Development of Thermoelectric Generator (TEG) For Energy Recovery in Perodua Myvi

by

David Bong

Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr. Mior Azman Meor Said)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2013

CERITIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except specified in the references and acknowledgements, and that the original work contained herin have not been undertaken or done by unspecified sources or persons.

DAVID BONG

ABSTRACT

Over the decades, the automotive industry has shifted its interest towards producing more and more fuel efficient car such as the hybrids which would not only reduce fuel consumption, but also maintaining as much as possible the great performance of a car. A technology such as thermoelectric generator has also play its role in the recent years with greater emphasis on recovering waste heat from the engine. Conventional ICE loses as much as 40% of energy from the fuel in the form of exhaust heat and recovering this portion of energy would therefore increase the engine efficiency as well as reducing unnecessary loads on the engine.

On a different perspective, such technology could also be developed in local brand car such as the Perodua Myvi. Thus, this project is introduced to implement the concept of heat recovery as well as producing a proof-of-concept prototype for such design. However, developing a TEG requires studies on mainly two components which are the exhaust system of the car and the thermoelectric panel. Thus, the objectives of this project is firstly to investigate those properties and by using the collected information, creating a functional TEG prototype.

Divided into two phases, the first phase of the project mainly tackles on data collection and analysis. This includes thermal mapping on the exhaust system of a Myvi as well as determining the true potential of an acquired TEG panel. Experimental studies are carried out to identify the most ideal location on the exhaust pipeline to install the TEG which is evaluated based on its temperature range and feasibility requirements. This collection of data compliments the second phase of the project which is the design process. During this phase, the design is developed from conceptual ideas into parametric design and finally fabrication process. The second phase of the project requires great consideration on various aspects such as product fabrication feasibility and materials rather than solely focusing on technicality.

In conjunction with Perodua Eco-Challenge 2013, the developed TEG is installed on the exhaust system of a Perodua Libero as part of the engineering challenge on fuel consumption. The integration of the project into the event has provides a better platform to place the prototype into test in terms of functionality and optimum performance.

ACKNOWLEDGEMENT

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ABBREVIATIONS AND NOMENCLATURES

TEG	Thermoelectric Generator
KERS	Kinetic Energy Recovery System
NASA	National Aeronautics and Space Administration

ICE	Internal Combustion Engine
MSME	Micro, Small and Medium Enterprise
DoE	Department of Energy
UTP	Universiti Teknologi PETRONAS
PEC	Perodua Eco-Challenge

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDY

With the never ending crisis on the environment with regards to greenhouse gas emission and the increase of fuel prices in the current modern world have spark more interest on the search for the best alternative energy to use or perhaps the usage of energy in the best way. One such humble technology is the thermoelectric generator (TEG) installed either within power plant station, automotive vehicle or even small electrical appliances. The simple working principle of TEG which is to convert heat energy from any extent of source including our body to acceptable electrical power has raised more studies and research in the recent years at which some even believe it may even able to replace reciprocating engine in the near future especially in the automotive industry.

Regardless of advanced research and development, no company is yet to produce an automotive car engine which produces more than enough power to spare and overcome energy loses. John W. Fairbanks (2012) of U.S. Department of Energy (DoE) in his conference has fairly confirm that the efficiency of most car are less than 50% in which more than half of the mechanical energy supplied from the engine is lost as shown in Figure 1.1 below.

The figure shows the distribution of energy from the internal combustion engine. The total energy produced through combustion of fuel does not fully transferred into mechanical energy but rather lost through a series of components as shown in the figure. Approximately only 21.5% of the energy from the fuel is used to actually move the car. This however does not represent any specified party but rather a brief summary of researches and studies that has been done over multiple cars with various specifications.

