جامعة الأمير محمد بن فهد
PRINCE MOHAMMAD BIN FAHD UNIVERSITY

College of Engineering

Department of Mechanical Engineering

Spring 2019

Senior Design Project Report

Waste Heat Recovery System

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in Mechanical Engineering

Team Members

	Student Name	Student ID
1	Fahad Alghamdi	200700827
2	Mohammed Alshammari	201400482
3	Ahmed Alrushidi	201400346
4	Thamer Alharbi	201500396
5	TurkiAlahmari	201401148

Project Advisor

Dr.Raguraman Kannan

Abstract

Efficiency enhancement is a major concern for every system and various techniques have been used for achieving higher efficiency and less fuel consumption. In internal combustion engine chemical energy is converted in to mechanical energy but less efficiently because most of the energy is dissipated as heat in the exhaust and coolant. Furthermore, the heat losses are 60-70% for internal combustion engine, it is important to recover that waste heat. There are two solutions to the said problem: a) to make the internal combustion engine very efficient so that it does not waste any energy and convert all the energy to useful work. b) To utilize the waste heat energy and convert it to useful work. The first solution has the limitation that not all the energy can be converted from one form to another without losses and the second solution can be achieve by converting heat energy directly in to electrical energy via thermocouples/thermoelectric generators.

In this Project, the aim is to develop a system which can recover the waste heat lost in the engine to improve the efficiency and reduce fuel consumption.

Acknowledgments

First, we would like to express our appreciation to our parents for their support, encouragement and funding, also we appreciate our advisor Dr. Raguraman Kannan for his continued support for our project and his sincere encouragement. Also, we express our sincere thanks to our co-advisor Dr.Panagiotis for sharing his expertise and guidance. We would like to extend our thanks and appreciation to Dr. Faramarz Djavanroodi, chair of the Mechanical Engineering Department at PMU, for his continued encouragement.

List of Acronyms (Symbols) used in the report:

Table 1: List of Acronyms

Symbol	**Definition**
TEG	Thermoelectric Generators
ΔT	Temperature Difference
Th	Higher Temperature
Tc	Lower Temperature
S	Seebeck Coefficient
σ	Electrical Conductivity
ρ	Electrical Resistivity
k	Thermal Conductivity
ZT	Figure of Merit
η	Efficiency
$\dot{Q}$	Heat Transfer Rate
$\dot{m}$	Mass Flow Rate
Cp	Specific Heat Constant of exhaust gases
P	Electrical Power
V	Voltage
I	Current

List of Figures:

Figure 5: Graph Analysis [10] .... **Error! Bookmark not defined.**
Figure 6: Graph Based on Thermocouple Position [14] .... **Error! Bookmark not defined.**
Figure 7: Leg current and x/l graph .... **Error! Bookmark not defined.**
Figure 8: Temperature and x/l graph .... **Error! Bookmark not defined.**
Figure 9: Power and no. of modules graph [15] .... **Error! Bookmark not defined.**
Figure 10: A typical heat recovery system 15
Figure 11: Thermoelectric Generator (TEG) internal architecture 25
Figure 12: Block diagram of waste heat recovery system using thermoelectric module 25
Figure 13: Figure of merit VS temperature for various TEGs 32
Figure 14: Schematic diagram of basic components of waste heat recovery system 33
Figure 15: Solidworks model 34
Figure 16: Waste Heat Recovery Prototype. a) Insulation for heat recovery to minimize heat loss from the exhaust system. b) Insulation with heat sink on top exhaust system for maintaining temperature difference. 34
Figure 17: Bread board 36
Figure 18: Water Pump 36
Figure 19: Temperature gun 37
Figure 20: Soldering Iron 38
Figure 21: Soldering Wire 38
Figure 22: Digital Multimeter 39
Figure 23: Measurement Tape 40
Figure 24: Stainless Steel Drive Hose Clamp 40
Figure 25: Thermal grease paste 41
Figure 26: Liquid Heat S 43
Figure 27: Honda WB30X Engine Water Pump Set 44
Figure 28: Exhaust Insulation 45
Figure 29: a) Actual system from which waste heat to be recovered. b) Installation of thermoelectric generators on top and bottom surfaces of heat exchanger. c) Heat sink installation on top and bottom surfaces. 45
Figure 30: Top surface arrangement. Thermoelectric generators sandwiched between heat exchanger (hot side) and heat sink (cold side). a) Side view. b) Top view 46
Figure 31: Seebeck coefficient for different cold end temperature 48
Figure 32: Seebeck coefficient for different hot end temperature 48
Figure 33: Output voltage for varying temperature at the cold side of a single TEG .... **Error! Bookmark not defined.**
Figure 34: Output voltage for varying temperature at the cold side of 8 TEGs Connected in series .... **Error! Bookmark not defined.**
Figure 35: CAD Design for Heat Sink 717
Figure 36: CAD Design for Heat Exchanger 68
Figure 37: CAD Design for Heat Sink 69
Figure 38: CAD Design for Sink Warshal 70
Figure 39: CAD Design for Heat Sink Inlet/Outlet 751
Figure 40: CAD Design for Heat Sink Surface 761
Figure 41: CAD Design for TEG 772

List of Tables:

Table 1: List of Acronyms 5
Table 2: Payment Bill and Budget 58
Table 3: Bill of Materials 69

***Table of* Contents**

Abstract.....2

Acknowledgments.....3

List of Acronyms (Symbols) used in the report:.....5

List of Figures:.....6

List of Tables:.....**Error! Bookmark not defined.**

Chapter 1: Introduction.....10

1.1 Project Definition.....10

1.2 Project Objectives.....10

1.3 Project Specifications.....11

Water Pump.....**Error! Bookmark not defined.**

1.4 Applications.....11

Chapter 2: Literature Review.....11

2.1 Project background.....11

2.2 Previous Work.....12

2.3 Comparative Study.....12

Chapter 3: System Design.....14

3.1 Design Constraintsand Design Methodology.....15

3.3 Theory and Theoretical Calculations.....15

3.4 Product Subsystems and selection of Components.....32

3.5 Manufacturing and assembly (Implementation).....30

Chapter 4: System Testing and Analysis.....35

4.1 Experimental Setup, Sensors and data acquisition system.....33

4.1.1: Bread Board:.....34

4.1.2: Water Pump:.....365

4.1.3: Temperature Gun:.....375

4.1.4: Soldering Iron:.....376

4.1.5: Soldering wire:.....387

4.1.6: Digital Multimeter:.....388

4.1.7: Measurement Tape:.....399

4.1.8: Stainless Steel Drive Hose Clamp:.....40

4.1.9: Thermal Grease Paste: 42
4.2 Results, Analysis and Discussion 43
Chapter 5: Project Management 47
5.1 Project Plan 47
5.2. Contributions of Each Team Member 50
5.3. Monitoring Project Execution 52
5.4. Challenges 53
5.4.1. Challenges 53
5.4.2. Issues of Testing and Safety 53
5.4.3. Design Problems 54
5.5. Payment Bill and Budget 54
Chapter 6: Project Analysis 55
6.1. Life-long Learning 56
6.1.1. Hardware Skills 56
6.1.2. Software Skills 56
6.1.3. Project Management 56
6.2. Engineering Solution's Impact 56
6.3. Addressing Contemporary Issues 57
Chapter 7: Conclusions and Future Recommendations 57
7.1 Conclusions 58
7.2 Future Recommendations 58
8. References 59
Appendix B: CAD drawings and Bill of Materials 60
Appendix C: Datasheets 72
Appendix D: Operation Manual 74

Chapter 1: Introduction

1.1 Project Definition

The design of waste heat recovery system that aims to generate electric power by using the exhaust heat that I produced from an internal combustion engine. Experimental studies were conducted to achieve electricity generation by the thermos electric generator (TEG). However, by this electrical generated we can utilize many applications such as charging battery or run some electronic components.

1.2 Project Objectives

The thermoelectric generator from waste heat exhaust of engine challenges to overcome the following objectives:

I. To design a system that operates at a high temperature engine exhaust to generate free electricity.

II. To develop a power generation method to fulfill the results that are expected from the system.

III. To apply the thermodynamics concept to design of cooling system.

IV. To apply heat transfer concept to study the amount of heat rate, surface area, and select the proper materials required for conductivity.

V. To fabricate hot exhaust fittings to power thermoelectric materials.

VI. The conversion of waste heat into free electricity by using thermoelectric generators (Thermocouples) and make it usable.

VII. Maintain the heat transfer from hot side to cold side of the system in order to make it more efficient.

1.3 Project Specifications

- Prepare and modify the prototype for study purpose.
- To design and develop a working thermoelectric power generator that utilizes the hot exhaust gas to produce the required power.
- To fabricate waste heat recovery system for thermoelectric system and calculated the power and heat required.
- Minimize the heat exhaust wastage.
- Provide proper cooler to create more temperature difference to get the power requirement.

1.4 Applications

- The heat in the engine coolant can also be utilized to generate power using the TEG, as nearly 30% of the energy from the fuel combustion accounts for this loss
- Energy Recovery
- The heat generated during braking can be utilized using this method
- Green Technology
- More efficient Electric Cars using this system in braking.

Chapter 2: Literature Review

2.1 Project background

Internal combustion engines are approximately 25% efficient and the remaining 75% is wasted as heat, depending on the operation and design of engine. The huge amount of energy wasted as heat in the exhaust gasses and coolant can be recovered with waste heat recovery system. The heat recovery system can potentially convert some of the wasted heat in to electrical energy in result reduce fuel consumption and less load on the engine. This wasted heat could be recovered with the help of thermocouples which directly converts heat energy in to electrical energy. Thermocouple technology has highly valuable attributes such as solid-state, highly scalable, and modular. It has no moving parts, no vibration, silent operation, and can outperform for small scale applications.

The waste heat sources are cement plant, petrochemical plant, coal fired power plant, refinery, and furnace. Moreover, most of the fuel energy is wasted as heat in all the mentioned plants and efficiency has not improved significantly in last 40 years for large scale power plants. Therefore, it is important to recover that waste heat. The effect on which a thermocouple works is known as Seebeck effect in which two dissimilar material junctions produces voltage difference when there is temperature difference across the two materials. The more the temperature difference the more electric power can be harnessed from the thermocouple.

2.2 Previous Work

There is a lot of work done so far for harnessing waste heat into useful work. It was started with heat wasted in steam power stations where 50% or more energy was wasted after fuel combustion process. Because the flue gasses took away the furnace heat into the environment without any vital work done. Therefore, to recover percentage of the wasted heat would increase the plant efficiency and reduce fuel consumption. So, the flue gasses where diverted in such a way to warm up the water beforehand entering the boiler and also after the water is converted into wet steam the flue gasses heat was harnessed in the super heater for converting the wet steam into dry steam. In addition, the remaining heat energy left in the flue gasses were used to warm the cold air entering the furnace for fast combustion process. Similarly, in many industries such as cement, petrochemical, refinery and furnace the waste heat is recovered through the process discussed previously.

2.3 Comparative Study

In a computer-aided experimental study, a new heat recovery system for heat pipes and hybrid vehicles has been tested for producing a thermoelectric module (TEM) and electricity. It proposes a new thermoelectric generation system (TEG) that uses heat channels to generate electricity from a limited hot surface. The current TEG system is directly connected to the exhaust pipe and the amount of energy generated by TEG is directly proportional to the heated surface. Existing exhaust pipes do not provide a sufficiently hot surface to recover the required heat loss with high efficiency. To overcome this, a new TEG system has been developed to increase the hot surface by adding ten heat pipes that serve as high efficiency heat transfer devices and which can transfer heat to many TEG. Recently, the new car modelshave this technology. For example, General Motors one of best car manufacturing has worked in this idea in of them this car which is suburban. This car has higher amount of heat from it exhaust.

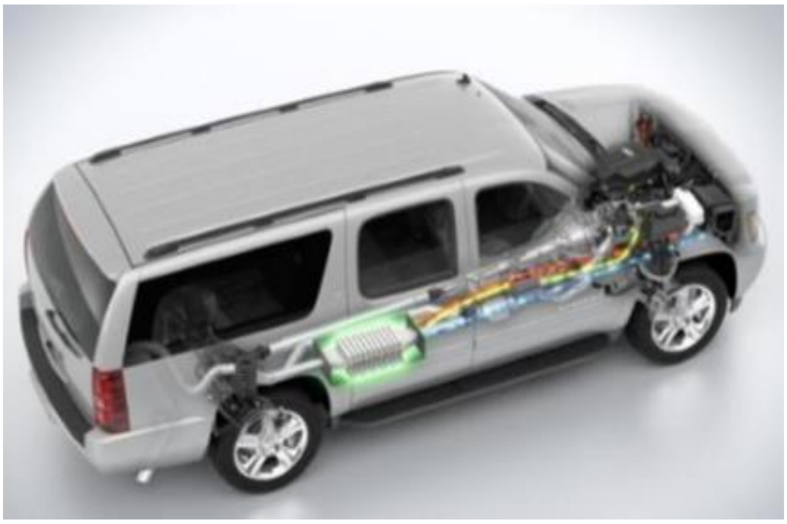


Figure1: GM CAR

In this project of GM car, they aim for developing the fuel economy by using this power for light dusty vehicles by using advanced cost optimization of TEG technology. Therefore, the efficiency of that project in GM shows a good result.

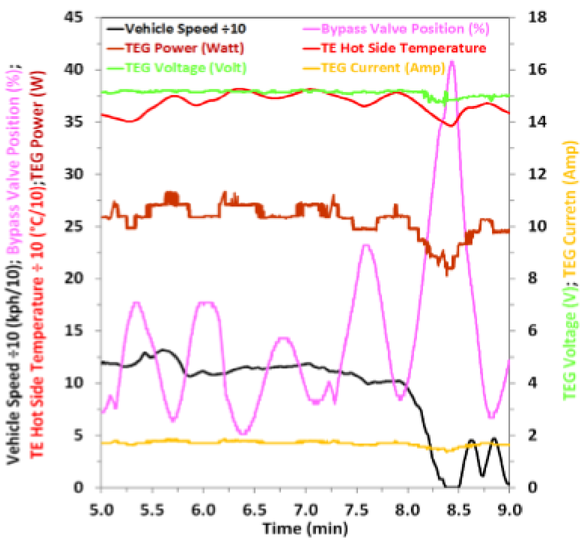


Figure2

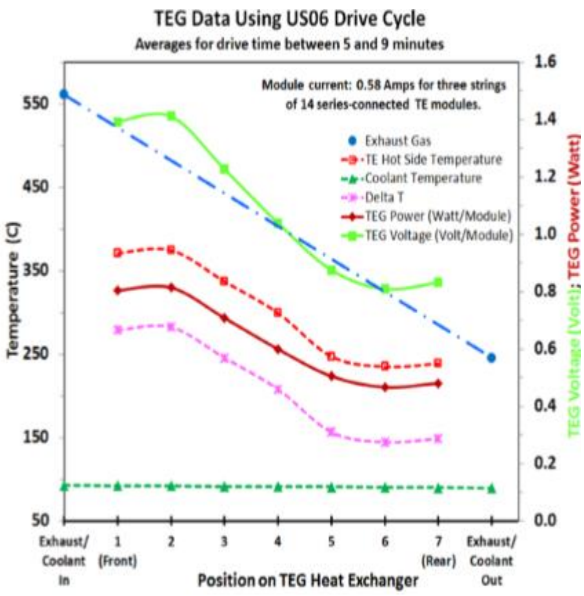


Figure3

Chapter 3: System Design

3.1 Design Constraints and Design Methodology

Geometrical constraints:

The geometrical constraint with our design is that the room surface connected to our engine has the thermoelectric generators area that in such a way there are s a lot of surface area that we cannot cover it with hear insulation and that will cause heat loss. In addition, beside the uncovered area on room surface the pipes carrying the hot exhaust gases has an open that we cannot make it smaller in order to maximize the heat temperature.

Sustainability:

Waste heat recovery makes the system sustainable in a way that, such as in our work, the system can generate its own electric power for future use. Furthermore, the energy obtained is totally free.

Environmental:

In our project we are generating renewable electrical power which is does not cause any pollution and noise.

Social and economic:

the project is going to help the society with harnessing green and fee energy. Clearly that the system will generate electrical energy and this I will help with reducing the cost of cost of one the most important energy source that used world-wide.

Ethical:

Similar projects have been done on small scale and large scale. The idea of generating power from waste heat is very old. Our idea to generate power from engine's heat locally and with easiness will help people to design their own system for waste heat recovery.

In figure 10 a typical waste heat recovery system is shown. Energy from fuel combustion does not convert fully into useful work. Portion of the energy is converted into useful work while the rest is wasted if not recovered. By incorporating the waste heat recovery system to the existing system reduces the waste heat but still some heat is lost as a friction and in coolant.

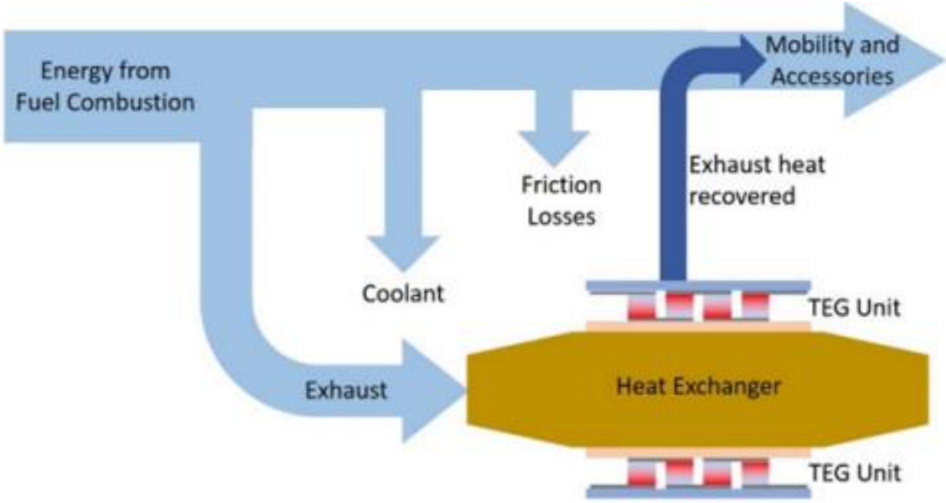


Figure 1: A typical heat recovery system

3.3 Theory and Theoretical Calculation

The direct conversion of thermal energy into electrical energy is called thermo electric power generation. A typical diagram for thermal heat recovery system is shown in figure 10 and also a waste heat recovery system block diagram is shown in figure 12. The device which is used for this conversion is called thermoelectric generator which works on the principle of Seebeck effect (Peltier effect). The thermoelectric/Seebeck effect is a phenomenon which converts temperature difference between two dissimilar materials into voltage difference between these two materials, this process is reversible.

The thermoelectric effect or the conversion of heat into electricity was first discovered in 1821 by a physicist Thomas Seebeck and was further investigated by a physicist Jean Peltier. Therefore, it is sometimes referred to as Peltier-Seebeck effect.

