thermal Analysis for Convection and Radiation

The designed geometry of the muffler was imported into the ANSYS workbench and a mesh was generated with a 3 mm element size as follows:

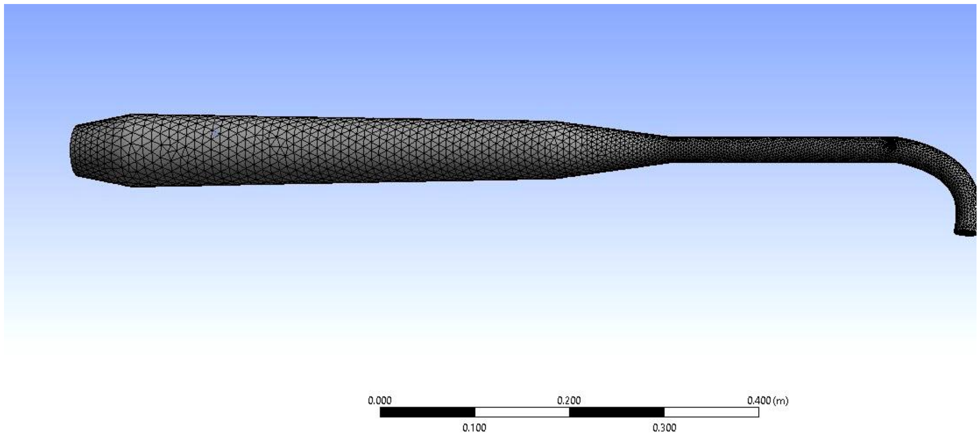

Figure 6: Meshing of the muffler with 3mm element size

Following solutions were obtained through convection and radiation processes for the exchanging of heat:

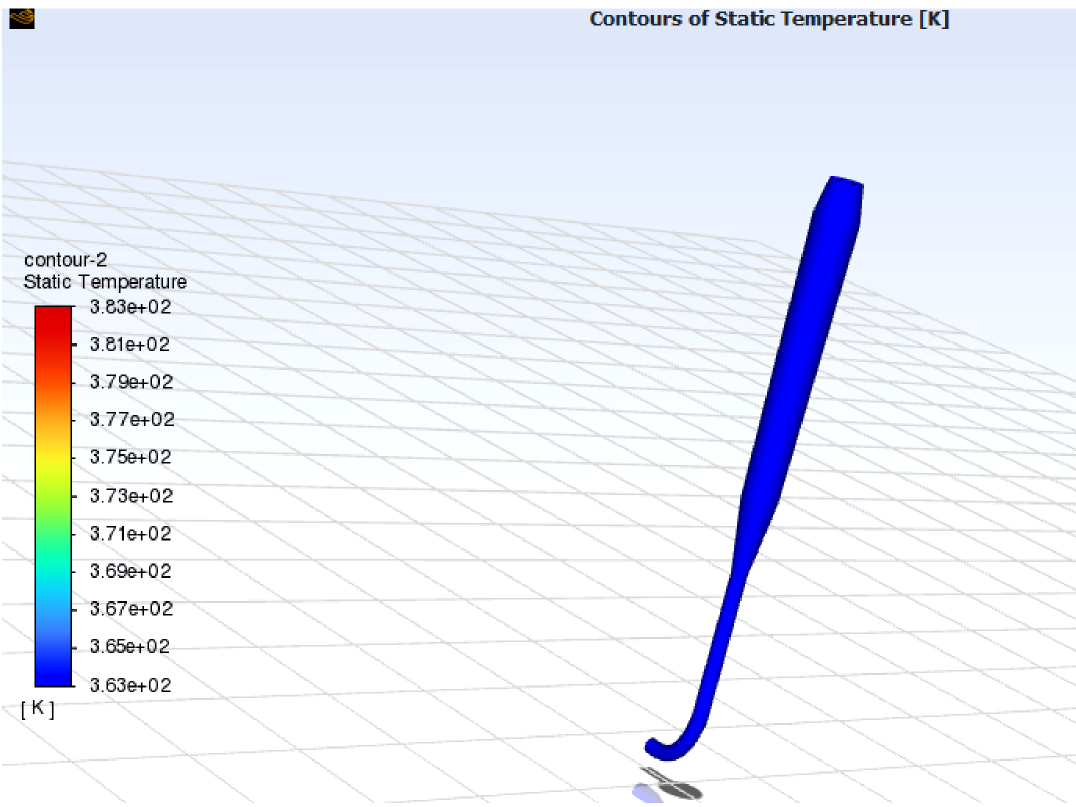

Figure 7: Contour of Static Temperature

The results obtained show that a temperature average of 100^{o}C was received on the outer surface of the muffler out of the initial 110^{o}C. There was 10^{o}C loss in heat exchanging through convection and radiation.