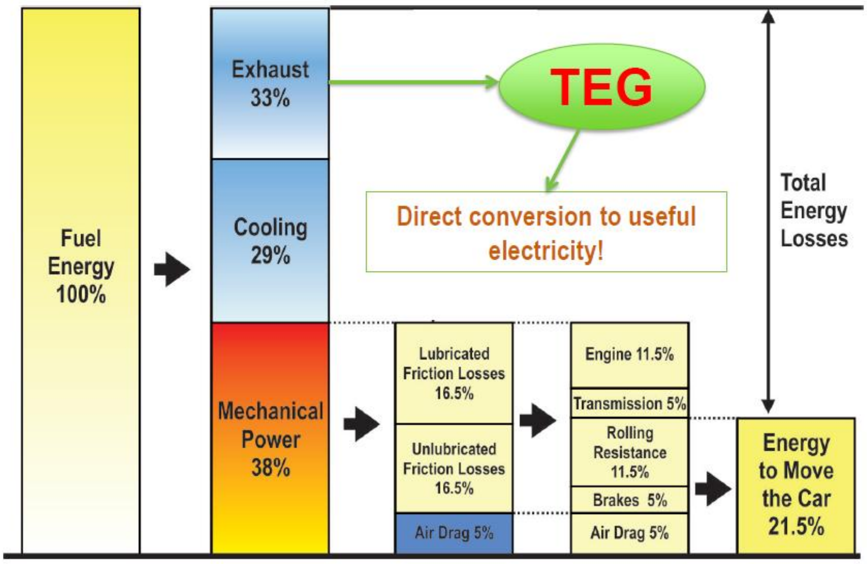


Figure 1.1: Distribution of fuel energy in a car by U.S. DoE

Therefore the application of TEG would enable the system to harvest the energy lost through the exhaust in the form of heat and convert it to electrical energy to power up either the accessories of car or even the air condition unit and the engine itself. Frank Stabler (2012) in his workshop on TEG also complimented that due to its potential, the automotive industry over the globe has seen a drastic plan in recent years to further research and developed this technology even for big company such as BMW and Toyota.

As for the future in Malaysia itself, it is never too late to participate in the rush for better car efficiency as in the application of TEG. Local car producers such as Proton and Perodua themselves have fairly capable and reliable engine in which further research would not only promise greater car performance through energy recovery (heat from the exhaust), but also would placed high demand due to less fuel consumption and more mileage.

1.2 PROBLEM STATEMENT

Depletion in source has causes the price for fuel keep inclining over the past decades which in turn switch the public interest from powerful and luxurious towards economical and efficient genre of automobile. This further fuels the needs for more studies and research in the automotive industry in the race for not only gaining the public trust through economic profit of selling, but also to produce a car which run on sustainable energy system.

Studies done have shown that a car loses its energy to different systems while running. Thus, the automotive industry is keen with the challenge to locate the exact part of the car which stole the energy and buy it back with energy conversion technologies. Formula One car for instance retrieved back the energy from the braking system through Kinetic Energy Recovery System (KERS) while TEG harvest the heat from the exhaust system. The exhaust system itself however comprises of different parts with different condition and prospect while running and thus present a challenge to locate the optimum area for energy recovery while not compromising the car performance and the device's operation.

An energy recovery device could somehow be deemed as parasite unless it could provide better car performance. Thus, the design of such device (TEG) should therefore be proposed to not only optimize the operation of the device, but also to hinder any drawbacks towards the performance of the car. Design specifications such as size, mass, mountings and control system should be developed in such a way that it would not impose negative effects on the running of the specified vehicle.

1.3 PROJECT OBJECTIVES

The main objectives of the proposed project are as follow:

1. Develop and validate thermal models of waste heat energy sources (exhaust system) of Perodua Myvi.
2. Characterize the performance of TEG for energy recovery in the exhaust system.
3. Fabricate and simulate a scale down proof-of-concept prototype of the developed system.