These devices are widely acceptable because it involves no moving parts and are maintenance free. In addition, it produces no noise and produces green energy unlike traditional heat engines. Furthermore, TEGs has no operation cost and are cheaper than the conventional heat-based power plants such as thermal power station, diesel power station, and gas thermal power plants. Energy extraction using thermoelectric generators offers some challenges and opportunities because of its low efficiencies, used in limited applications, and the most important that it requires relatively constant heat source.

Mostly thermoelectric generators are highly preferred in low power applications where conventional systems are highly expensive to be used. There is a lot of research and development going on to increase efficiency, decrease cost and convert body heat into electrical pulses.

As discussed previously that the waste heat can be recovered with the help of thermocouples also known as thermoelectric generators TEGs. The design of TEG is depicted in figure 10 in which there are junctions of p-type and n-type semiconductor. Both the materials are encapsulated with copper and again further encapsulated with electrical insolated ceramic. When there is a temperature difference across p-type and n-type material a potential difference appears across the copper conductor. For potential difference to be appear one material should have higher temperature Th and the other lower temperature Tc.

For theoretical calculation four different temperatures were considered as it shown below:

TEG calculations (Theoretical):

$$V = S\Delta T$$

Where:

V is the output voltage from the couple (generator) in volts

S is the average See beck coefficient in volts/°K

ΔT Is the temperature difference across the couple in °K where ΔT = Th-Tc at Junctions

When a load is connected to the thermoelectric couple the output voltage (V) drops as a result of internal generator resistance.

The current through the load is:

$$I = \frac{S\Delta T}{RC + RL}$$

Where:

I is the generator output current in amperes

R_c is the average internal resistance of the thermoelectric couple in ohms

R_L is the load resistance in ohm

$$Qh = (S \text{ x } Th \text{ x } I) - (0.5 \text{ x } I^2 \text{ x } Rc) + (Kc \text{ x } DT)$$

Where:

Qh is the heat input in watts

Kc is the thermal conductance of the couple in watts/°K

Th is the side of the couple in °K

The efficiency of the generator (η_g) is:

$$\eta g = \frac{VI}{Qh}$$

At $\Delta \boldsymbol{T} = \boldsymbol{270K}$

Temperatures (K)	Current(A)	voltage	K(w/m/k)	Rc(Ω)	Rl(Ω)	Seebeck coefficient in volts/°K
T_h=573 K	**4 A**	**10.6 V**	**1.8 w/m/k**	**5.4 Ω**	**2.7 Ω**	**0.12 Volts/°K**
T_c=303K						
T_{ave}=438						
$\Delta T = 270\ K$						

$$Qh = (S \text{ x } Th \text{ x } I) - (0.5 \text{ x } I^2 \text{ x } Rc) + (Kc \text{ x } DT)$$

$$\text{Qh} = (0.12 \times 573 * 4) - (0.5 \times 4^2 \times 5.4) + (1.8 \times 270)$$
$$= 717.84\text{W}$$

$$\eta g = \frac{\text{VI}}{Qh}$$

$$\eta g = \frac{4 \times 10.6}{717.84} = 0.0641 \times 100 = 6.41\%$$

At $\Delta \boldsymbol{T} = \mathbf{245}\boldsymbol{K}$

Temperatures (K)	Current(A)	voltage	K(w/m/k)	Rc(Ω)	Rl(Ω)	Seebeck coefficient in volts/°K
T_h=548K	3.6A	10 V	1.6 w/m/k	5.2 Ω	2.7 Ω	0.116 volts/°K
T_c=303 K						
T_{ave}=425.5 K						
$\Delta T = 245K$						

$$\text{Qh} = (S \text{ x Th x I}) - (0.5 \text{ x I^2 x Rc}) + (\text{Kc x DT})$$

$$\text{Qh} = (0.116 \times 548 \times 3.6) - (0.5 \times 3.6^2 \times 5.2) + (1.6 \times 245)$$
$$= 562.62\text{W}$$

$$\eta g = \frac{\text{VI}}{Qh}$$

$$\eta g = \frac{3.6 \times 10}{562.62} = 0.063 \times 100 = 6.3\%$$

@ $\Delta T = 220K$

Temperatures (K)	Current(A)	voltage	K(w/m/k)	Rc(Ω)	Rl(Ω)	Seebeck coefficient in volts/°K
T_h=523 k	3.2A	8.4 V	1.5 w/m/k	5 Ω	2.7 Ω	0.112 volts/°K
T_c=303 K						
T_{ave}=413 K						
$\Delta T = 220K$						

$$\text{Qh} = (S \text{ x Th x I}) - (0.5 \text{ x I^2 x Rc}) + (\text{Kc x DT})$$

$$Qh = (0.112 \times 523 \times 3.2) - (0.5 \times 3.2^2 \times 5) + (1.5 \times 220)$$
$$= 491.84W$$

$$\eta g = \frac{VI}{Qh}$$

$$\eta g = \frac{3.2 \times 8.4}{491.84} = 0.05465 \times 100 = 5.46\%$$

At $\Delta \boldsymbol{T} = \mathbf{195}\boldsymbol{K}$

Temperatures (K)	Current(A)	voltage	K(w/m/k)	Rc(Ω)	Rl(Ω)	Seebeck coefficient in volts/°K
T_h=498 K	2.8A	7.8 V	1.4 w/m/k	4.8Ω	2.7 Ω	0.1076 volts/°K
T_c=303K						
T_{ave}=400.5						
$\Delta T = 195K$						

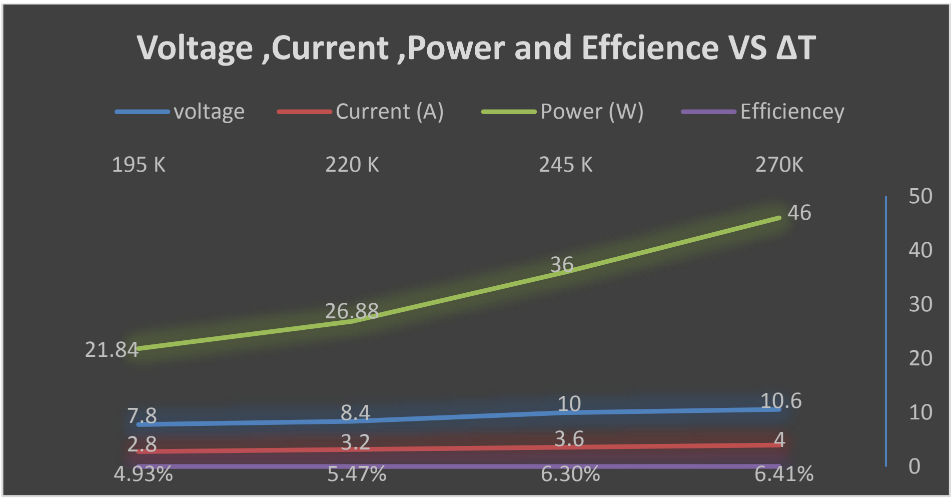
Qh = (S x Th x I) − (0.5 x I^2 x Rc) + (Kc x DT)

$$Qh = (0.1076 \times 498 \times 2.8) - (0.5 \times 2.8^2 \times 4.8) + (1.5 \times 195)$$
$$= 443.22W$$

$$\eta g = \frac{VI}{Qh}$$

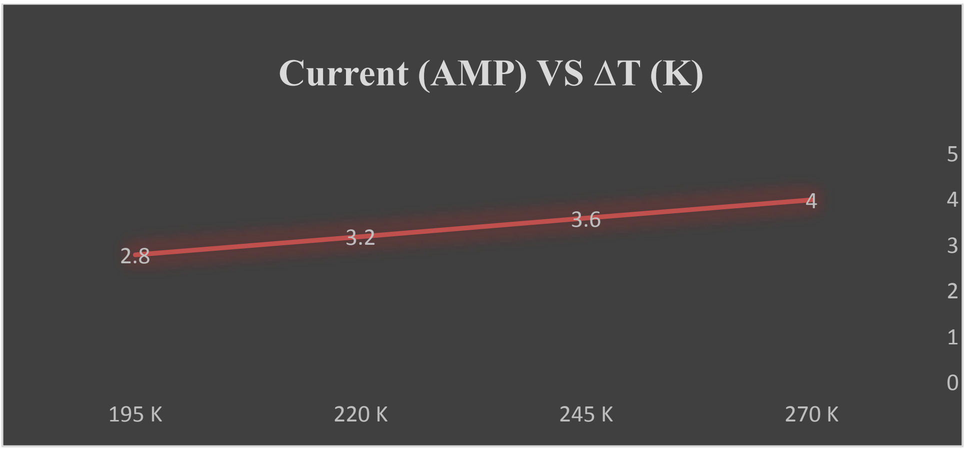
$$\eta g = \frac{2.8 \times 7.8}{443.22} = 0.0423 \times 100 = 4.42\%$$

ΔT= Temperature difference	voltage	Current (A)	Power (W)	Efficiencey
270K	10.6	4	46	6.41%
245 K	10	3.6	36	6.30%
220 K	8.4	3.2	26.88	5.47%
195 K	7.8	2.8	21.84	4.93%



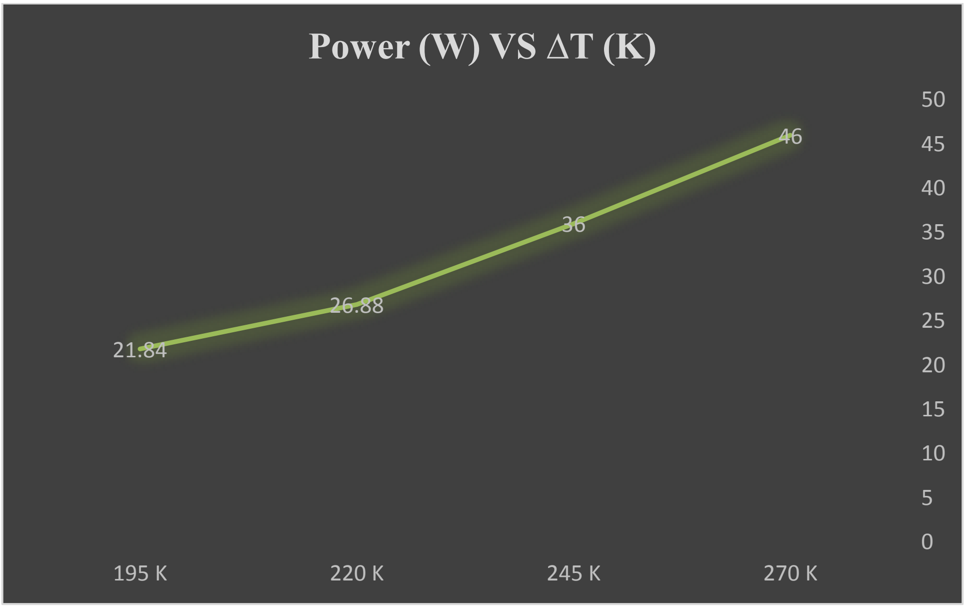
Power, current, voltage, and efficiency graph

ΔT= Temperature difference	Current
270 K	4
245 K	3.6
220 K	3.2
195 K	2.8



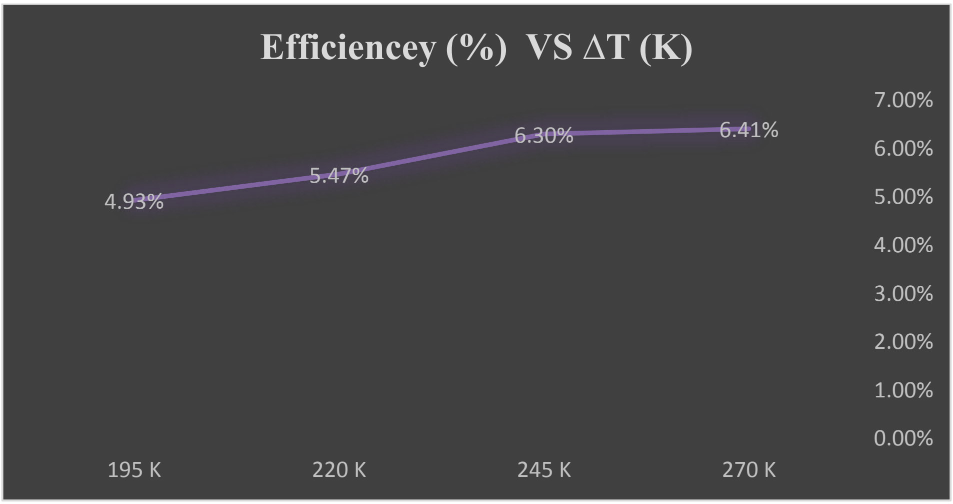
Current

ΔT= Temperature difference (K)	Power (W)
270 K	46
245 K	36
220 K	26.88
195 K	21.84



Power

ΔT= Temperature difference (K)	Efficiency
270 K	6.41%
245 K	6.30%
220 K	5.47%
195 K	4.93%



Efficiency

System calculations:

The below equations where used to theoretically calculate the system efficiency at different temperatures:

Heat Transfer Rate

$$\dot{Q} = \dot{m}\, Cp(\Delta T)$$

Where:

$\dot{Q}$ Heat Transfer Rate

$\dot{m}$ Mass Flow Rate

Cp Specific Heat Constant

ΔT Different between the inlet and outlet exhaust temperatures

Mass Flow Rate

$$\dot{m} = \rho v$$

Where:

$\dot{m}$ Mass Flow Rate

ρ Density of the material

v Velocity of the exhaust

Efficiency of the system:

$$\eta = \frac{\mathrm{VI}}{\dot{Q}}$$

Where:

V Voltage output

I Current output

$\dot{Q}$ Heat Transfer Rate

At $\Delta \boldsymbol{T} = \mathbf{200}\boldsymbol{K}$

Temperatures (K)	ρ	v	Cp	I	V
T_{inlet}=573 k	1.562g/m^3	25 m/s	0.0819(kJ/gK)	9A	3.8
T_{out}=373 K					
$\Delta T = 200K$					

$\dot{m} = \rho v$

$\dot{m} = 1.562 * 25$ =39.05g/sec

$\dot{Q} = \dot{m}\, Cp(\Delta T)$

$\dot{Q} = 39.05 * 0.0819(200) = 639.63W$

$\eta = \frac{\text{VI}}{\dot{Q}}$

$\eta = \frac{34.2}{639.63} = 0.0534 * 100 = 5.35\%$

At $\boldsymbol{\Delta T = 170K}$

Temperatures (K)	ρ	v	Cp	I	V
T_{inlet}=523 k	1.562g/m^3	25 m/s	0.0819(kJ/gK)	8A	2.5
T_{out}=353 K					
$\Delta T = 170K$					

$\dot{m} = \rho v$

$\dot{m} = 1.562 * 25$ =39.05g/sec

$\dot{Q} = \dot{m}\, Cp(\Delta T)$

$\dot{Q} = 39.05 * 0.0819(170) = 543.6W$

$\eta = \frac{\text{VI}}{\dot{Q}}$

$\eta = \frac{20}{543.6} = 0.0368 * 100 = 3.68\%$

$@\ \Delta \boldsymbol{T} = \mathbf{140}\boldsymbol{K}$

Temperatures (K)	ρ	v	Cp	I	V
T_{inlet}=473k	1.562g/m^3	25m/s	0.0819(kJ/gK)	6.5A	2.2V
T_{out}=333 K					
$\Delta T = 170K$					

$\dot{m} = \rho v$

$\dot{m} = 1.562 * 25 =$39.05g/sec

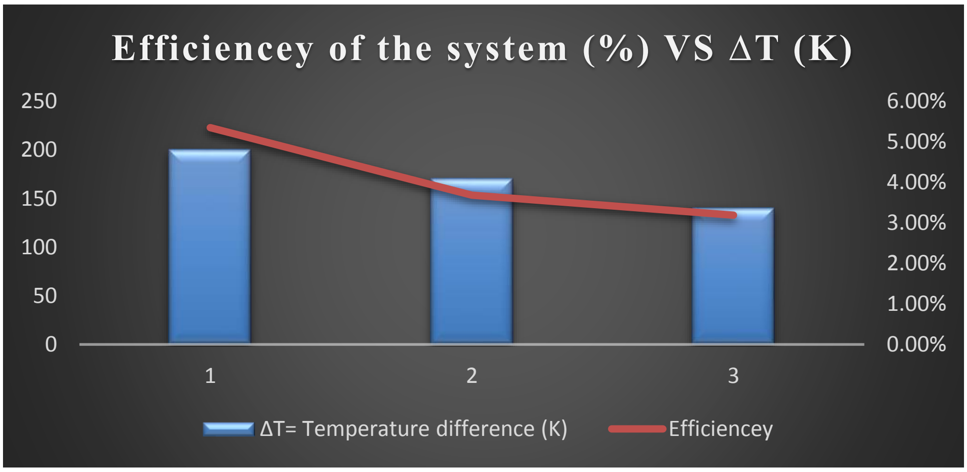
$\dot{Q} = \dot{m}\ Cp(\Delta T)$

$\dot{Q} = 39.05 * 0.0819(140) = 447.74W$

$$\eta = \frac{\text{VI}}{\dot{Q}}$$

$$\eta = \frac{14.3}{447.74} = 0.0319 * 100 = 3.19\%$$

ΔT= Temperature difference (K)	Efficiencey
200	5.35%
170	3.68%
140	3.19%



Efficiency of the system

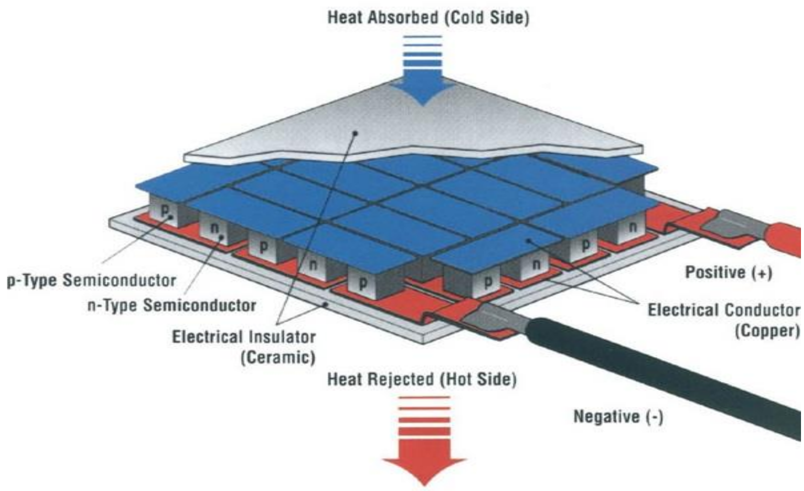


Figure 2: Thermoelectric Generator (TEG) internal architecture

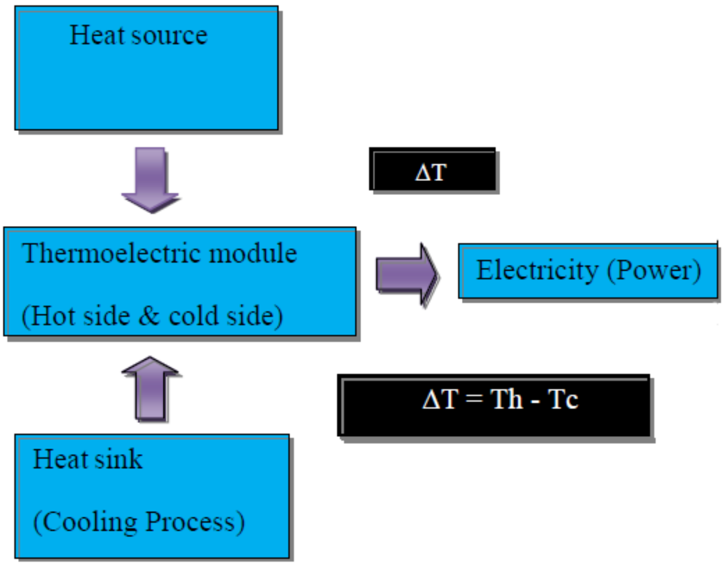


Figure 3: Block diagram of waste heat recovery system using thermoelectric module