Steady-State Thermal Analysis for Conduction

A similar analysis was carried out again but this time for heat transfer between the structural steel muffler and the mild steel wrapping around it. Due to direct contact between the surfaces of both materials, there will be conduction.

Following is the mesh of the geometry of the muffler with mild steel wrapping around it:

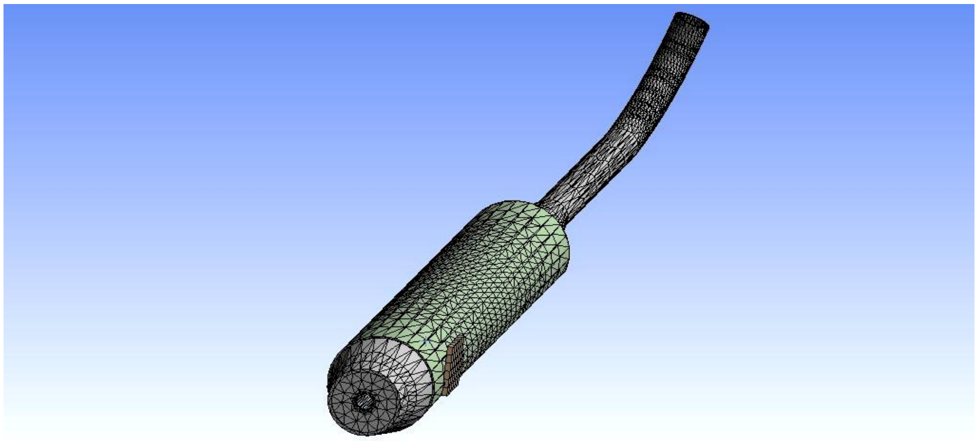

Figure 8: Mesh quality of muffler with mild steel wrapping

After compiling the solutions, the static temperature received on the outer shell of the mild steel wrapping was simulated to be in the range of 96°C to 82°C. A loss of nearly 11°C after conduction from the muffler to the mild steel surface. This temperature is the temperature of the hot side of the Peltier module.