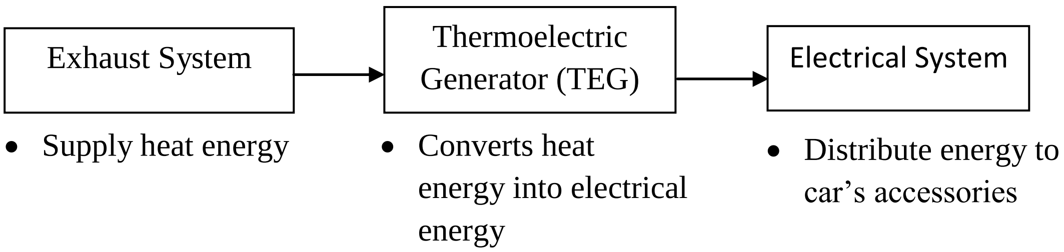
The supporting objectives are listed below:

1. Investigate and study the car electrical and exhaust system in order to verify the feasibility of the proposed TEG model.
2. Conceptually design TEG according to selected requirements and specifications.

3. Validate compatibility of TEG with Perodua Myvi automobile.
4. Carry out proper and accurate experimental design and engineering analysis either within the university laboratory and facilities or external sources.
5. Apply and adapt creativity and problem solving method, basic engineering skills and ethical conduct while ensuring the milestone of the project is achieved.

1.4 SCOPE OF STUDY

The project comprises of three major components which are the Myvi exhaust system, the developed TEG and the electrical system of the car itself in which all of them compliments each other in working towards the goals of the project.



The waste heat from the combustion passes through the exhaust system which heats up the surface as it travels along the pipe. Heat transfer across the surfaces of the pipe in contact with the TEG would convert the heat flow into electrical charges that flow through the electrical system of the car while the excess heat from the TEG is releases into the heat sink. The electrical power produced from this energy recovery system shall reduce the load on the alternator of the car's engine, which therefore diverts more mechanical power into actually moving the car rather than power up the accessories.

Figure 1.2: 1.3L 4-Cylinders Perodua Myvi released in 2005

Table 1.1: Perodua Myvi specifications

Dimension and Weight		
Overall length/width/height	(mm)	3690/1665/1545
Wheelbase	(mm)	2440
Front seat distance to ground	(mm)	595
Track front/rear	(mm)	1455/1465
Minimum road clearance	(mm)	160
Kerb weight	(kg)	950
Seating Capacity		5
Min. turning radius	(m)	4.7
Engine		
Engine type		K3-VE
Valve mechanism		DOHC, 16V with DVVT
Total displacement	(cc)	1298
Bore x stroke	(mm)	72.0 x 79.7
Compression ratio		10.0:1
Fuel system/capacity	(litres)	Electronic fuel injection (EFI)/40.0

The installed TEG itself is hoped to be able to recover the lost heat energy from the exhaust system and provide additional electrical power to the accessories of the car including the air conditioning unit in which would reduce the power load supplied by the alternator. Thus, further studies should first be done on the car specifications itself especially in terms of electrical power system as well as the exhaust system in order to be able to validate the compatibility of the TEG on the car as every car differs variously from each other with regards to the specifications of the engine as well as the electrical and exhaust components in them. This is followed by investigation on the TEG itself in which the detailed product specifications should be verified beforehand especially in terms of its temperature limits and power generation capacity in order to properly converts those information into actual working design. Finally would be the development of the TEG itself which involves the product parametric structure, cooling system, the mounting on the specified location and the electrical distribution for the car.

CHAPTER 2

LITERATURE REVIEW

2.1 THERMOELECTRIC GENERATOR (TEG)

The nature of TEG which allows energy conversion without any moving parts and noise has raised attention to it over the past 30 years whether within small applications such as a wrist watch or to the extent of NASA probes orbiting the space. Surprisingly this device which could be as small as a microchip works within a simple concept of heat transfer and closed circuit current. G. Jeffrey Sneider (2008) in his article of "Small Thermoelectric Generator" illustrates the concept of electrical current production through a series of heat flow that drives the free electron, e^- and holes, h^+ in a series connection. This is further shown by Gregory P. Meisner (2011) in his lecture in which he added the amount of electricity produced however depends on variables such as the materials of the modules as proven in Equation (1) and (2).