As we know that heat transfer from one point to another until equilibrium is achieved. In our project heat is transferred from the heat exchanger towards heat sink where cold water extracts that heat. In the heat sink the water should carry away that heat so that there exists temperature difference across the thermocouple for electric power generation. For maintaining that temperature difference the water should circulate at a specific flow rate for maintaining a specific heat transfer per second known as rate of heat transfer. Rate of heat transfer is defined as:

$$\frac{Q}{t} = \dot{m}.Cp.\Delta T$$

Where:

Q/t = Heat transfer rate

ṁ= Mass flow rate of the object

Cp= Specific heat of the object material

ΔT= Temperature difference

Seebeck Coefficient Calculation:

$$S = \sqrt{\frac{ZT\rho K}{T}}$$

Where:

S= Seebeck coefficient

ρ= Electrical resistivity

T= Temperature

K= Thermal conductivity

ZT= Figure of merit

For Bismuth Telluride as a thermoelectric generator:

ZT= 1.1 @ 70°C from figure 13 given below

ρ= $0.6\times10^{-5}\Omega$m

T=343.15 K

K=1.20 W/ (m. K)

So,

$$S = \sqrt{\frac{1.1\times0.6\exp(-5)\Omega\text{m} \times 1.20\ \text{W/(m.K)}}{343.15\ \text{K}}} = 150\mu\text{V/K}$$

TEG calculations (Experimental):

For voltage calculation:

$$V = S\Delta T$$

Where:

V is the output voltage from the couple (generator) in volts
S is the average Seebeck coefficient in volts/°K
ΔT Is the temperature difference across the couple in °K where ΔT = Th-Tc at junctions
When a load is connected to the thermoelectric couple the output voltage (V) drops as a result of internal generator resistance. The current through the load is:

$$\mathrm{I} = \frac{S\Delta T}{\mathrm{RC} + \mathrm{RL}}$$

Where:

I is the generator output current in amperes
Rc is the average internal resistance of the thermoelectric couple in
RL is the load resistance in ohm

For thermocouples Heat Rate calculation:

$$\mathrm{Qh} = (\mathrm{S\ x\ Th\ x\ I}) - (0.5\ \mathrm{x\ I\hat{}2\ x\ Rc}) + (\mathrm{Kc\ x\ DT})$$

Where:

Qh is the heat input in watts
Kc is the thermal conductance of the couple in watts/°K
Th is the hot side of the couple in °K

The efficiency of the generator (Eg) is:

$$Efficiency\ (g) = \frac{\mathrm{VI}}{Qh}$$

At $\Delta \boldsymbol{T} = \mathbf{261}\boldsymbol{K}$

Temperatures (K)	Current(A)	voltage	K(w/m/k)	Rc(Ω)	Rl(Ω)	Seebeck coefficient in volts/°K
T_h=547 K	**3.68 A**	**10.1 V**	**1.7w/m/k**	**5.3 Ω**	**2.7 Ω**	**0.12 volts/°K**
T_c=286K						
T_{ave}=416.5						
$\Delta T = 261\ K$						

$$Qh = (S \times Th \times I) - (0.5 \times I^2 \times Rc) + (Kc \times DT)$$

$$Qh = (0.12 * 547 * 3.68) - (0.5 \times 3.68^2 \times 5.3) + (1.7 \times 261)$$
$$= 649.37W$$

Power from thermocouples calculation:

$$P = IV$$
$$P = 3.68 * 10.1 = 37.168W$$

Thermocouples Efficiency:

$$Efficiency\ g = \frac{VI}{Qh}$$

$$Eg = \frac{3.68 * 10.1}{649.37} = 0.0573 * 100 = 5.73\%$$

Heat Transfer Rate of the exhaust:

$$\dot{Q} = \dot{m}\ Cp(\Delta T)$$

Where:
$\dot{Q}$ Heat Transfer Rate
$\dot{m}$ Mass Flow Rate
Cp Specific Heat Constant
ΔT Different between the inlet and outlet exhaust temperatures

Mass Flow Rate

$$\dot{m} = \rho v$$

Where:
$\dot{m}$ Mass Flow Rate
ρ Density of the material
v Velocity of the exhaust

Efficiency of the system:

$$\eta = \frac{VI}{\dot{Q} + Pwater\ pmp}$$

Where:
V Voltage output
I Current output
$\dot{Q}$ Heat Transfer Rate
Pwater pump is the power of the water pump

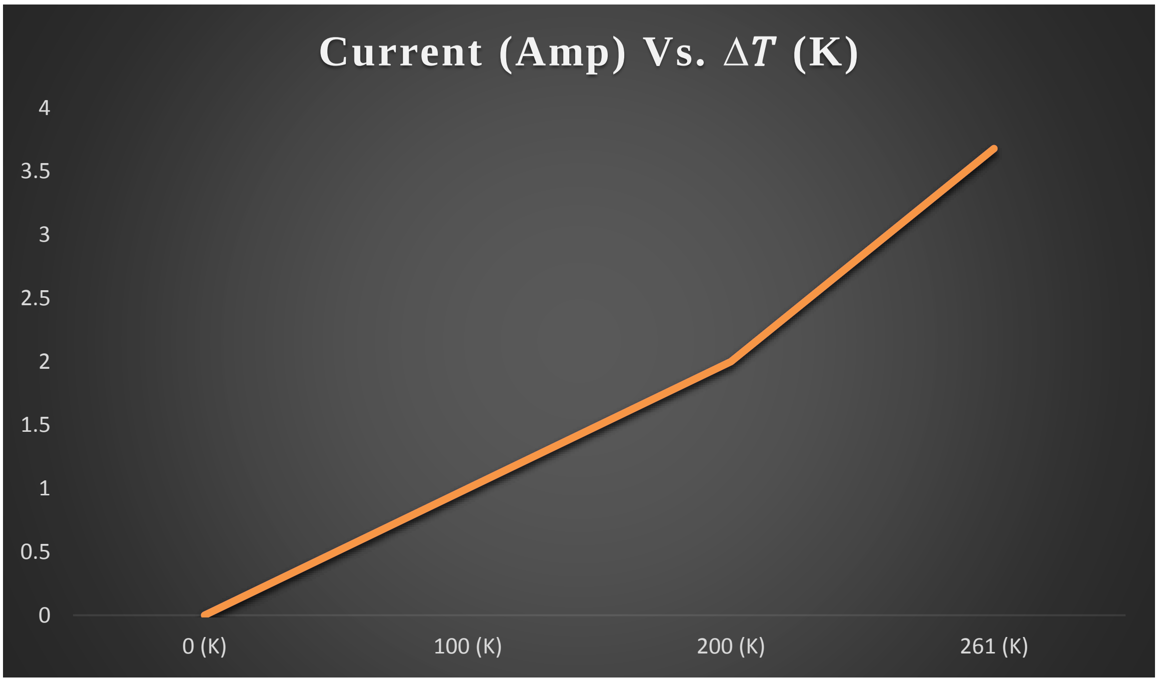
At $\Delta T = 261K$

Temperatures (K)	ρ	v	Cp	I	V
T_{inlet}=573 k	1.562g/m^3	24 m/s	0.0819(kJ/gK)	3.68	10.1
T_{out}=373 K					
$\Delta T = 200K$					

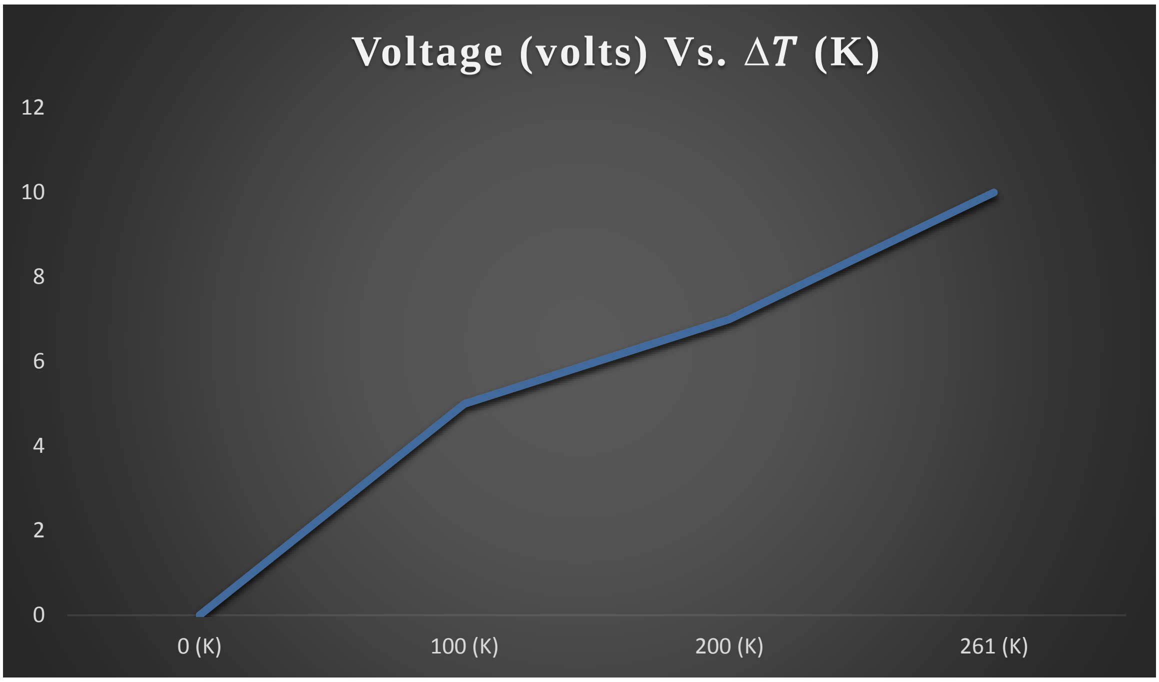
$\dot{m} = \rho v$
$\dot{m} = 1.562 * 24$ =37.49g/sec

$\dot{Q} = \dot{m}\, Cp(\Delta T)$
$\dot{Q} = 37.49 * 0.0819(261) = 801.34W$

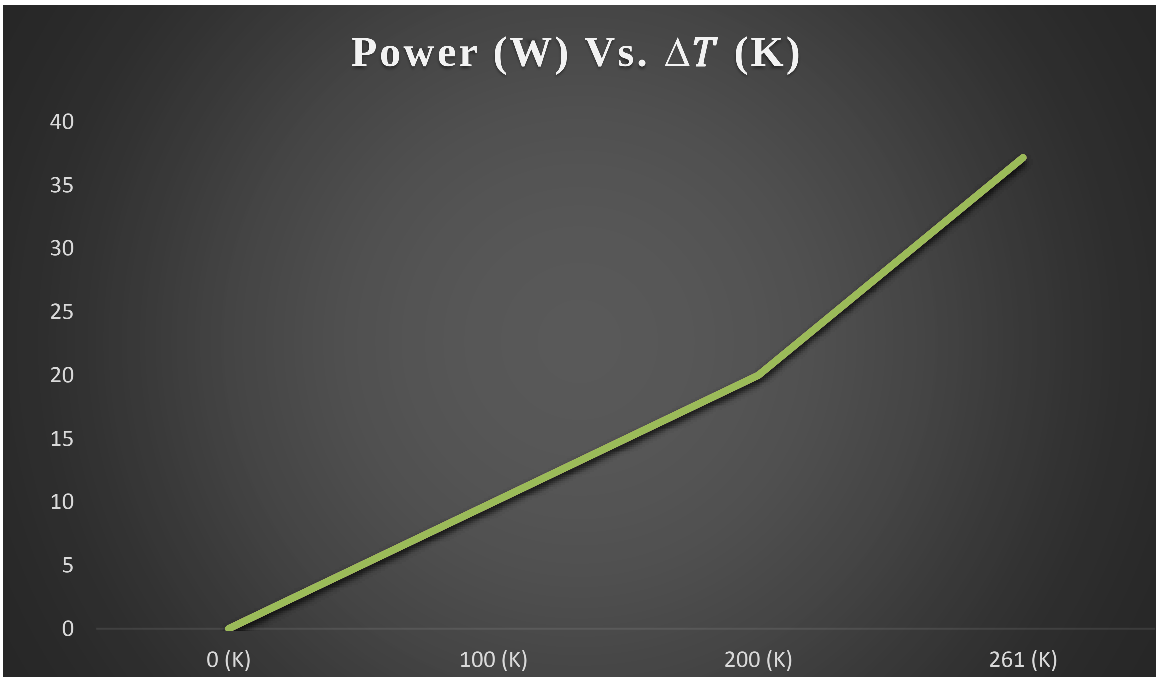
$$\eta = \frac{\text{VI}}{\dot{Q} + Pwater\ pump}$$
$$\eta = \frac{37.168}{801.34 + 19} = 0.04530 * 100 = 4.530\%$$



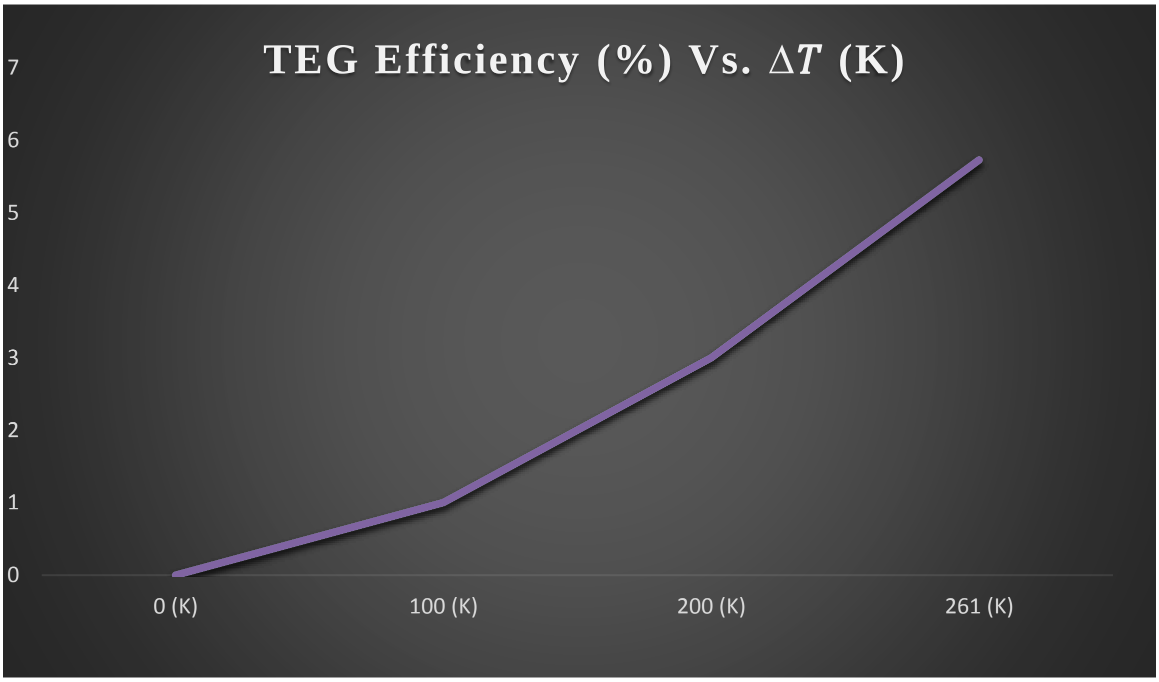
Current Vs. (ΔT) Graph



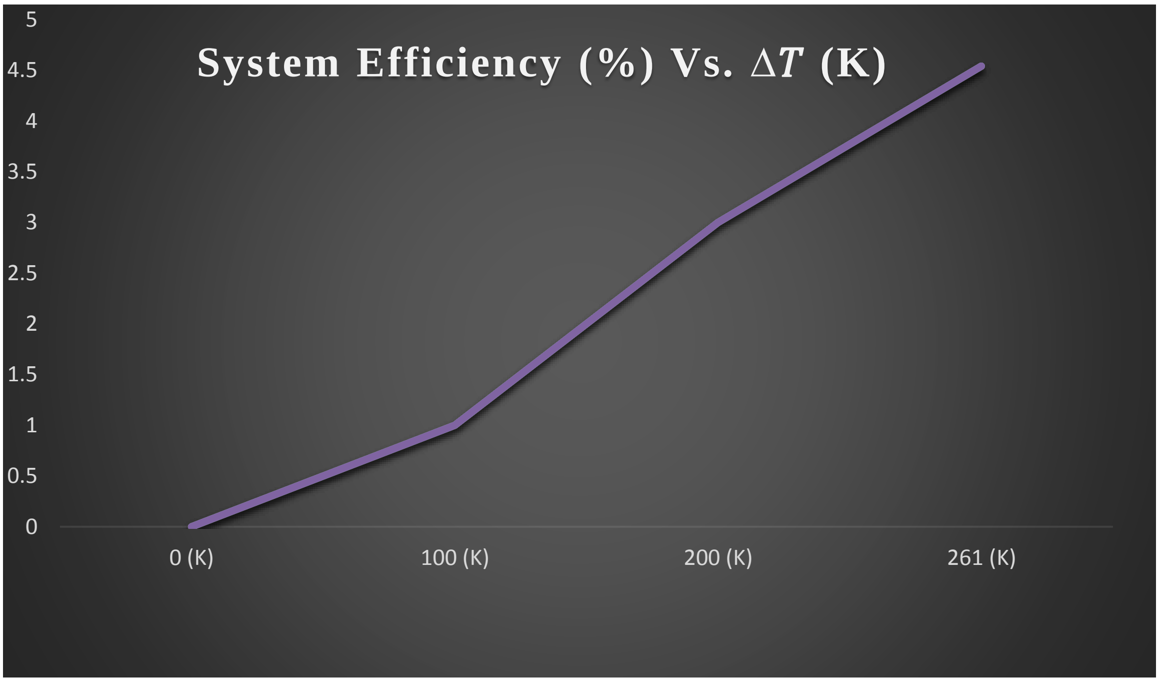
Voltage Vs. (ΔT) Graph



Power Vs. (ΔT) Graph



TEG Efficiency Vs. (ΔT) Graph



System Efficiency Vs. (ΔT) Graph

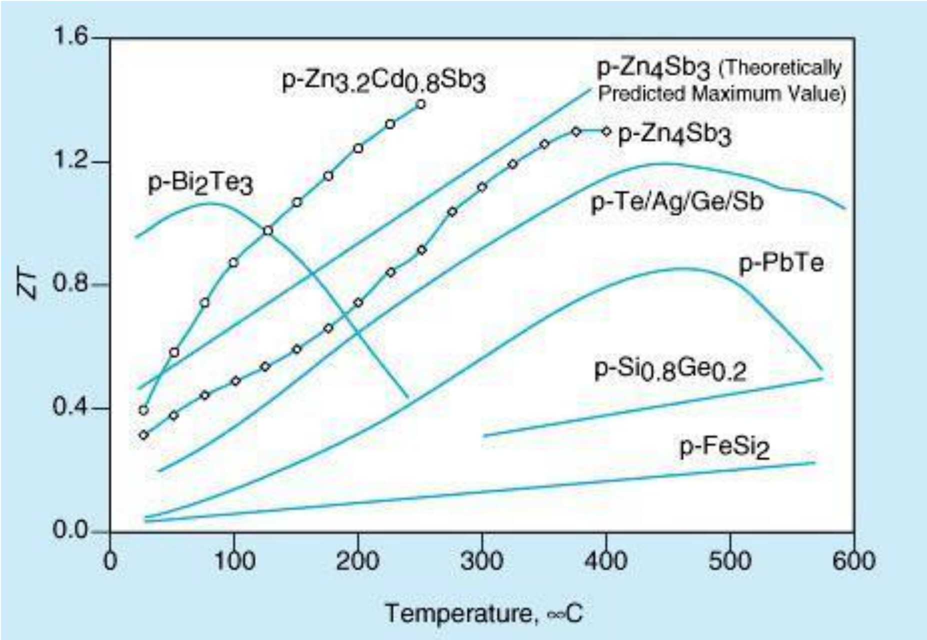


Figure 4: Figure of merit VS temperature for various TEGs

3.4 Product Subsystems and selection of Components

The main components of waste heat recovery system are:

1) **Motor (engine):** used to build up the desired heat in the exhaust.
2) **Room surface:** attached directly to engine exhaust designed with citrine areas for placing the thermocouples in top and bottom of it in order to gain the desired heat.
3) **Thermoelectric modules:** Thermoelectric modules convert heat energy directly into electrical energy. It is the most important component of the system which can withstand high temperature.
4) Exhaust heat insulation: the main purpose of it is to reduce the heat loss.
5) **Heat sink:** It is used to maintain the temperature at the cold side of the module. It needs to be efficient to provide a good temperature gradient.
6) **Battery:** to generate the required output electrical power to turn the cooler pump on.
7) **Auxiliaries:** Coolant pump, temperature sensors, electronic unit.