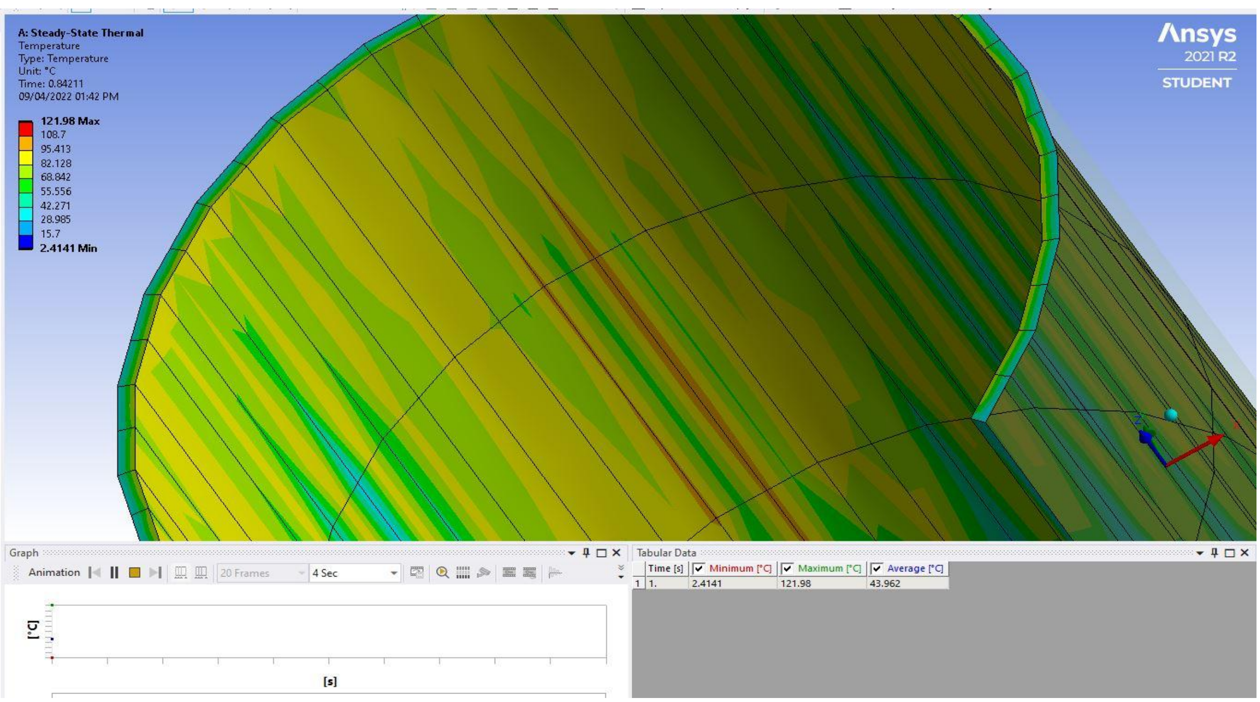

Figure 9: Temperature at the mild steel surface of the WHR system

Thermal Electric Analysis on the Designed WHR System

Now, a thermal-electric analysis is carried out. The simulation will be done on a single Peltier and calculations will be optimized for the four Peltier modules connected in series. The above two simulations gave us results. The total data for this simulation is given below:

Table 5: Data for the thermal-electric simulation

The temperature at the hot end of the Peltier junction, P-Type	The temperature at the cold end of the Peltier junction, N-Type	Bike Running Time	Temperature Difference
81°C	14°C	30 minutes	67°C

Additional data for the Peltier module (alumina) is as follows:

Table 6: Additional data of the Peltier junctions of Peltier 12706

P-Type Junction		N-Type Junction	
Isotropic Thermal Conductivity	1.5 $Wm^{-1}K^{-1}$	Isotropic Thermal Conductivity	1.5 $Wm^{-1}K^{-1}$
Isotropic Seebeck Coefficient	53 mVK^{-1}	Isotropic Seebeck Coefficient	-53 mVK^{-1}
Isotropic Resistivity	0.0864 Ωm	Isotropic Resistivity	0.0864 Ωm

The results obtained from the above simulation data are as follows:

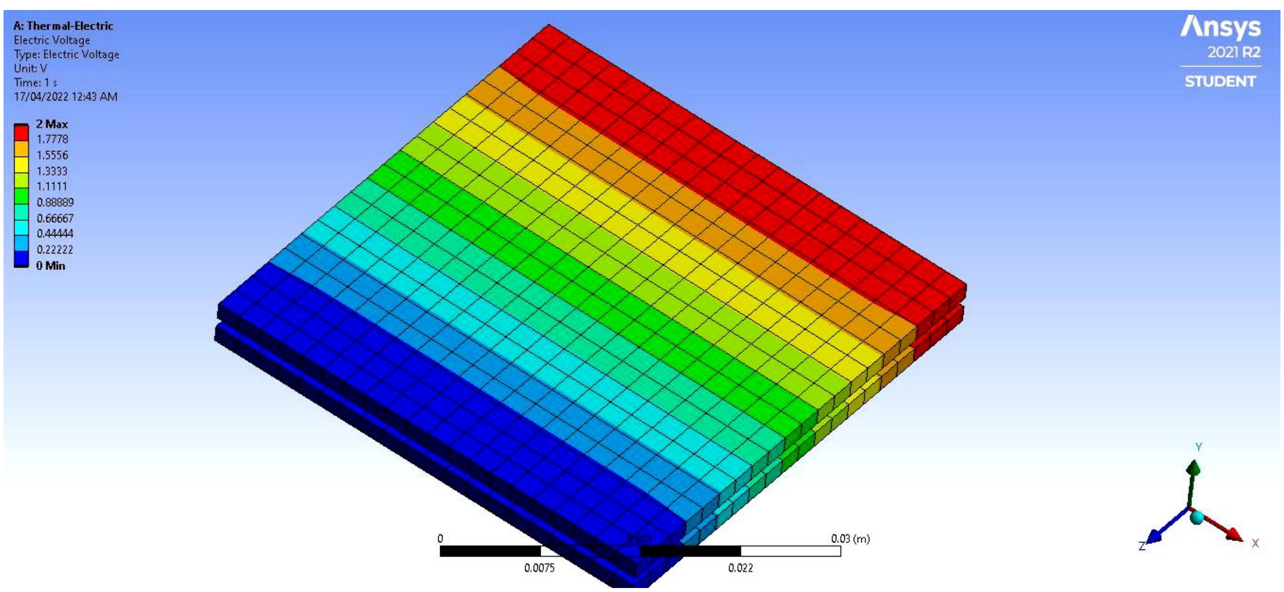

Figure 10: Voltage generated by a single Peltier module

The result shows that one Peltier module would give a maximum voltage output of 2V. A series of four connected Peltier modules can give out a voltage of around 8V in ideal conditions.