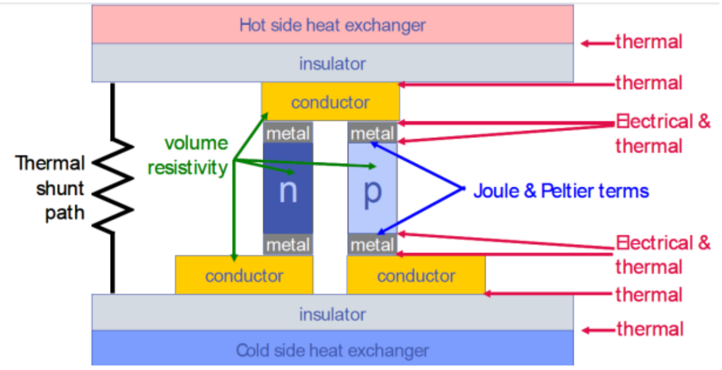


Figure 2.1: Schematic diagram of TEG module

The efficiency of TEG works upon Carnot cycle in which the efficiency is given as;

$$\eta = \left[\frac{T_H - T_C}{T_H}\right]\left[\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+{}^{T_C}/_{T_H}}\right] \quad (1)$$

In which ZT is the Figure Merit of the module and is given as;

$$ZT = \frac{\sigma\alpha^2}{(K_e+K_L)} T \text{ where;} \quad (2)$$

$$\sigma = electrical\ conductivity$$

$$\alpha^2 = Seebeck\ coefficient,$$

$$K_e + K_L = the\ total\ thermal\ conductivity$$

$$T = temperature\ dependent\ material\ property$$

Based on the equation above, higher ZT is desired in which it depends on opposite nature of heat conductivity and electrical resistance of the particular materials while in most cases, semiconductor are preferred since it produces optimum amount of ZT.

The application of TEG in automotive industry is somehow not new and different car companies have produce their own set of devices in which most of them claimed the test result had shown an almost 5% fuel savings on car running with TEG. The 3rd International Conference of Thermoelectric goes Automotive (2012) had presented a methodological concept development of TEG which includes procedural design of simulation, construction. FE analysis, assembly, vehicle integration and Dyno test bench that follows Figure 2.2.

2.2 EXHAUST WASTE HEAT BASED TEG

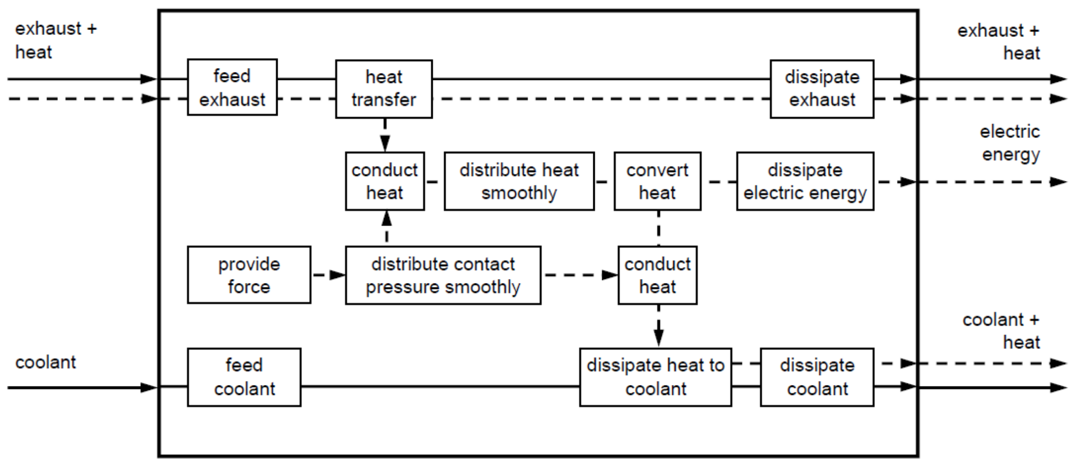


Figure2.2: TEG concept development based on functions structure

TEG however does not fit into the car configuration without a control system which is crucial to not only ensure the device works perfectly in desired proportion but also to ensure the performance of the car is not compromised by the installation. Some of crucial control functions are the following;

- TEG Heat Exchanger by-pass to protect the device from overheating as well as protect the engine from excessive backpressure.
- Coolant Flow/Pump Control to optimize power usage and coolant flow and provide warm coolant for rapid engine warm-up.
- Generator control to optimize the fuel economy in the case of light electrical loads.
- DC/DC Converter Control to match the TEG voltage output to the battery.