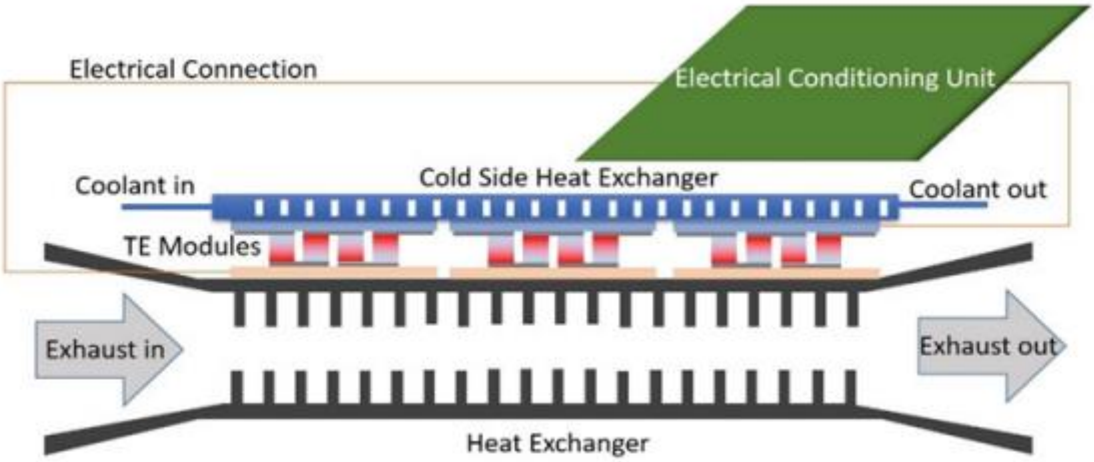


Figure 5: Schematic diagram of basic components of waste heat recovery system

3.5 Manufacturing and assembly (Implementation)

First of all, choosing engine that will produce the required amount of heat was one of the highest priorities of the project. Then deigning the room surface that will help to gain the desired heat temperature that the thermocouples required to produce the power output. After designing the surface room and attached it to the engine exhaust, temperature was checked with the help of laser temperature gun by pointing the gun on the room surface. The value of temperature was note down for calculation purpose which was around150℃. The next stem was to choose best possible design for recovering waste heat. For that a TEG, datasheet given in Appendix D, was selected. There should be temperature difference across TEG so that the hot side was placed on the surface, connected with the help of thermal glue, and the cold side connected to the heat sink. The purpose of the heat sink is to take away the heat received so that the temperature difference is maintained across TEG. The heat sink used in this project is liquid heat sink connected to a water pump for the circulation of water. By this process a waste heat is recovered and converted to electrical energy. The output energy depends directly on temperature difference injecting a cold liquid to the heat sink increases the power output as shown in the TEG datasheet and, also in equations described in previous section.in addition, room surface was covered with exhaust insulation to reduce the loss of heat.

Figure 15 and 16, in chapter 4, represents the actual hardware arrangement of our project. The actual values of temperature and output voltage are measured with laser temperature gun and digital multimeter respectively. In figure 15 a prototype model is presented having thermoelectric modules sandwiched between the room surfce and heat sink.

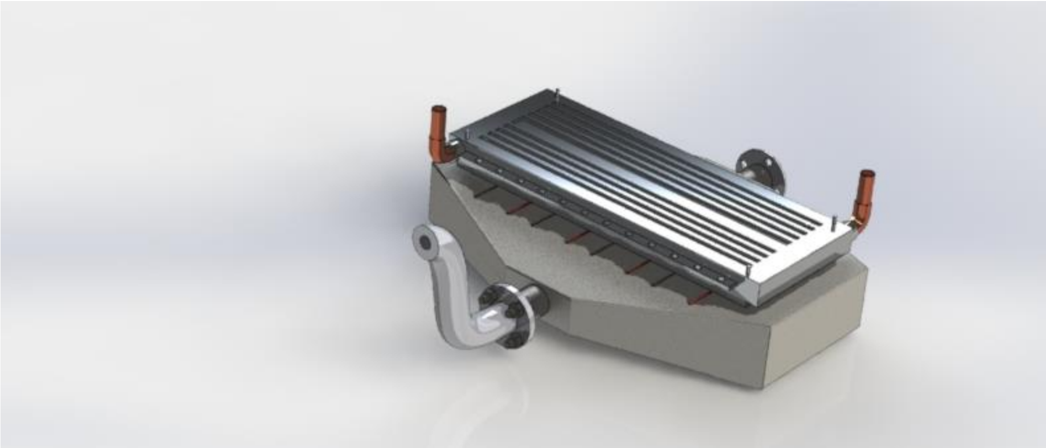
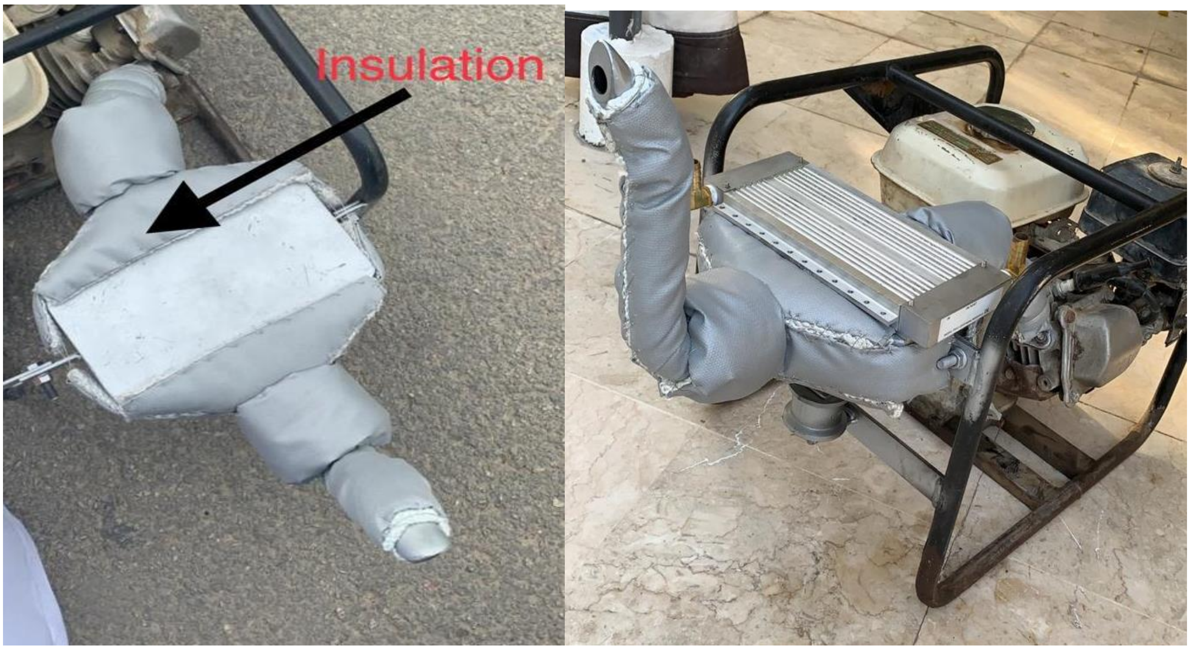


Figure 6: Solidworks model



a) b)

Figure 7: Waste Heat Recovery Prototype. a) Insulation for heat recovery to minimize heat loss from the exhaust system. b) Insulation with heat sink on top exhaust system for maintaining temperature difference.

Chapter 4: System Testing and Analysis

4.1 Experimental Setup, Sensors and data acquisition system

4.1.1: Bread Board:

Bread board is used for implementing the hardware design. It is easy to use board and does not require any soldering or de-soldering. The circuit built on bread board can easily be modified once the circuit is confirmed then similar circuit is fabricated on PCB.

Specification:

- Accepts most electronic components, including integrated circuits and transistors for digital and/or analog circuitry
- 0.1" hole spacing
- Pins are identified by numbered rows and columns
- Ideal for high frequency and low noise circuits
- Use to breadboard and debug circuit designs
- Low static, plastic body - CMOS safe
- Components are easily interconnected using 20-28 AWG wire such as(**350-pc wire jumper kit** & **350-pc wire jumper refill**)
- Terminal strips: 1
- Bus strips: 2
- Contact points: 400
- Breadboard size: 3.25"L x 2.125"W
- Weight: 1.82 oz. (0.114 lbs.)

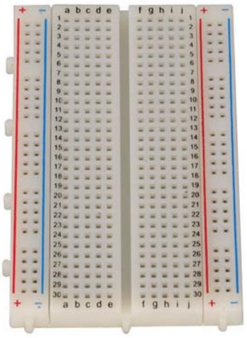


Figure 8: Bread board

4.1.2: Water Pump:

The purpose of the water pump is to circulate the water in the heat sink for cooling purpose.

<u>Specification:</u>

- Inlet/Outlet: 1/2" male thead
- Voltage: 12V -24V DC (if you use 24v power supply pls test it first)
- Maximum Rated Current: 1000MA
- Power: 19W
- Max Flow Rate: 800 L/H
- Max Water Head: 5 meters
- Max circulating water temperature: 100°

Figure 9: Water Pump

4.1.3: Temperature Laser Gun:

Specifications:

- Resolution: 0.1℃/0.1°F
- Distance Spot Ratio: 12:1
- Emissivity: 0.95 (fixed)
- Red Laser Power: less than 0.5 MW
- Product Dimension: 140 x 85 x 35mm(L*W*H)
- Temperature range: -50 ~ 330℃ (-58~626°F)
- Accuracy: ±1.5% or ±1.5℃

Figure 10: Temperature gun

4.1.4: Soldering Iron:

Specifications:

- Soldering Iron Length: 18.5cm
- Cable Length: 145cm
- Working Voltage: 220V
- Power: 60W

Figure 11: Soldering Iron

4.1.5: Soldering wire:

Specifications:

- Material: tin-lead
- Diameter type: 0.8mm
- Melting point:250 ℃
- Weight: 50g

Figure 12: Soldering Wire

4.1.6: Digital Multimeter:

Specifications:

- DCV: 200mV ±0.5%; 2-20-200V ±0.8%; 1000V ±1.0%

- ACV: 200mV ±1.2%; 2-20-200V ±1.0%; 750V ±1.2%
- DCA: 20u-200u-2000u-20mA ±1.8%; 200mA ±2.0%; 2-20A ±2.0%
- ACA: 20uA ±2.0%; 200u-2m-20m-200mA ±2.0% 2-20A ±2.5%
- OHM: 200-2K-20K-200K-2M-20M ±1.0%
- Cap: 2000p-20n-200n-2u-20uF ±4.0%
- Fre.: 2K-20KHZ ±3.0%
- Temperature: -40~1370° ±2.5%
- Transistor hFE Test: PNP & NPN 0-1000
- Resistance: 200Ω ±1.0%; 2K-20K-200K-2M-20MΩ ±1.0%; 200MΩ ±5%
- Power Supply: 1 x 9V battery/6F22 (not included)
- Dimension: 176 x 88 x 38mm

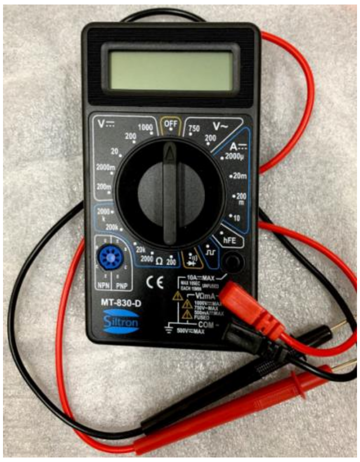


Figure 13: Digital Multimeter

4.1.7: Measurement Tape:

Specifications:

- Material: Stainless Steel
- Measure Range and Dimensions, tape width: app.
- 7.5m: 80mmx95mm/3.15x3.74in, 25mm/ 0.98in
- 5m: 70mmx80mm/ 2.76x 3.15in, 19mm/ 0.75in
- 3m: 60mmx70mm/ 2.36x 2.76in, 16mm/ 0.63in

Figure 14: Measurement Tape

4.1.8: Stainless Steel Drive Hose Clamp:

Specifications:

- Material: Stainless steel
- Color: Silver
- Band Width: 8mm
- Size: Type 1: 8mm-12mm
- Type 2: 10mm-16mm
- Type 3: 13mm-19mm

Figure 15: Stainless Steel Drive Hose Clamp

4.1.9: Thermal Grease Paste:

Specifications:

- Color: Grey
- Paste weight: 30g / 1.1oz
- Thermal conductivity: >1.829W/m-k
- Thermal resistance: <0.123°c-in2>
- Item size: 2 * 7.5cm / 0.8 * 3.0in

Figure 16: Thermal grease paste

4.1.10: Air Velocity Measuring Device:

Specifications:

MODEL: MS6252A

MATERIAL: ABS

PRIMARY FUNCTIONS: WIND SPEED TESTING

SCOPE OF APPLICATION: INDUSTRIAL, AGRICULTURAL

PRODUCT SIZE: 16.50 X 8.50 X 3.80 CM / 6.48 X 3.34 X 1.49 INCHES

Air Velocity Measuring Device

4.1.11: Heat Sink:

The purpose of heat sink is to extract the heat from the system and cool it down. Heat sink is made from a material of high thermal conductivity such as Aluminum. The special type of heat sink used in this project is made from Aluminum material and is designed in such a way that it contains liquid flow arrangement for taking the heat as fast as possible. The design also saves power by creating turbulent flow with low flowing water thereby maximizing mixing of the liquid to pick up maximum heat flux. All of this is done with parallel flow.

Specifications:

- All Aluminum construction for the liquid sink
- ½” ID 5/8” OD barbed fittings for both in port & out port.
- Mate to a ½” ID silicon tube for best results with 3/16” wall thickness.
- Low flow low pressure drop design.
- Flow rates are 1 liter to 3 liters per minute with on slight back pressure
- Optimal flow rate is 1.5 liters per minute.
- All flow is in parallel NO serial flow.
- Up to 12 modules can be placed on a 3-deck design.
- ~8.5” long x ~4.25” wide x ~1” thick

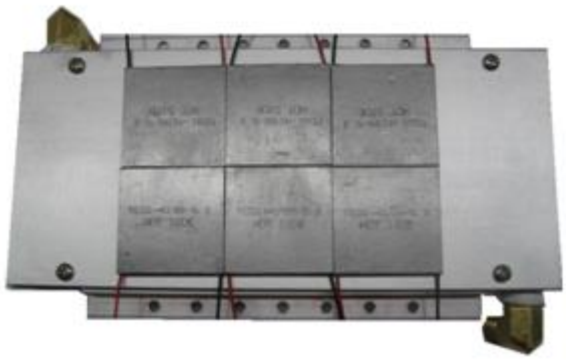


Figure 17: Liquid Heat Sink

4.1.12: Engine Water Pump:

Water pumps are indispensable for farming, construction sites, supplying water during a drought and removing water in the event of a flood caused by a disaster or other emergency. There are a number of types according to the respective application.

General- purpose pumps are used in fields for irrigation and at various construction sites.

High-pressure pumps are used when water needs to be pumped up to high elevations or over long distances, and ultra-lightweight pumps can be easily taken anywhere.

Regardless of the type of pump, engine performance has a large influence on the quality of the pump, since water pumps are generally operated for many hours at a constant speed. Honda water pumps incorporate the GX engine, which is highly renowned throughout the globe as the standard for commercial use power products because of its world-class environmental performance and durability.

Specifications:

Type:	Air cooled 4 strokes
Rated power (kw):	2.9 kw/3600 rpm
Size (mm):	80*80
Max. discharged (ltr/min):	900 lts/min
Weight (kg.):	27k

Figure 18: Honda WB30X Engine

4.1.12: Exhaust Insulation:

It offers high temperature exhaust insulation blankets for any type of exhaust system, including gas, diesel exhaust systems, backup or portable power generation, and even mobile home or bus exhaust systems. The main purpose of the insulation is to keep the heat as long as it can in the system.