Booster Circuits Analysis

A circuit design of booster circuits was created on MATALB as shown in the figure below:

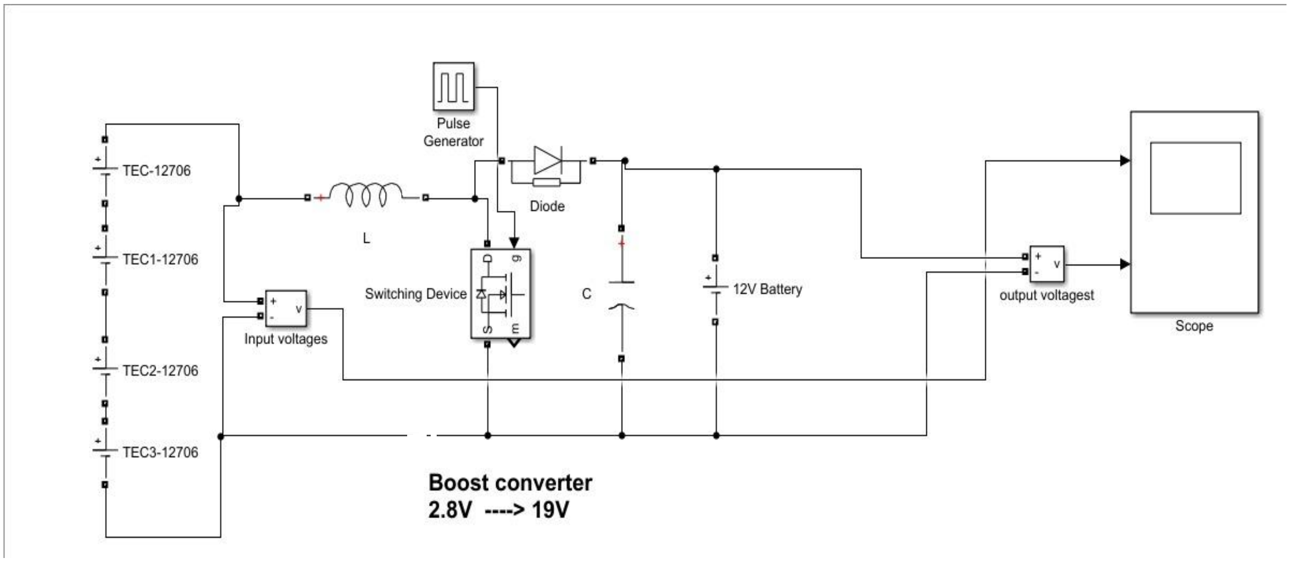

Figure 11: Booster circuit design

The input and output voltages simulation boosting the induced voltages up to a minimum value of 19V is as follows:

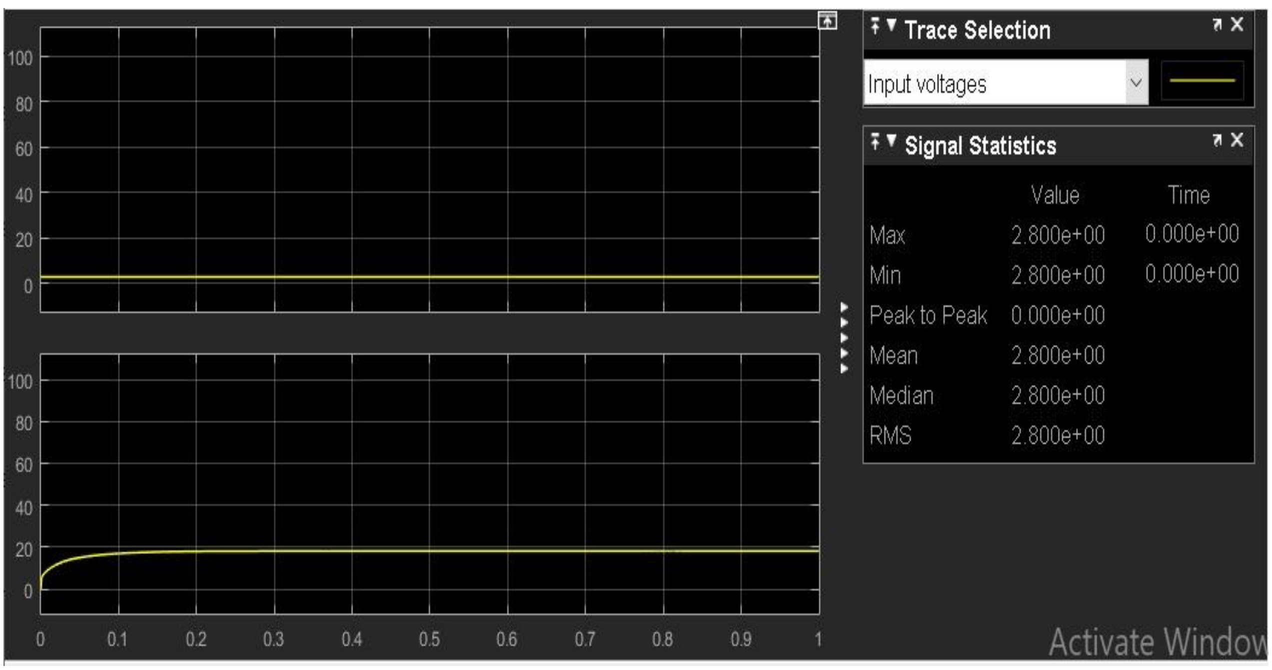

Figure 12: Input voltages simulation

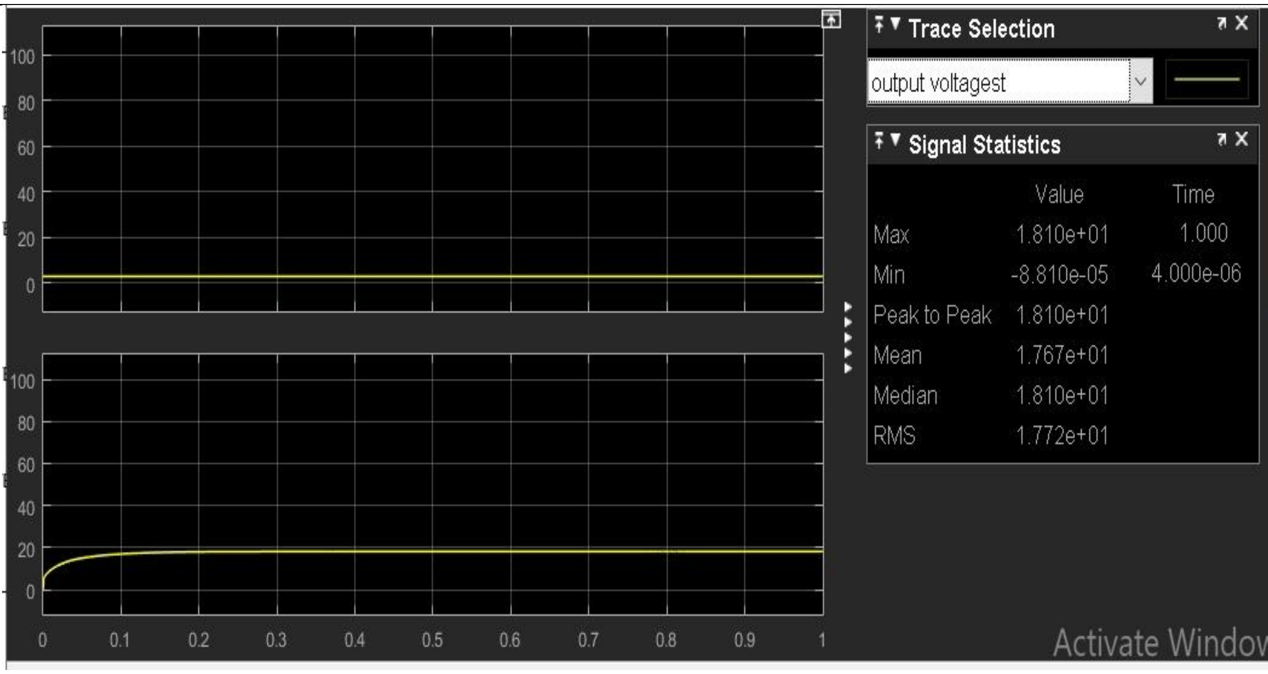

Figure 13: Output voltages simulation

Experimentation

This section will envelop the results obtained from the fabricated model of the waste heat recovery system for the exhaust system of a vehicle. The output variable is the voltage obtained using the waste heat of the system. Fabricated model of the waste heat recovery system based on the SOLIDWORKS model in the previous chapter is as follows:

Figure 14: Fabricated model of WHR system

The model shown in the above figure is attached to the muffler to help visualize how it is attached to the exhaust system of the vehicle.