On the theoretical side however, George Casano and Steve Pive (2010) as well as several authors had published their research specifically based on Fourier's Law and Seebeck effect in which a mathematical models are able to simulate the impact of relevant factors such as the exhaust mass flow rate, temperature and mass flow rate of different types of cooling fluid, convection heat transfer coefficient, height of PN couple, the ratio of external resistance to internal resistance of the circuit on the output power and efficiency. Some of the significant result includes the output power and efficiency increase by changing the convection heat transfer coefficient of the high-temperature side than that of low-temperature-side.

As for the future of TEG system itself, further developments are currently being carried out especially in terms of architectural design to increase the power density as well as mass production feasibility. On the output energy, improvements shall be made on the overall system either in steady or dynamical states within driving cycles while further research are being done to produce TEG that can withstand greater temperature and able to operates within hybrid or extended range vehicles

2.3 CONVENTIONAL CAR EXHAUST SYSTEM STUDY

With respect to thermal analysis on the exhaust system itself, I. P. Kandylas and A. M. Stamelos (2009) has published their finding on the design of engine exhaust system based on heat transfer computation in which the main challenges in accurately estimating the parameters are due to the complex geometry of the exhaust line as well as the special flow conditions. In the published paper as well they have tabulated exhaust pipe transient heat transfer model in which the model characterize the heat transfer mode in the form of rate expression and equation according to particular cases.

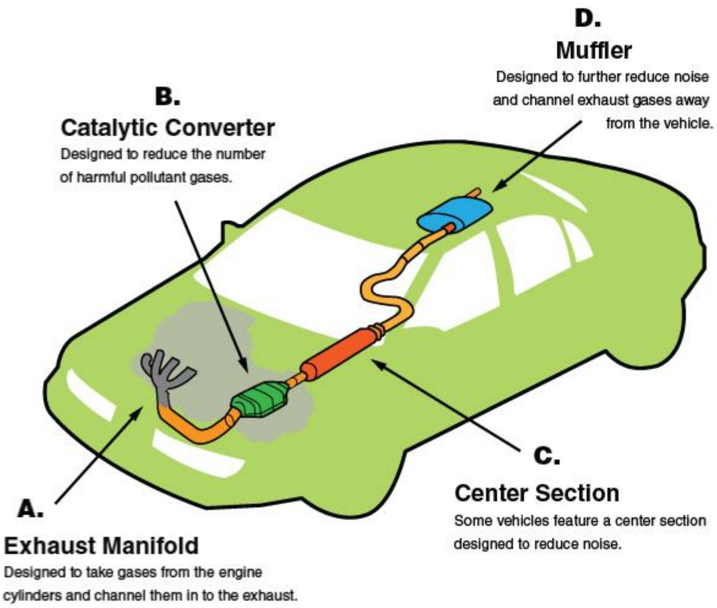


Figure 2.3: Components of exhaust system in a car

The exhaust system is comprised mainly of pipes in several different shapes, each designated to connect to one another and shaped to conform to a specific plart of the underside of the car. The pipes however are usually bent to wrap around or accommodate other nearby components under the car such as the axles and sensors. However, each pipe itself is responsible to move the exhaust gas towards the back, but many of the sections are specialized in function.

In the 3rd International Conference of Thermoelectrics goes Automotive, M. Kober, C. Hafele and H. Friedrich (2012) have developed a methodical concept development of TEG in which they focused on finding the best TEG architecture for vehicle application through procedural method. On the conference itself, they presented an analysis on the exhaust system of BMW 535i to determine the vehicle boundary conditions. The analysis was done in the form of experiment testing in which the temperatures along different parts of the exhaust system are measured under different velocity. The result of the analysis could be summarized as shown in Figure 2.4.