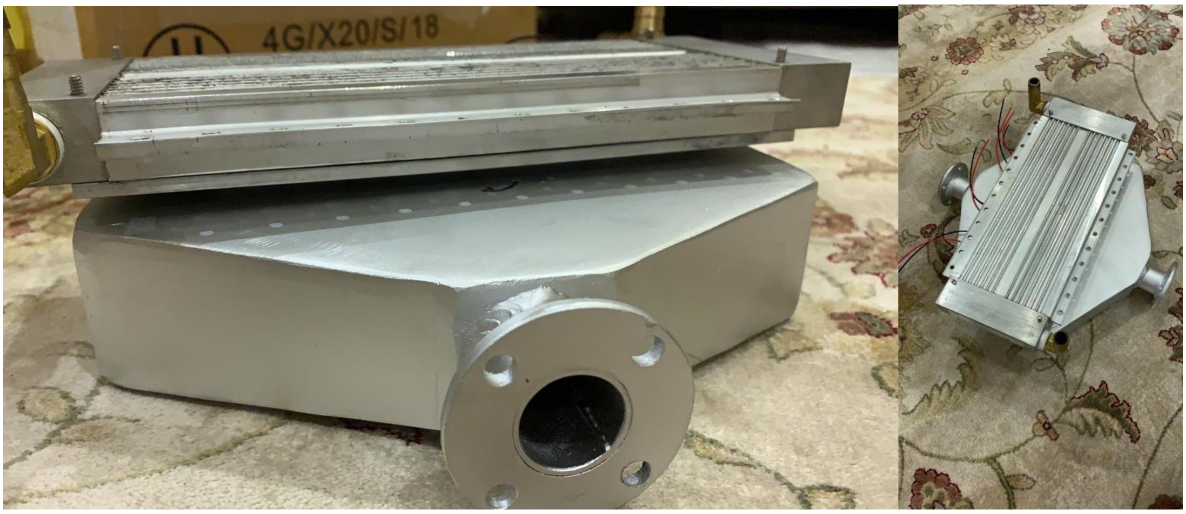
Specifications:

- Stainless Steel Mesh Exterior
- Teflon Coated Exterior
- Complete Enclosure System: Stainless Steel Lacing Anchors & Wires
- Corrosion Resistant
- Available Sound Dampening Features Upon Request
- Meets & Exceeds OSHA “Touch Safe” Rating

Figure 19: Exhaust Insulation

a) b) c)

Figure 20: a) Actual system from which waste heat to be recovered. b) Installation of thermoelectric generators on top and bottom surfaces of heat exchanger. c) Heat sink installation on top and bottom surfaces.

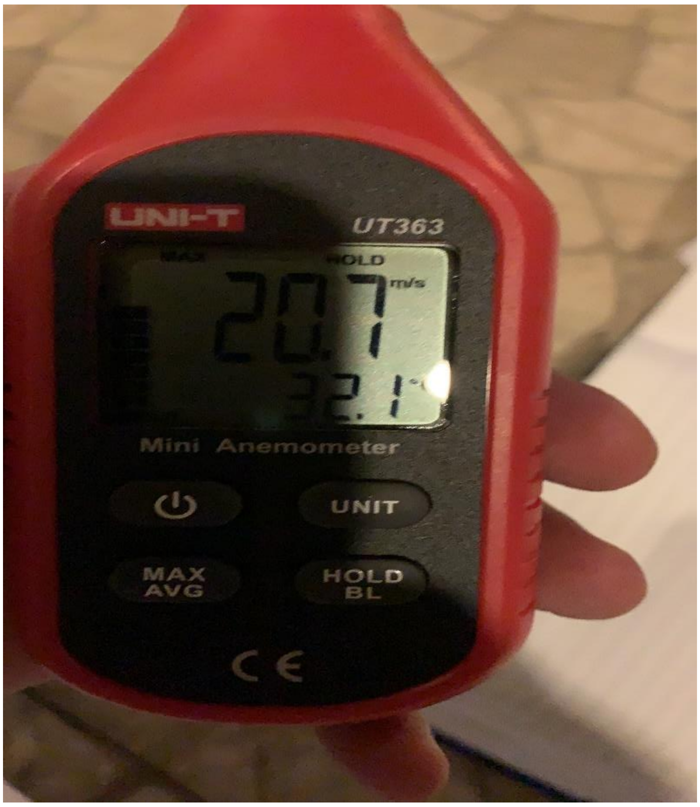


a) b)

Figure 21: Top surface arrangement. Thermoelectric generators sandwiched between heat exchanger (hot side) and heat sink (cold side). a) Side view. b) Top view

4.2 Results, Analysis and Discussion

In this section results are analyzed and discussed. The results are taken by measuring the temperatures at the hot side T_h 274 ℃, cold side Tc 16℃ which is the heat sink coolant. The coolant temperature at the inlet is measured as 16℃ and then measured at the outlet at 32℃. Then temperature difference or the heat absorbed by the coolant is measured with temperature gun and also calculated by taking the difference of outlet and inlet temperature. With measuring the temperatures, in parallel the output voltages for each temperature is also measured and recorded to be 10.1 Volts and 3.68 Ampere. The velocity of the exhaust gas was measured at the output of the system which was 20.7 m/s in order to obtain the flow rate value.



In figure 31 the Seebeck coefficient is calculated my measuring the temperatures and the output voltage correspondingly. In our project we have tested our prototype first without heat exhaust insulation and then with heat exhaust insulation. The temperature of the hot side without insulation was maximum at 70°C and with insulation it went up to 280°C. So, taking the temperature of hot side at 280°C and varying the cold side temperature changes the Seebeck coefficient as shown in the figure 31. The curve clearly indicates that when the temperature difference between hot and cold side reduces the Seebeck coefficient reduces which results in the output voltage.

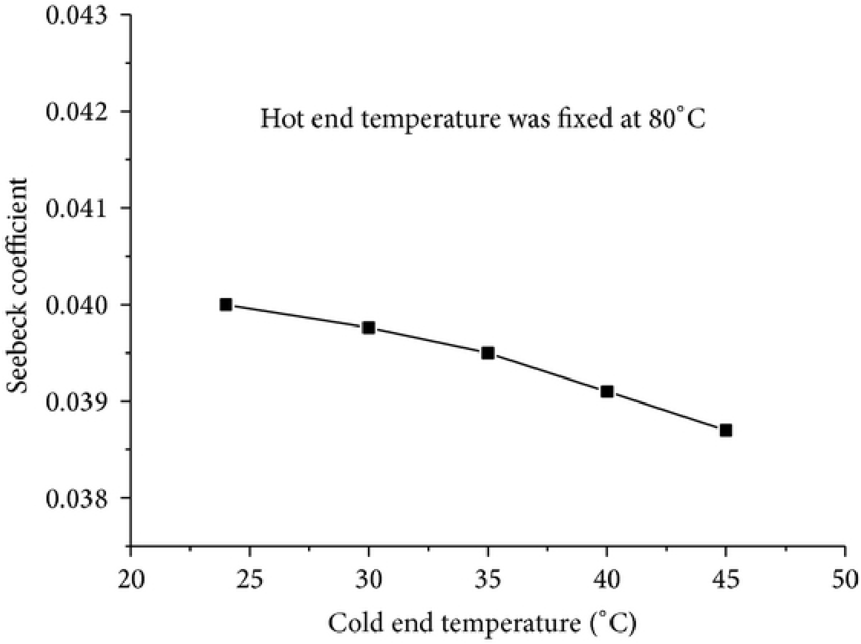


Figure 22: Seebeck coefficient for different cold end temperature

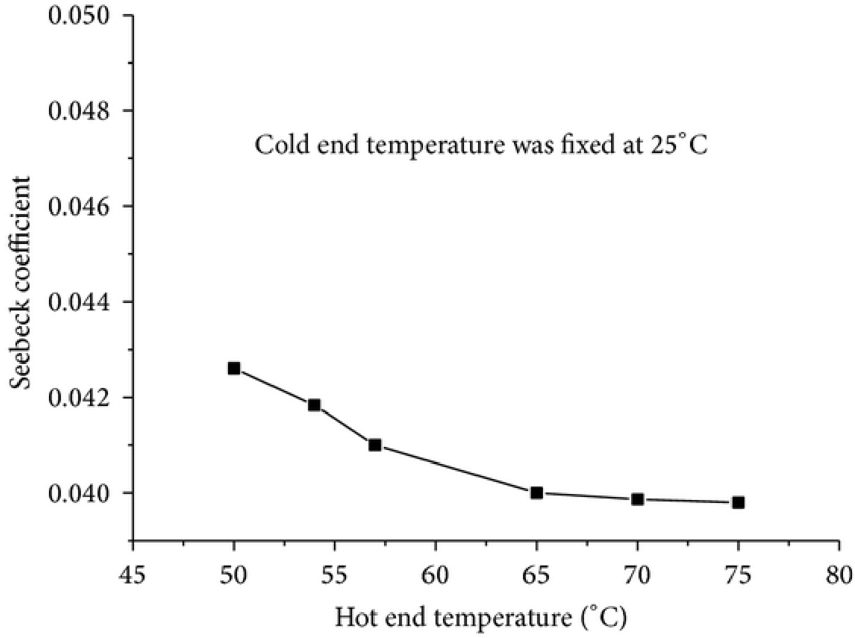


Figure 23: Seebeck coefficient for different hot end temperature

For the power output we got 37 Watts which is not the expected due to the cooling system errors, where the coolant was heating up fast and differing the temperature. The maximum current that was planned to achieve was 4 Amperes, but the maximum that was measured is 3.68 Amp which is close enough to our goal.

TEG connection in parallel

Current Reading

The TEGs were connected in parallel circuit in order to obtain more current, the top and the bottom TEGs were connected in series in order to add up the voltage that will be produced.

Voltage Reading

The voltage was planned to be 10.6 Volts and experimentally it was measured to be 10.1 V which is close enough to the expected value. The efficiency of the TEG was 5.732 % and for the system 4.543%. The system is fully functional and operating as expected, but it is not producing high power because more TEG's need to be added in order to obtain high power and efficiency. Once the combustion engine is turned off, the TEG power start to drop down due to the reduction of the temperature difference.

Chapter 5: Project Management

5.1 Project Plan

Our project can be divided into many tasks. These tasks are assigned either to one or multiple members of the team. The following tables are used to depict all the relevant information regarding each activity, and team members. Moreover, it also presents the duration of every task i.e. its starting and ending time. The following table i.e. table 5.1 has been used to present the details of tasks and their durations, whereas table 5.2 has been used to illustrate the description of tasks and the members to whom the tasks have been assigned.

Table 5.1: Tasks and Their Durations

<table>
<tr><th>No.</th><th colspan="2">Task</th><th>Start</th><th>End</th><th>Duration</th></tr>
<tr><td>01</td><td colspan="2">Chapter 01. Intro</td><td>16-02-2019</td><td>20-02-2019</td><td>04 Days</td></tr>
<tr><td rowspan="3">02</td><td rowspan="3">Chapter 02. Literature</td><td>Background of the Project</td><td rowspan="3">21-02-2019</td><td rowspan="3">27-02-2019</td><td rowspan="3">06 Days</td></tr>
<tr><td>Previous Relevant Work</td></tr>
<tr><td>Comparative Analysis</td></tr>
<tr><td rowspan="4">03</td><td rowspan="4">Chapter 03. Design of the System</td><td>Designing Constraints and Methodology</td><td rowspan="4">27-02-2019</td><td rowspan="4">01-04-2019</td><td rowspan="4">30 Days</td></tr>
<tr><td>Standards of Engineering Design</td></tr>
<tr><td>Theoretical Calculations</td></tr>
<tr><td>Analyzing Product's Subtypes and Choosing Components</td></tr>
</table>

		Manufacturing and Assembling			
04	Chapter 04. Testing and Analysis of the System	Experimental Setup of Sensor and its relevant data Results, Analysis & Discussion	01-04-2019	05-04-2019	04 Days
05	Chapter 05. Project Management	Project Plan Team member's Contribution Project Execution Monitoring Challenges and Decision Making Bill of Materials & Budget Details	05-04-2019	13-04-2019	08 Days
06	Chapter 06. Project Analysis	Life Long Lesson Engineering Solution Impact Addressing Contemporary Issues	13-04-2019	19-04-2019	06 Days
07	Chapter 07. Conclusion and Recommendations	Conclusion Recommendations	19-04-2019	23-04-2019	04 Days
08	Prototype Design	Fan Shape Cavity Location	03-02-2019	09-02-2019	06 Days
09	Purchasing Parts	Car Battery Sensors Light Wire	09-02-2019	14-02-2019	05 Days

		Alternator			
10	Manufacturing	Welding the Structure	14-02-2019	17-02-2019	03 Days
		Grinding			
		Blades Bending			
11	Testing	Changing Wires	13-03-2019	14-03-2019	01 Day
		Various Speeds	22-03-2019	26-03-2019	04 Days
		Adding Extra Blades	10-04-2019	12-04-2019	02 Days
		Re-testing	13-04-2019	15-04-2019	02 Days

Table 5.2: Tasks Assigned to Members

No.	Task	Assigned to Members
01	Introduction	All Team
02	Literature Review	Mohammed Al-Shammari
		Thamer Al-Harbi
		Turki Al-Ahmari
03	System Design	All Team
04	Testing and Analysis	All Team
05	Project Management	Mohammed Al-Shammari
		Thamer Al-Harbi
		Fahad Al-Ghamdi
06	Project Analysis	Mohammed Al-Shammari
		Thamer Al-Harbi
		Ahmed Al-Rushidi
07	Conclusion and Recommendations	Mohammed Al-Shammari
		Thamer Al-Harbi
		Ahmed Al-Rushidi
08	Prototype Design	Turki Al-Ahmari
		Fahad AL-Ghamdi
09	Purchasing Parts	All Team
10	Manufacturing	Turki Al-Ahmari
		Fahad AL-Ghamdi

11	Testing and Retesting	All Team

5.2. Contributions of Each Team Member

Depending on the nature of the task and on the strengths and weaknesses of our team members, the tasks have been assigned to the entire team, three or two members. The decision that which task should be assigned to which members of the team has been made on the basis of time required for the task and the ability of the members of doing a particular task. The following table i.e. Table 5.3. has been used to present the tasks and the contribution of each member in percentage in meeting or fulfilling the task.

Table 5. 3: Contributions of Members in Fulfilling Tasks

No	Task		Assigned To	Contribution in %
01	**Introduction**		All Team	100
02	**Literature**	Background	Al-Shammari	33
			Al-Harbi	33
			Al-Ghamdi	34
		Related Work	Al-Shammari	33
			Al-Harbi	34
			Al-Ahmari	33
		Comparison	Al-Shammari	34
			Al-Harbi	33
			Al-Rushidi	33
03	**System Design**	Designing Constraints and Methodology	Al-Shammari	25
			Al-Harbi	25
			Al-Rushidi	25
			Al Ghamdi	25
		Standards of Engineering Design	Al-Shammari	25
			Al-Harbi	25
			Al-Rushidi	25
			Al Ghamdi	25
		Theoretical Calculations	Al-Shammari	25
			Al-Harbi	25
			Al-Rushidi	25

05			Al Ghamdi	25
		Analyzing Product's Subtypes and Choosing Components	Al-Shammari	25
			Al-Harbi	25
			Al-Rushidi	25
			Al Ghamdi	25
		Manufacturing and Assembling	Al-Shammari	25
			Al-Harbi	25
			Al-Rushidi	25
			Al Ghamdi	25
04	**Testing and Analysis of the System**	Experimental Setup of Sensor and its relevant data	All Team	100
		Results, Analysis & Discussion	All Team	100
05	**Project Management**	Project Plan	AlGhamdi Al-Shammari	100
		Team member's Contribution		
		Project Execution Monitoring		
		Challenges and Decision Making		
		Bill of Materials & Budget Details		
06	**Project Analysis**	Life Long Lessons	Al-Ghamdi Al-Rushidi	100
		Engineering Solution Impact		
		Addressing Contemporary Issues		
07	**Conclusion and Recommendations**	Conclusion	All Team	100
		Recommendations		

08	**Prototype Design**	Final Shape Cavity Location	Al-Ghamdi AL-Ghamdi	100
09	**Purchasing Parts**	Car Battery Sensors Light Wire Alternator	All Team	100
10	**Manufacturing**	Welding the Structure Grinding Blades Bending	Al-Ahmari AL-Ghamdi	100
11	Testing	Changing Wires Various Speeds Adding Extra Blades Re-testing	All Team	100

5.3. Monitoring Project Execution

One of the most important aspects of project management is the process of monitoring, monitoring is carried out in every knowledge area. However, monitoring becomes of special significance when it has to be carried out during the execution of a project. Just like it happens during any project, our project also consists of many activities that have to be performed in order to enhance the project. These activities are the required meetings or follow ups, and also concern those events which are related to the senior projects. In the following table i.e. table 5.4. a list of all the meetings and other such happenings during the course of our spring semester has been provided.

Table 5. 4: Frequency and Dates of Events and Activities

Date and Frequency	Events and Activities
Once a Week	Assessment Class
Once a Week	Group Members Meeting
Twice a Month	Meeting the Advisors
15th February 2019	Delivering First Prototype
22nd March 2019	Maiden Test of the System
3rd April 2019	Presentation at Midterm
19th April 2019	Delivering Final Prototype
21st April 2019	System Testing
26th April 2019	Report Submission
3rd May 2019	Final Presentation

5.4. Challenges

Throughout the course of this project i.e. during different phases of this project, our project team came across numerous challenges. In this subsection we enlist a few of those challenges.

5.4.1. Challenges

We have made use of different tools and devices, and as a matter of fact we came across some difficulties whose nature was actually technical. At the end of the day we overcame those challenges and the devices functioned exactly how they were supposed to.

- Choosing the engine: in the initial stage of the project, we opted for motor bike in order to make use of its exhaust for the for the purpose of transforming the heat of exhaust to electric power, but we failed because the engine did not produced enough amount of heat the TEG required, so that we had to change the engine.
- TEG ordering: we experienced a hug problem with the ordering the TEG from outside the kingdom since they are not available here, once TEG reached the Saudi costumes they holed it for security reasons, and we had to visit them to explain where we are going to use them.

- Heart loss: in the first trail of the project we failed to achieve the desired heat eve we changed the engine, but our advisor Dr.Raguramam has advised us to use the exhaust insulation in order to minimize the heat loss.

5.4.2. Issues of Testing and Safety

For testing and for collecting the output results, we carried out the process of testing ourselves. The process was not easy and it had a certain deal of danger associated with it, however, we were successful in collecting the output results i.e. current, voltage, and power output. The main objective of this project that is to recover the surface exhaust heat to transform the recovered it into useful electric energy has successfully been achieved.

5.4.3. Design Problems

In order to achieve our desire objective, we had decided in the beginning of the project that we will make use of project management principles. That is why we could successfully recognize some of the design problems in the beginning of the project. Before we began the design phase, we had started considering the following points and design issues:

- Pump
- Thermocouples
- Heat sink
- Surface of area
- Engine with high temperature
- Engine should produce high temperature around 240c
- Design the base for engine

5.5. Payment Bill and Budget

The following i.e. Table 5.5. Presents a bill of the materials that had to be bought in order to make this project a success. The costs of the materials have been presented in SR i.e. Saudi Riyals.