Experimental Results

The bike running time is 60 minutes at the speed of 30 km/hr. Following table represents the results obtained from the experimentation:

Table 7: Experimental results of WHR system, NA = Not Applicable

Waste Heat Recovery							
Sr. No.	**Time duration (minutes)**	**Temperature at the muffler (^oC)**	**Temperature at the cold side (^oC)**	**Temperature at the hot end (^oC)**	**Temperature difference (^oC)**	**Voltage (V)**	**Boosted Voltage (V)**
1	10	52.14	30.00	42.00	12.00	0.16	NA
2	20	54.50	30.00	44.30	14.30	0.32	NA
3	30	63.00	33.00	52.20	22.20	0.48	NA
4	40	73.16	34.00	62.30	28.30	0.98	NA
5	50	79.80	35.00	69.50	34.50	1.63	NA
6	60	84.58	37.00	77.40	40.40	2.56	15.00

The following graph represents the waste heat recovery process with the dependent variable (voltage) on the y-axis and the independent variable (temperature difference) on the x-axis:

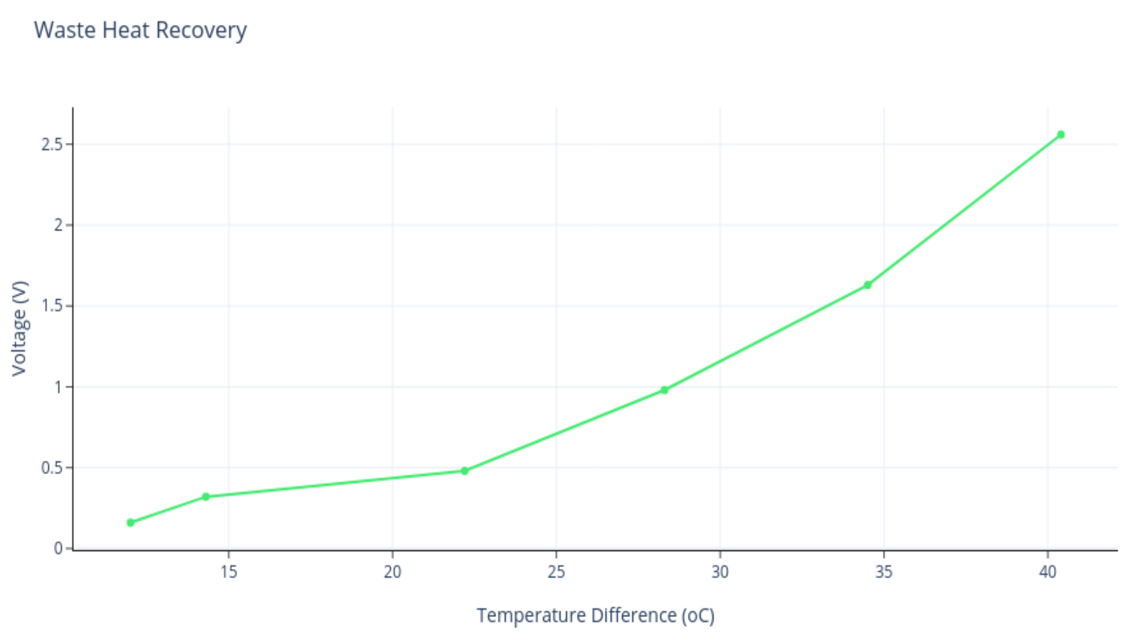

Figure 15: Graphical Presentation of Waste Heat Recovery

Conclusion

Our study shows that waste heat can be recovered using a thermoelectric generator from the exhaust system of a vehicle. The amount of waste heat recovered determines the quantity of induced voltage. Furthermore, the output voltage can vary depending on weather patterns, driving conditions, quality and quantity of the Peltier module(s), quality of the heat sink, cooling source and the heating source. All these factors can affect the system in ways that can change the output.

This study is applied on a system with very less waste heat. In industries, where waste heat footprints are huge, a similar system can be designed that can generate electricity to power up different systems in the industrial or commercial areas.

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