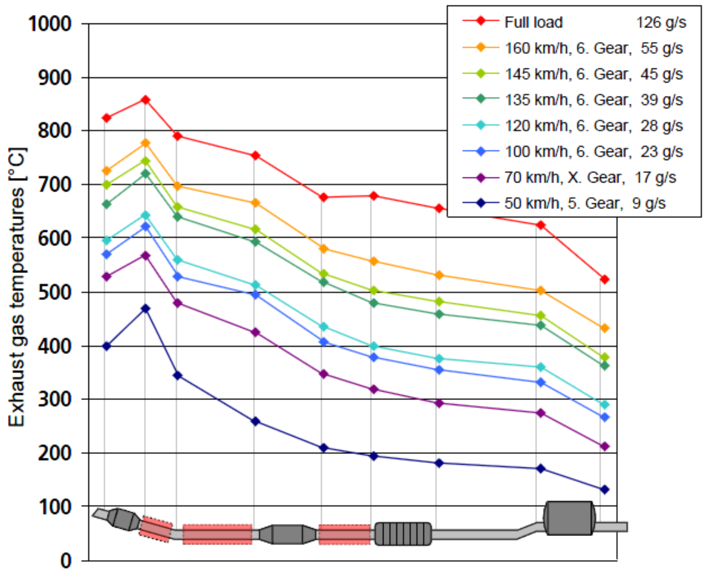


Figure 2.4: Temperature profiles along exhaust system

2.4 CONVENTIONAL ELECTRICAL SYSTEM OF A CAR

In general, the electrical system of a car comprises of the battery, starter and alternator. The battery provides the power surge needs to the starter. Once the car is up and running, the alternator supplies electrical power to charge the battery for the rest of the journey. If one of these parts failed, the car would not be able to start or run properly.

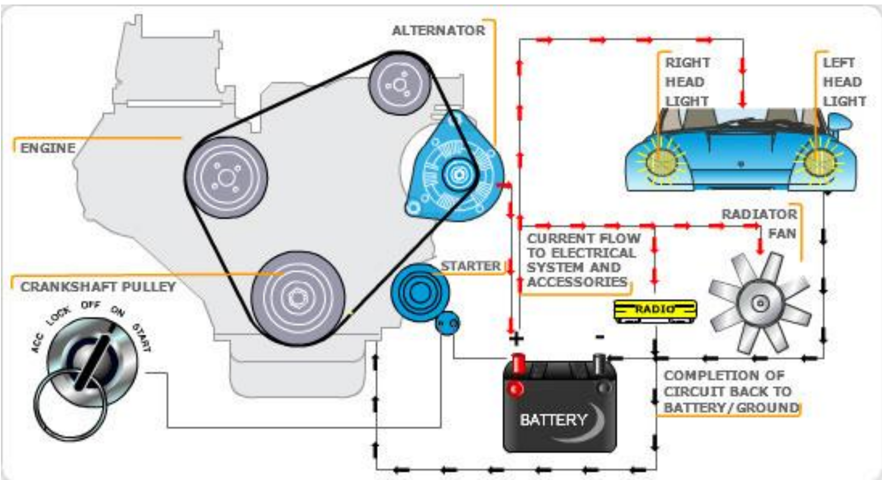


Figure 2.5: Process flow of car electrical system

- **Battery –** Prior to the start-up of the engine, the battery provide electrical current to the entire car including the current to the ignition and fuel systems which responsible for the combustion and running of the engine.
- **Starter –** While the battery supplies the power to start the car, the starter is actually the one which gets the engine running. The battery supplies a small amount of power to the starter motor which then rotates flywheel that turns the crankshaft and begins the movement of the engine's pistons.
- **Alternator –** As the car running, the alternator keeps the battery charged and the electrical system going. In the case of a faulty alternator, the car would still be able to start but however only to an extent period of time in which the batter has completely discharge.