Table 2: Payment Bill and Budget

No.	Material	Cost in Saudi Riyals
01	THERMOCOUPLES	1387 SR
02	HEAT SINK	1238 SR
03	THERMOMETER LASER GUN	76 SR
04	WATER PUMP	75 SR
05	SOLDERING PEN	35 SR
06	Bread BOARD	25 SR
07	MANUFACTURING SKUTTURDITE	389 SR
08	FITTING	410 SR
09	INSULATION BLANKET	460 SR
10	CLAMPS	10 SR
11	WATER HOSE	30 SR
12	ENGINE	550 SR
13	Miscellaneous	700 SR
Total		5385 SR

Chapter 6: Project Analysis

6.1. Life-long Learning

What we realized and learned during the course of the project is that apart from hard skills, soft skills are extremely important for making a project successful. In order to succeed as a team, the most important and significant things are some of the areas highlighted by project management. Moreover, skills related to software, and hardware have also been polished and enhanced.

6.1.1. Hardware Skills

The use of thermocouples, which is used for generating electric current as result of heat difference, Another hardware device that we have used is the heat sink, it is used to cool down the TEG cold side so that temperature difference can happen. We have also used a water pump for water circulation and some other hardware as well.

6.1.2. Software Skills

With every passing day, technology improves, that is not only due to the advancements in hardware but in software as well. That is why, we have realized that software skills are as important as hardware knowledge, skills or expertise. During the course of this project, our team has been able to explore a few software and has been able to learn MS office, and Solidworks.

6.1.3. Project Management

We have been able to explore and realize the importance of many of project management's knowledge areas. These areas include: project time management, project communication management, and project cost management. Moreover, we have also been able to learn about and use project planning, project initiation, project execution and project monitoring and assessment.

Project time management is a process that is not only dynamic but it also asks for inputs from various members of a team either simultaneously and sequentially. What we learned is that even if a single member from the team is not able to meet a deadline the whole team is going to go down.

Communication management is the key to the success of projects. For a team to successfully achieve the objectives of a project, it has to communicate effectively, failing to do so might lead to total chaos. We have come to know that a project might fail even if a single member is not communicating effectively. We have also learned that with communication information about the project, about the skills and knowledge, strengths and weaknesses etc. are shared.

Project cost management deals with the procedure of forecasting and managing the budget of a project. Many activities are involved in this process, these activities include: planning, estimation, budgeting and financing etc.

6.2. Engineering Solution's Impact

Our project influences the society in numerous ways, these ways include societal, economical, and environmental etc. As far as the societal impact is concerned, our project is going to recover surface exhaust heat for converting the recovered heat to electric energy.As far as the impact on the economy is concerned, our project will produce useful electric energy that will help to decreases that cost of electrical energy. Our project is actually environment friendly due to the fact that it produces energy from any heat source that already existe in another word it will not create another source of pollution . Also, the stated energy of this system can also be stored in batteries for later use.

6.3. Addressing Contemporary Issues

The main objective of this project was to come up with such an idea with the help of which we would be able to address some contemporary issues. And as a matter of fact, we have done exactly that. We are able to successfully fabricate a recovery generator that is based on exhaust gas. The generator is eco-friendly, which means that the power generation performed is actually not going to cause any harm to the environment. This project cannot only be applied for domestic use but for commercial use as well, that too at a decent price. We have successfully recovered surface heat to transform it to electric energy. In order to increase the power, we can connect numerous TEG's (Thermo-Electric Generators). Another issue that has been addressed is that the generated energy can be used for powering auxiliary devices.

Chapter 7: Conclusions and Future Recommendations

7.1 Conclusions

In conclusion, the design proposed in this project recover waste heat from the engine exhaust gasses. The heat from the room surface that is attached to engine exhaust is converted to electrical output via thermoelectric generators connected in series on top and back surface of the room surface. That output power can serve various purpose such as charging a battery, lightening of lamp or in any low wattage appliances. Out unique contribution to previous work is that our work can be utilized by everyone domestically and commercially due to its simple design.

There were problems faced in the designing of this project mostly in the calculation portion and choosing the right tools for the right job. But all the problems have contributed to our knowledge bank and hardware skills. Commissioning this project step by step made us know about the design, calculation, hardware, and theory. We came to know that there exists some loss after the recovery of waste heat on which more work could be done and there is always room for improvement.

7.2 Future Recommendations

- Shell and tube heat exchanger design optimization for TEG system.
- Look for better Thermocouples.
- Explore other design concept for waste heat recovery like turbocharge and generate power by using turbines.

8. *References*

[1] H. J. V. Tyrrell, D. A. Taylor, and C. M. Williams, "The 'Seebeck Effect' in a Purely Ionic System," *Nature,* vol. 177, pp. 668-669, 1956/04/01 1956.

[2] T. H. Geballe and G. W. Hull, "Seebeck Effect in Germanium," *Physical Review,* vol. 94, pp. 1134-1140, 06/01/ 1954.

[3] A. W. Van Herwaarden and P. M. Sarro, "Thermal sensors based on the seebeck effect," *Sensors and Actuators,* vol. 10, pp. 321-346, 1986/11/12/ 1986.

[4] T. H. Geballe and G. W. Hull, "Seebeck Effect in Silicon," *Physical Review,* vol. 98, pp. 940-947, 05/15/ 1955.

[5] F. D. Rosi, "Thermoelectricity and thermoelectric power generation," *Solid-State Electronics,* vol. 11, pp. 833-868, 1968/09/01/ 1968.

[6] V. A. Drebushchak, "The Peltier effect," *Journal of Thermal Analysis and Calorimetry,* vol. 91, p. 311, 2007/07/11 2007.

[7] D. M. Rowe and G. Min. (1996, Design theory of thermoelectric modules for electrical power generation. *IEE Proceedings - Science, Measurement and Technology143(6),* 351-356. Available: https://digital-library.theiet.org/content/journals/10.1049/ip-smt_19960714

[8] B. I. A. Ismail, Wael H., "Thermoelectric Power Generation Using Waste-Heat Energy as an Alternative Green Technology," *Electrical and Electronic Engineering Technologies,* vol. 2, pp. 27-39(13), 2009.

[9] S. B. Schaevitz, A. J. Franz, K. F. Jensen, and M. A. Schmidt, "A Combustion-Based MEMS Thermoelectric Power Generator," in *Transducers '01 Eurosensors XV*, Berlin, Heidelberg, 2001, pp. 30-33.

[10] A. Rodríguez, J. G. Vián, D. Astrain, and A. Martínez, "Study of thermoelectric systems applied to electric power generation," *Energy Conversion and Management,* vol. 50, pp. 1236-1243, 2009/05/01/ 2009.

[11] A. Bitschi, "Modelling of thermoelectric devices for electric power generation," *research-collection.ethz.ch,* 2009.

[12] C. Zhang, K. Najafi, L. P. Bernal, and P. D. Washabaugh, "An Integrated Combustor-Thermoelectric Micro Power Generator," in *Transducers '01 Eurosensors XV*, Berlin, Heidelberg, 2001, pp. 34-37.

[13] F. J. DiSalvo, "Thermoelectric Cooling and Power Generation," *Science,* vol. 285, p. 703, 1999.

[14] S.-K. Kim, B.-C. Won, S.-H. Rhi, S.-H. Kim, J.-H. Yoo, and J.-C. Jang, "Thermoelectric Power Generation System for Future Hybrid Vehicles Using Hot Exhaust Gas," *Journal of Electronic Materials,* vol. 40, pp. 778-783, 2011/05/01 2011.

[15] R. J. Stevens, S. J. Weinstein, and K. S. Koppula, "Theoretical limits of thermoelectric power generation from exhaust gases," *Applied Energy,* vol. 133, pp. 80-88, 2014/11/15/ 2014.

[16] C. Baker, P. Vuppuluri, L. Shi, and M. Hall, "Model of Heat Exchangers for Waste Heat Recovery from Diesel Engine Exhaust for Thermoelectric Power Generation," *Journal of Electronic Materials,* vol. 41, pp. 1290-1297, 2012/06/01 2012.

[17] J. G. Haidar and J. I. Ghojel, "Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators," in *Proceedings ICT2001. 20 International Conference on Thermoelectrics (Cat. No.01TH8589)*, 2001, pp. 413-418.

[18] K. M. Saqr, M. K. Mansour, and M. N. Musa, "Thermal design of automobile exhaust based thermoelectric generators: Objectives and challenges," *International Journal of Automotive Technology,* vol. 9, pp. 155-160, 2008/04/01 2008.

Appendix A: Progress Reports

	SDP – WEEKLY MEETING REPORT
	Department of Mechanical Engineering **Prince Mohammad bin Fahd University**

SEMESTER:	SPRING	ACADEMIC YEAR:	2019
PROJECT TITLE	Waste Heat Recovery System		
SUPERVISORS	Fahad AL-Ghamdi		

Month: February

ID Number	Member Name
201400482	Mohammed Al-Shammari
201500396	Thamer Al-Harbi
201400346	Ahmed Al-Rushidi
201401148	Turki Al-Ahmari

List the tasks conducted this month and the team member assigned to conduct these tasks

#	Task description	Team member assigned	Progress 0%-100%	Delivery proof
1	Choose the project and looking for the advisor .	ALL TEAM		
2	Held the meeting to distribute the job	All Team		
3	Follow up with advisor to start with the project	Fahad Mohammed		
4	SPD1,2,3,4	Fahad Mohammed		
5	Spare Parts	Fahad Mohammed Thamer		
6	Gent chart	Thamer Turki Fahad		
7	Mile stone 2	Mohammed Thamer Fahad Ahmed		
8	Mile Stone 3	Thamer Mohammed Fahad		

9	**Receiving the spare parts**	Mohmmed Fahad Ahmed		
10	**Mid Term presentation**	Mohmmed Fahad Thamer Ahmed		

List the tasks planned for the month of March and the team member/s assigned to conduct these tasks

#	Task description	Team member/s Assigned
1	**CAD drawing for received new items**	Fahad Ahmed
2	**Calculations final review**	Fahad Thamer Ahmed
4	**Parts assembly**	Mohmmed Fahad Thamer
3	**Working on the prototype**	Mohmmed Fahad Thamer Ahmed
4	**Final presentation**	Mohammed Fahad Thamer Ahmed

- **To be Filled by Project Supervisor and team leader:**
- **Please have your supervisor fill according to the criteria shown below**

Outcome f: An understanding of professional and ethical responsibility.				
Criteria	**None (1)**	**Low (2)**	**Moderate (3)**	**High (4)**
f1. Demonstrate an understanding of engineering professional and ethical standards in dealing with public safety and interest	Fails to Demonstrate an understanding of engineering professional and ethical standards in dealing with public safety and interest	Shows limited and less than adequate understanding of engineering professional and ethical standards in dealing with public safety and interest	Demonstrates satisfactory an understanding of engineering professional and ethical standards in dealing with public safety and interest	Understands appropriately and accurately the engineering professional and ethical standards in dealing with public safety and interest

Outcome d: An ability to function on multidisciplinary teams.				
Criteria	**None (1)**	**Low (2)**	**Moderate (3)**	**High (4)**
d1. Ability to develop team work plans and allocate resources and tasks	Fails to develop team work plans and allocate resources and tasks	Shows limited and less than adequate ability to develop team work plans and allocate resources and tasks	Demonstrates satisfactory ability to develop team work plans and allocate resources and tasks	Understands and applies proper and accurate team work plans and allocate resources and tasks
d2. Ability to participate and function effectively in team work projects	Fails to participate and function effectively in team work projects	Shows limited and less than adequate ability to participate and function effectively in team work projects	Demonstrates satisfactory ability to participate and function effectively in team work projects	Understands and participates properly and function effectively in team work projects
d3. Ability to communicate effectively with team members	Fails to communicate effectively with team members	Shows limited and less than adequate ability to communicate effectively with team members	Demonstrates satisfactory ability to communicate effectively with team members	3. Understands and communicates properly and effectively with team members

Indicate the extent to which you agree with the above statement, using a scale of 1-4 (1=None; 2=Low; 3=Moderate; 4=High)

#	Name	Criteria (d1)	Criteria (d2)	Criteria (d3)	Criteria (f1)
1	**FahadAlghamdi**	4	4	4	3
2	**Ahmed Alrashidi**	3	4	3	4
3	**Mohammed Alshammari**	4	3	4	4
4	**ThamerAlharbi**	3	4	3	4
5	**TurkiAlahmari**	3	3	4	3

	SDP – WEEKLY MEETING REPORT
	Department of Mechanical Engineering **Prince Mohammad bin Fahd University**

SEMESTER:	SPRING	ACADEMIC YEAR:	2019
PROJECT TITLE	Waste Heat Recovery System		
SUPERVISORS	DR. Raguraman Kannan		

Month: March 2019

#	ID Number	Member Name
1	200700827	Fahad Alghamdi
2	201400482	Mohammed Al-Shammari
3	201500396	Thamer Al-Harbi
4	201400346	Ahmed Al-Rushidi
5	201401148	Turki Al-Ahmari

List the tasks conducted this month and the team members assigned to conduct these tasks

#	Task description	Team member assigned	Progress 0%-100%	Delivery proof
1	Choose the project and looking for the advisor.	ALL TEAM	100%	
2	Held the meeting to distribute the job	ALL TEAM	100%	
3	Follow up with advisor to start with the project	Fahad Mohammed	100%	
4	SPD1,2,3,4	Fahad Mohammed	100%	
5	Spare Parts	Fahad Mohammed Thamer	100%	
6	Gannt chart	Thamer Turki Fahad	100%	
7	Milestone 2	Mohammed Thamer Fahad Turki	100%	
8	Milestone 3	Thamer Mohammed Fahad	100%	
9	Receiving the spare parts	Mohmmed Fahad	100%	

		Ahmed		
10	Mid Term presentation (Milestone 4)	ALL TEAM	100%	

List the tasks planned for the month of April and the team member/s assigned to conduct these tasks

#	Task description	Team member/s assigned
1	CAD drawing for received new items	Fahad Ahmed Mohammed
2	Calculations and final review	Fahad Thamer Ahmed
3	Parts assembly	ALL TEAM
4	Milestone 5	ALL TEAM
5	Working on the prototype	ALL TEAM
6	Milestone 6	ALL TEAM
7	Peer Evaluation	ALL TEAM
8	Final presentation	ALL TEAM

- **To be Filled by Project Supervisor and team leader:**
- **Please have your supervisor fill according to the criteria shown below**

Outcome f:
An understanding of professional and ethical responsibility.

Criteria	None (1)	Low (2)	Moderate (3)	High (4)
f1. Demonstrate an understanding of engineering professional and ethical standards in dealing with public safety and interest	Fails to Demonstrate an understanding of engineering professional and ethical standards in dealing with public safety and interest	Shows limited and less than adequate understanding of engineering professional and ethical standards in dealing with public safety and interest	Demonstrates satisfactory an understanding of engineering professional and ethical standards in dealing with public safety and interest	Understands appropriately and accurately the engineering professional and ethical standards in dealing with public safety and interest

Outcome d:
An ability to function on multidisciplinary teams.

Criteria	None (1)	Low (2)	Moderate (3)	High (4)
d1. Ability to develop team work plans and allocate	Fails to develop team work plans and allocate	Shows limited and less than adequate ability to develop team work plans and	Demonstrates satisfactory ability to develop team work plans and	Understands and applies proper and accurate team work

resources and tasks	resources and tasks	allocate resources and tasks	allocate resources and tasks	plans and allocate resources and tasks
d2. Ability to participate and function effectively in team work projects	Fails to participate and function effectively in team work projects	Shows limited and less than adequate ability to participate and function effectively in team work projects	Demonstrates satisfactory ability to participate and function effectively in team work projects	Understands and participates properly and function effectively in team work projects
d3. Ability to communicate effectively with team members	Fails to communicate effectively with team members	Shows limited and less than adequate ability to communicate effectively with team members	Demonstrates satisfactory ability to communicate effectively with team members	3. Understands and communicates properly and effectively with team members

Indicate the extent to which you agree with the above statement, using a scale of 1-4 (1=None; 2=Low; 3=Moderate; 4=High)

#	Name	Criteria (d1)	Criteria (d2)	Criteria (d3)	Criteria (f1)
1	**Fahad Alghamdi**	4	4	4	4
2	**Ahmed Alrashidi**	4	4	4	4
3	**Mohammed Alshammari**	4	4	4	4
4	**Thamer Alharbi**	4	4	4	4
5	**Turki Alahmari**	4	4	4	4

Appendix B: CAD drawings and Bill of Materials

Table 3: Bill of Materials

Material	Cost (Saudi Riyal)
THERMOCOUPLES	1387 SR
HEAT SINK	1238 SR
THERMOMETER LASER GUN	76 SR
WATER PUMP	75 SR
SOLDERING PEN	35 SR
Bread BOARD	25 SR
MANUFACTURING SKUTTURDITE	389 SR
FITTING	410 SR
INSULATION BLANKET	460 SR
CLAMPS	10 SR

WATER HOSE	30 SR
ENGINE	550 SR

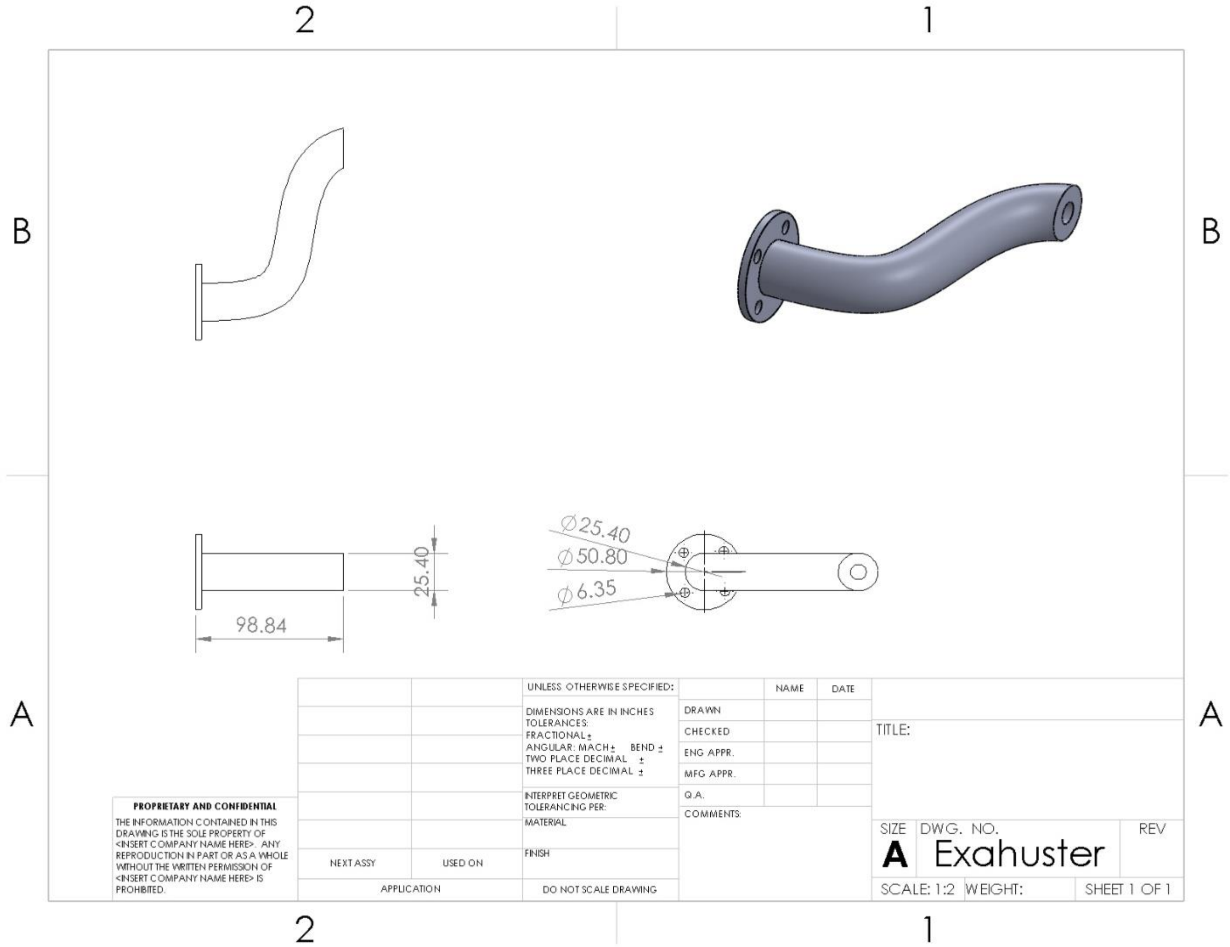


Figure 31: CAD design for Exhaust

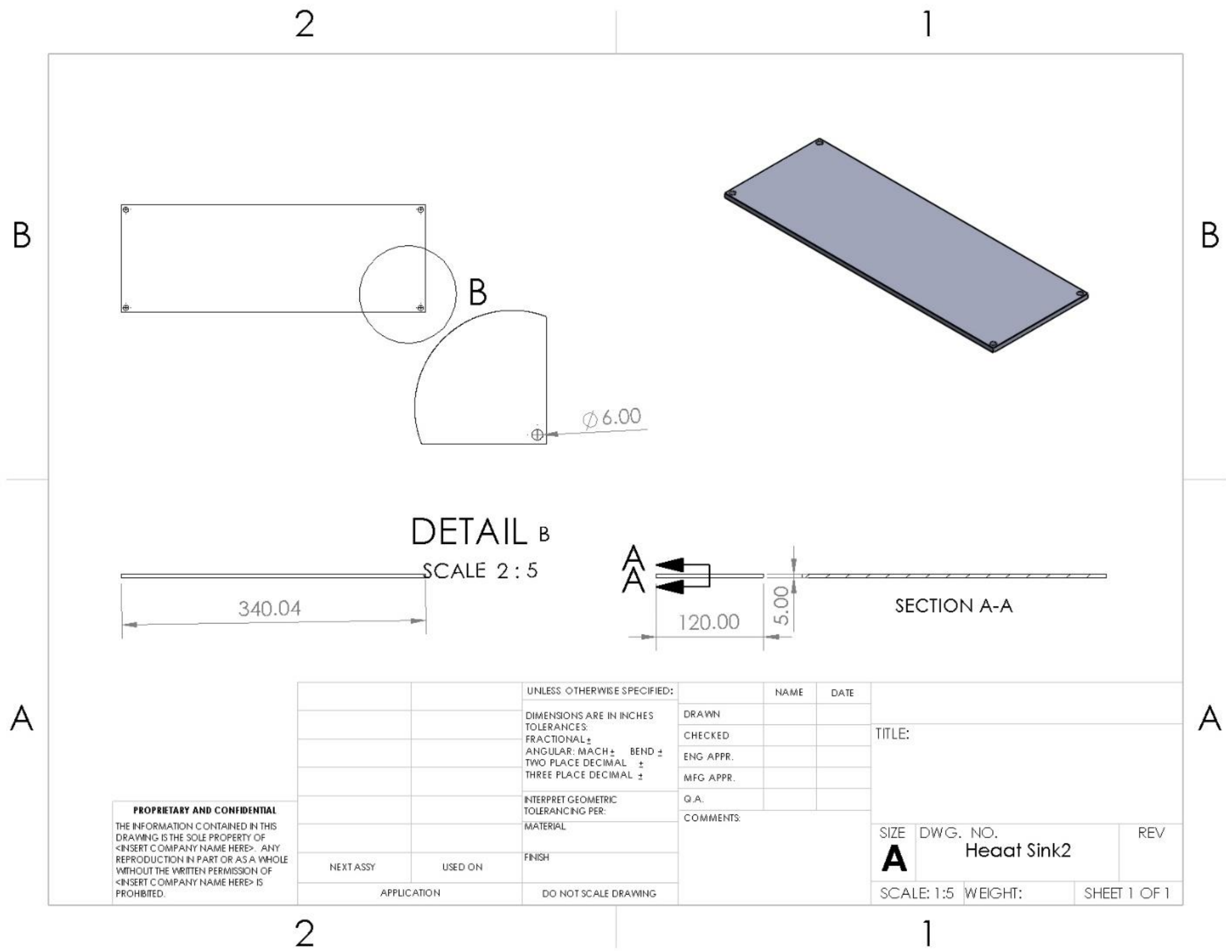


Figure 24: CAD Design for Heat Sink

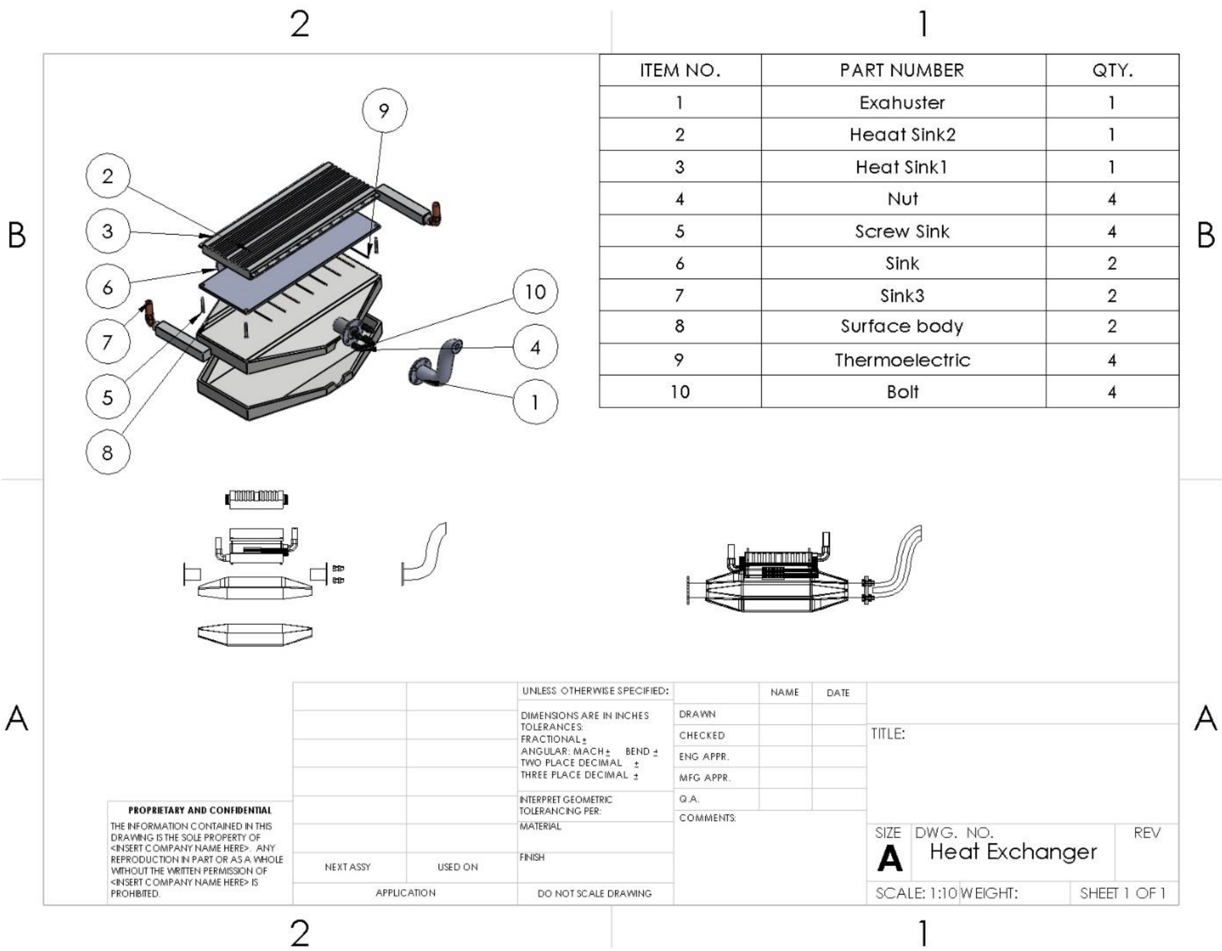


Figure 25: CAD Design for Heat Exchanger

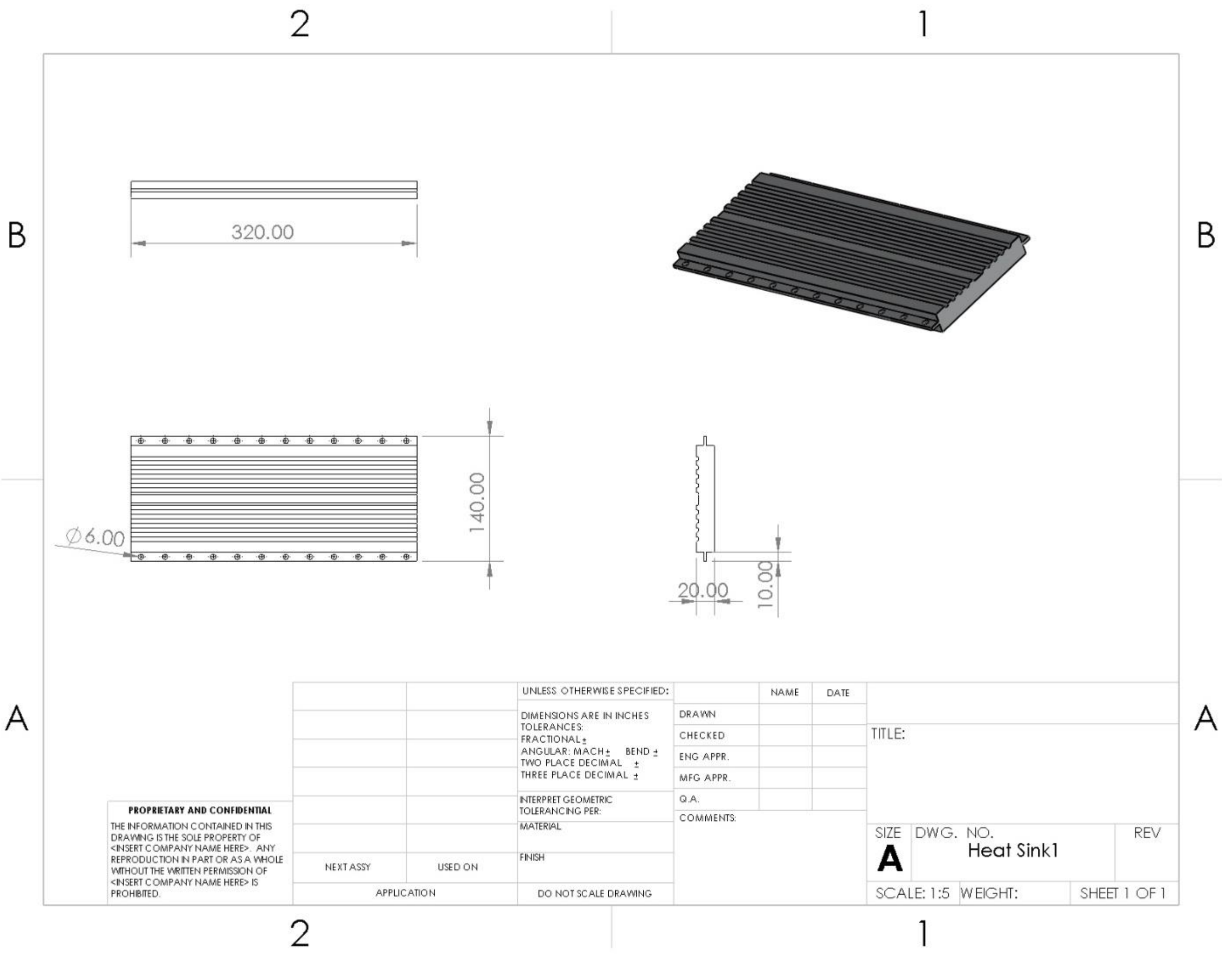


Figure 26: CAD Design for Heat Sink

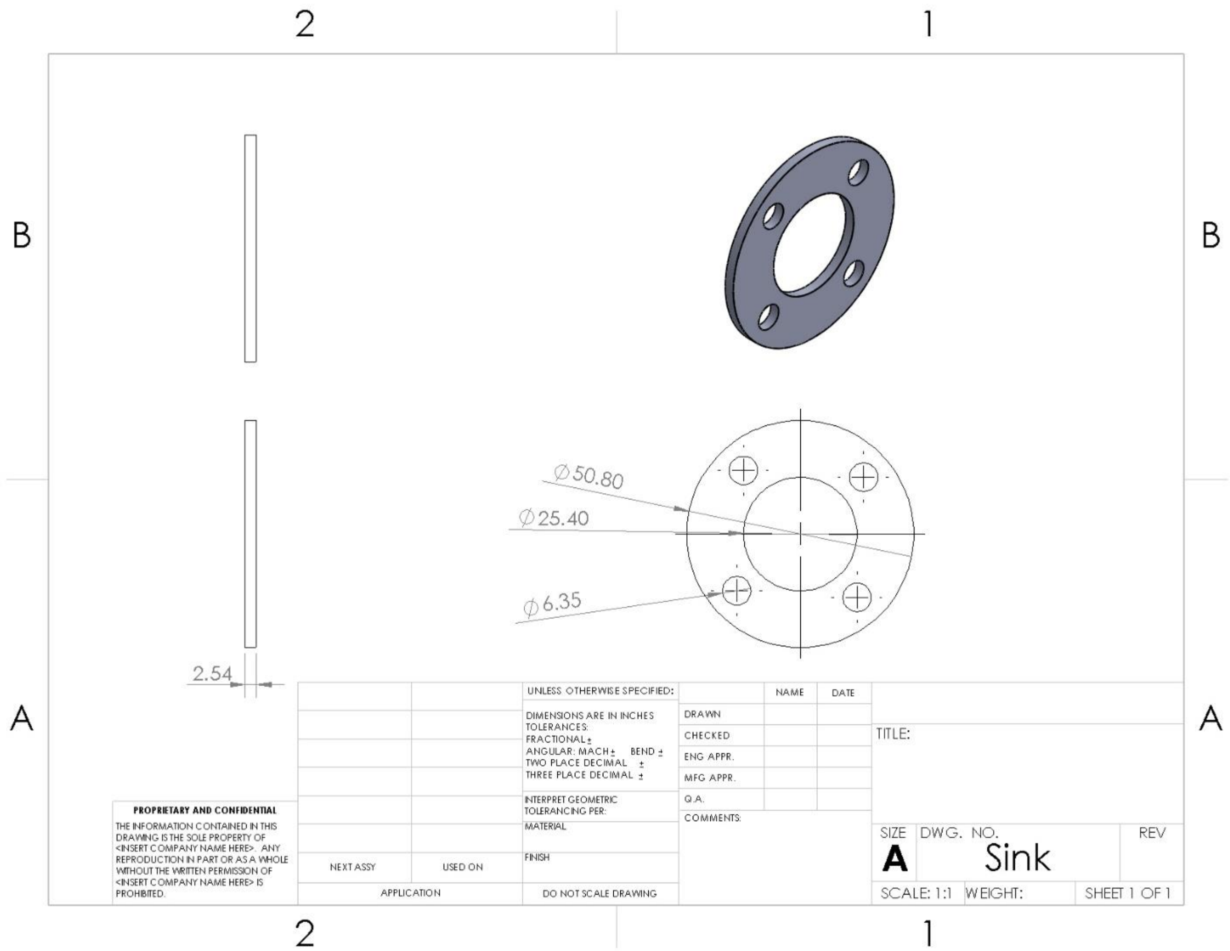


Figure 27: CAD Design for Sink Washer

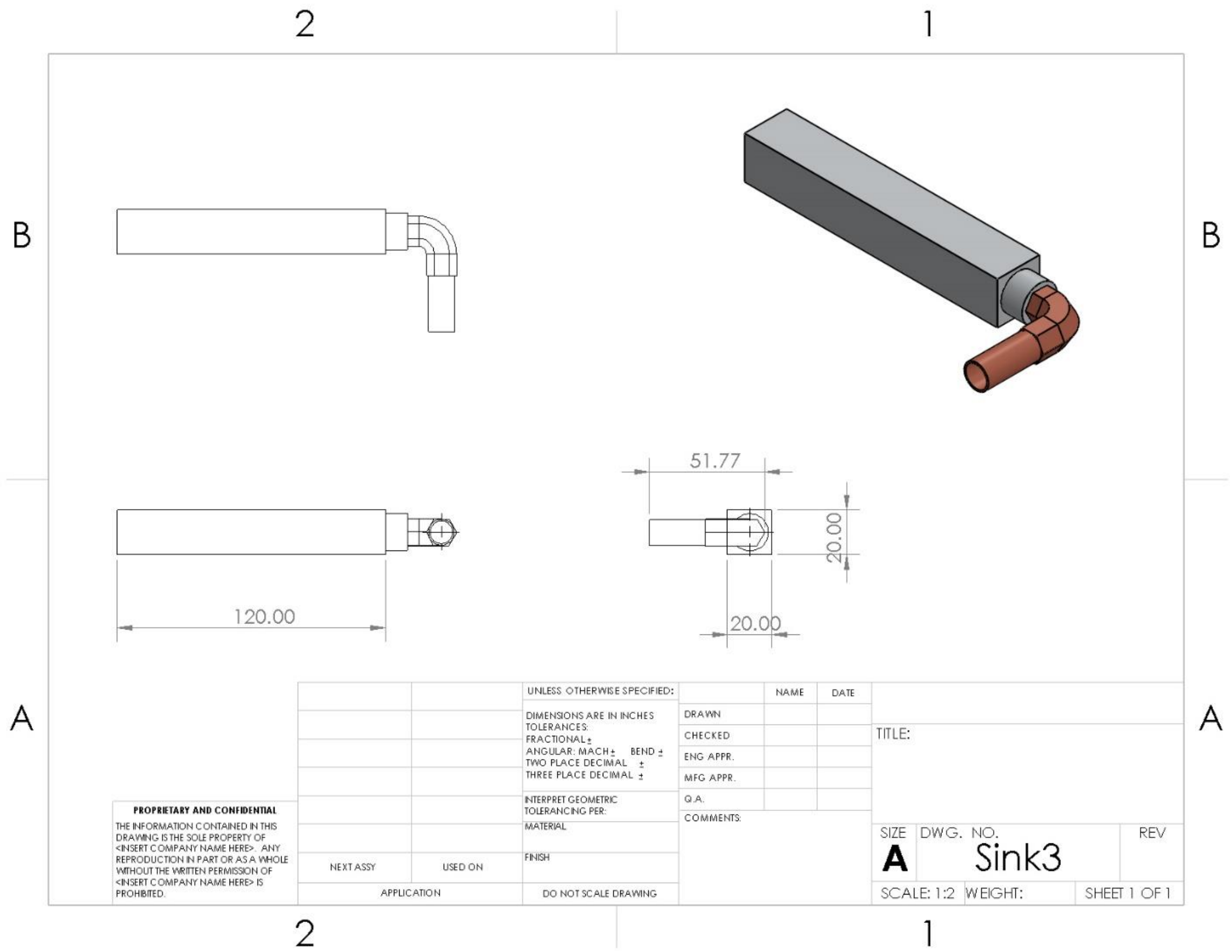


Figure 28: CAD Design for Heat Sink Inlet/Outlet

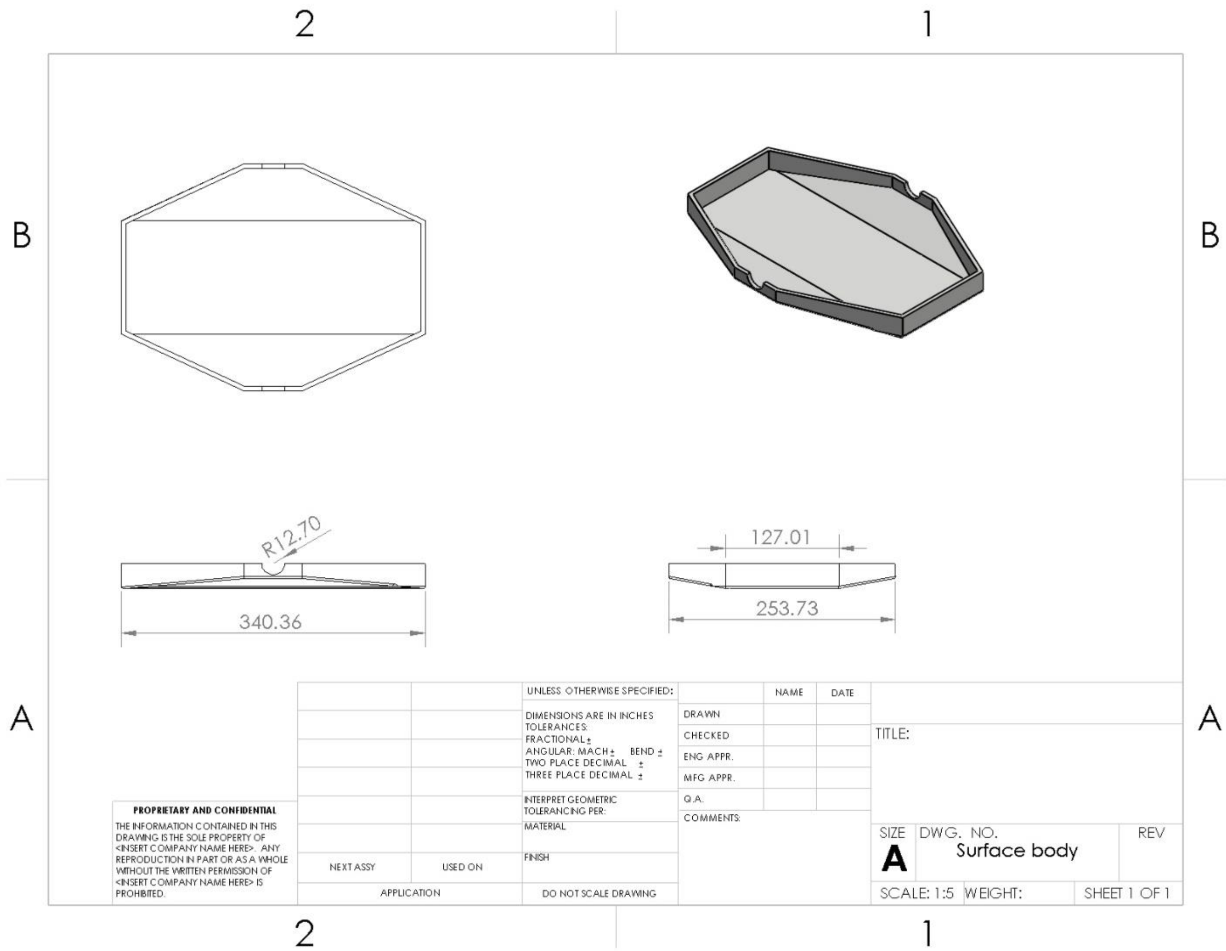


Figure 29: CAD Design for Heat Sink Surface

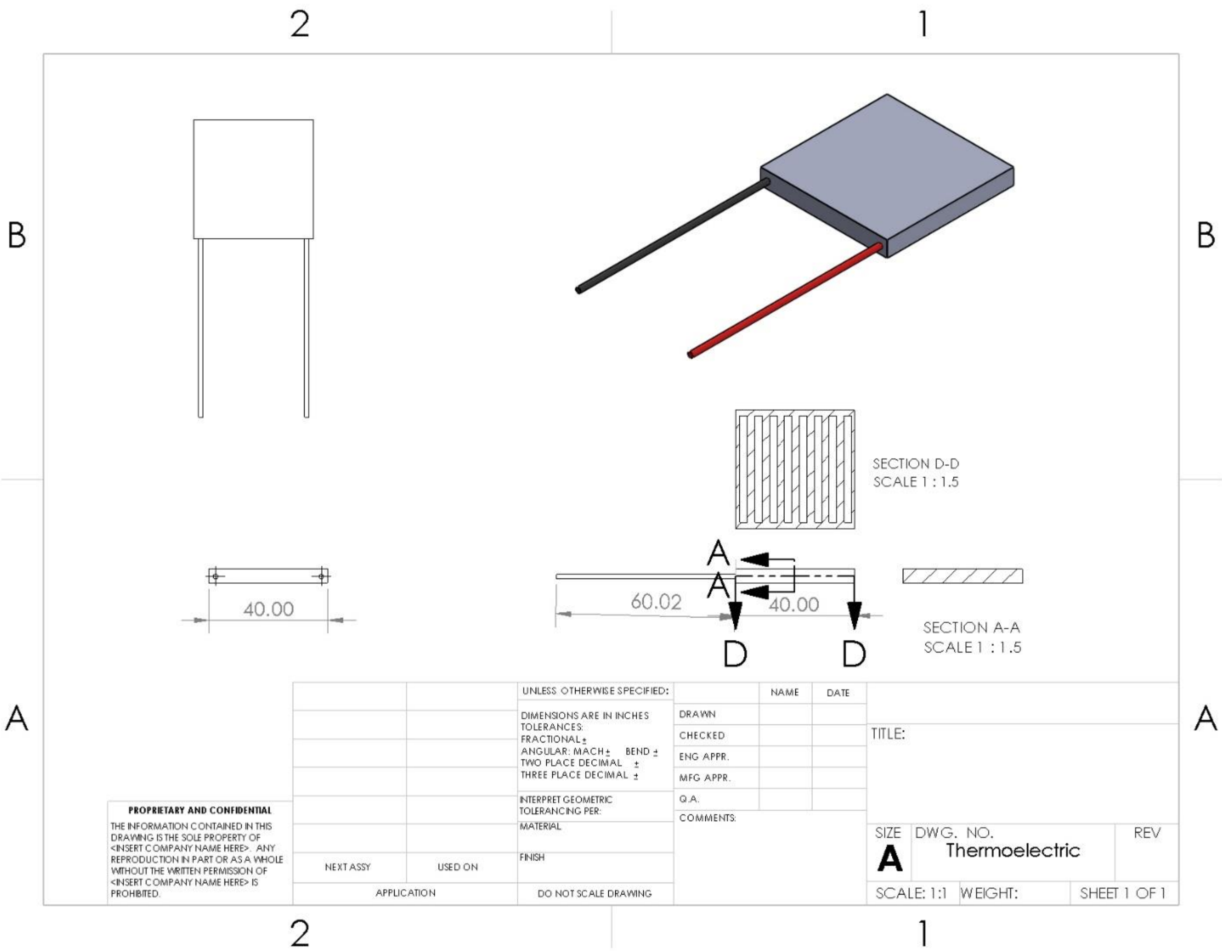


Figure 30: CAD Design for TEG

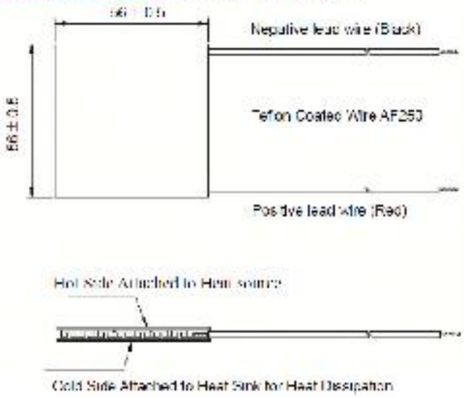
Appendix C: Datasheets

Specifications TEG Module TEG1-12611-6.0

SNAPSHOT SPECIFICATION OF TEG1-12611-6.0

Hot Side Temperature (℃)	300
Cold Side Temperature (℃)	30
Open Circuit Voltage (V)	8.4
Matched Load Resistance (ohms)	1.2
Matched load output voltage (V)	4.2
Matched load output current (A)	3.4
Matched load output power (W)	14.6
Heat flow across the module(W)	≈ 365
Heat flow density(W/cm²)	≈ 11.6
AC Resistance(ohms) Measured under 27℃ at 1000Hz	0.5~0.7

Geometric Characteristics Dimensions in millimeter



Tecteg@rogers.com N.A 1-800-769-2395 World 1-905-751-1362 website: www.Thermoelectric-generator.com

Appendix D: Operation Manual

To run the prototype, kindly follow these steps:

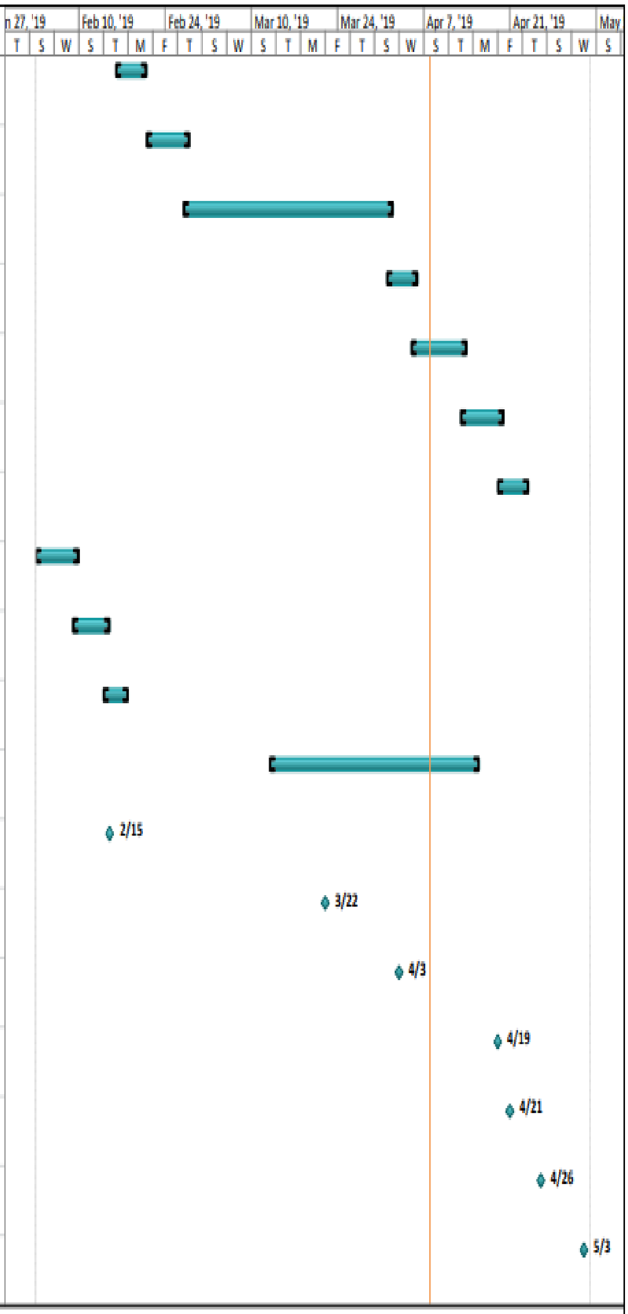
- Switch on the generator and measure the temperature of the heat exchanger with the help of temperature gun.
- Also measure the temperature of heat sink so that temperature difference can be known.
- Measure the output current and voltage of the TEGs using digital multi meter

The expected results from this operation are:

- Voltage and Current

Appendix E: Gantt chart

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		Introduction	4 days	Sat 2/16/19	Wed 2/20/19	
2		Literature	5 days	Thu 2/21/19	Wed 2/27/19	
3		System Design	24 days	Wed 2/27/19	Mon 4/1/19	
4		Test & Analysis	5 days	Mon 4/1/19	Fri 4/5/19	
5		Project Management	7 days	Fri 4/5/19	Sat 4/13/19	
6		Project Analysis	6 days	Sat 4/13/19	Fri 4/19/19	
7		Conclusion & Recommendations	3 days	Fri 4/19/19	Tue 4/23/19	
8		Prototype Design	7 days	Sun 2/3/19	Sat 2/9/19	
9		Purchasing Parts	5 days	Sat 2/9/19	Thu 2/14/19	
10		Manufacturing	3 days	Thu 2/14/19	Sun 2/17/19	
11		Test	24 days	Wed 3/13/19	Mon 4/15/19	
12		Delivering 1st Prototype	0 days	Fri 2/15/19	Fri 2/15/19	
13		1st Test of the System	0 days	Fri 3/22/19	Fri 3/22/19	
14		Midterm Presentation	0 days	Wed 4/3/19	Wed 4/3/19	
15		Final Prototype Delivery	0 days	Fri 4/19/19	Fri 4/19/19	
16		System Testing	0 days	Sun 4/21/19	Sun 4/21/19	
17		Submit Report	0 days	Fri 4/26/19	Fri 4/26/19	
18		Final Presentation	0 days	Fri 5/3/19	Fri 5/3/19	

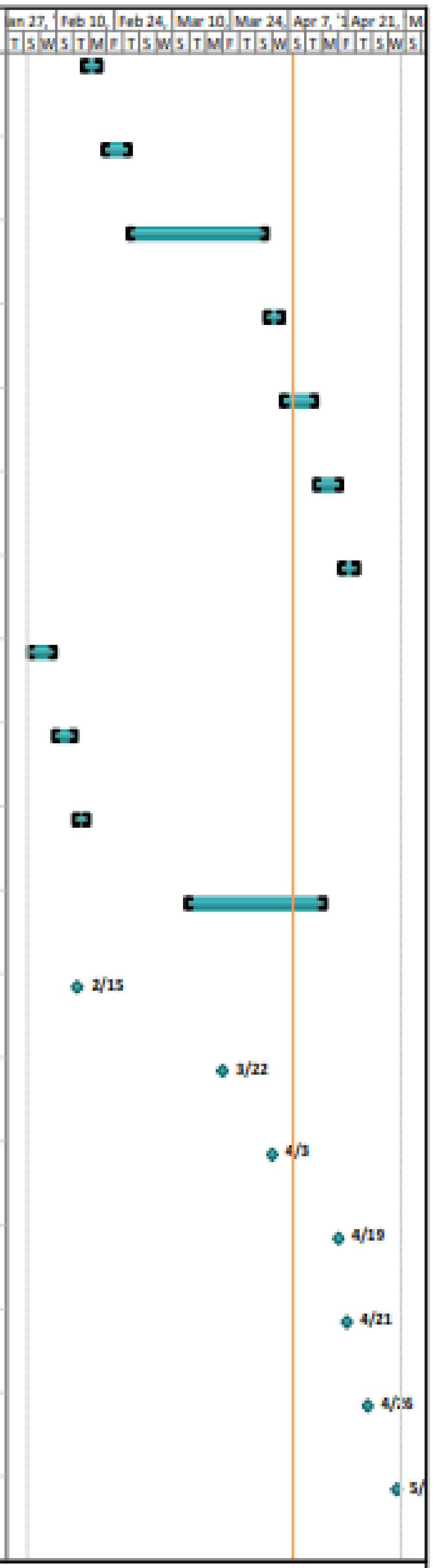


Project: Project1
Date: Mon 4/8/19

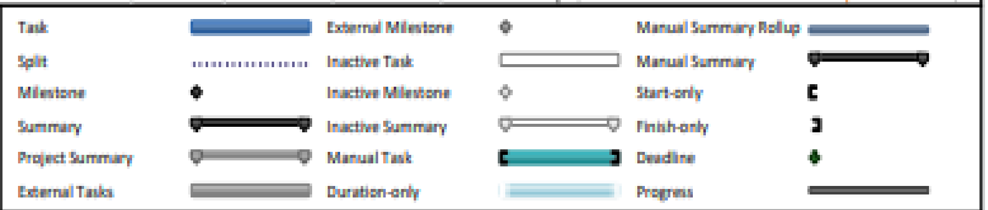
Task		External Tasks		Manual Task		Finish-only	
Split		External Milestone		Duration-only		Deadline	
Milestone		Inactive Task		Manual Summary Rollup		Progress	
Summary		Inactive Milestone		Manual Summary			
Project Summary		Inactive Summary		Start-only			

Page 1

ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors
1			Introduction	4 days	Sat 2/16/19	Wed 2/20/19	
2			Literature	5 days	Thu 2/21/19	Wed 2/27/19	
3			System Design	24 days	Wed 2/27/19	Mon 4/1/19	
4			Test & Analysis	5 days	Mon 4/1/19	Fri 4/5/19	
5			Project Management	7 days	Fri 4/5/19	Sat 4/13/19	
6			Project Analysis	6 days	Sat 4/13/19	Fri 4/19/19	
7			Conclusion & Recommendations	3 days	Fri 4/19/19	Tue 4/23/19	
8			Prototype Design	7 days	Sun 2/3/19	Sat 2/9/19	
9			Purchasing Parts	5 days	Sat 2/9/19	Thu 2/14/19	
10			Manufacturing	3 days	Thu 2/14/19	Sun 2/17/19	
11			Test	24 days	Wed 3/13/19	Mon 4/15/19	
12			Delivering 1st Prototype	0 days	Fri 2/15/19	Fri 2/15/19	
13			1st Test of the System	0 days	Fri 3/22/19	Fri 3/22/19	
14			Midterm Presentation	0 days	Wed 4/3/19	Wed 4/3/19	
15			Final Prototype Delivery	0 days	Fri 4/19/19	Fri 4/19/19	
16			System Testing	0 days	Sun 4/21/19	Sun 4/21/19	
17			Submit Report	0 days	Fri 4/26/19	Fri 4/26/19	
18			Final Presentation	0 days	Fri 5/3/19	Fri 5/3/19	



Project: Project1
Date: Mon 4/8/19



Page 1