2.5 CAR FUEL CONSUMPTION AND MILEAGE

The study of mileage or the amount of energy (fuel) consumed per unit of distance travelled requires a detailed analysis of the forces that oppose a vehicle's motion. The total force opposing the vehicle's motion multiplied by the distance through which the vehicle travels represents the work that the vehicle's engine must provide.

$$F = \frac{dW}{ds} \approx \text{mileage} \tag{3}$$

The amount of work generated by the vehicle's power source would be proportional to the amount of fuel consumed by the engine assuming the efficiency is the same regardless of power output. The fuel consumption of a conventional ICE engine vehicle generally depends on the following:

- The thermodynamic efficiency of the engine
- The frictional forces within the mechanical system that delivers the output of the engine
- The frictional forces between the wheels and the road (rolling friction)
- Internal forces that places load on the engine (aerodynamic drag)
- External forces that resist the motion

The energy required to power up the electrical components of the vehicle including headlights, battery charging, circulating fan, accessories and other electronic devices places load on the alternator which then draws up more energy from the engine thus increases the fuel consumption of the particular vehicle. With a typical engine efficiency of 40%, a belt efficiency of 98% and an alternator efficiency of 55% this leads to an overall energy conversion of only 21%. Mike Bradfield (2011) of MSME had described how improving the alternator efficiency measurably reduces fuel consumption. However, reducing the load on the alternator could certainly produces the same result which could be achieved by introducing alternative electrical power source such as TEG. John W Fairbanks (2012) of USA Department of Energy had presented a report which explains the development of TEG by several automotive companies such as BMW which so far have shown promising result with significant increase in fuel economy as shown in Figure 2.6 below.

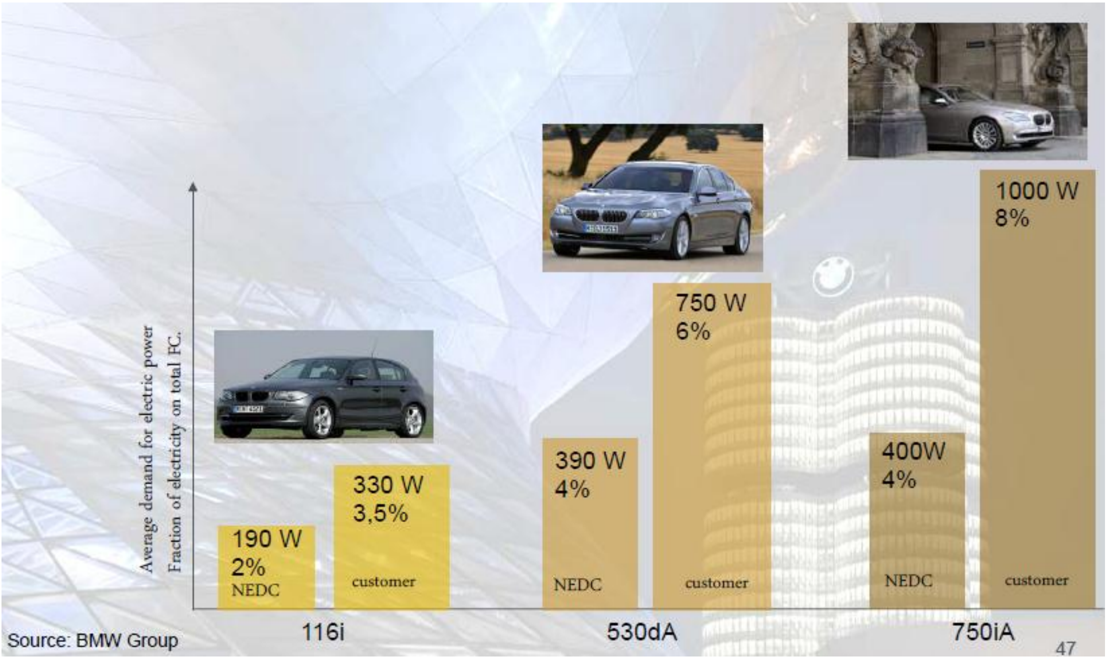


Figure 2.6: TEG development by BMW Group

CHAPTER 3

PROJECT WORK

3.1 RESEARCH METHODOLOGY

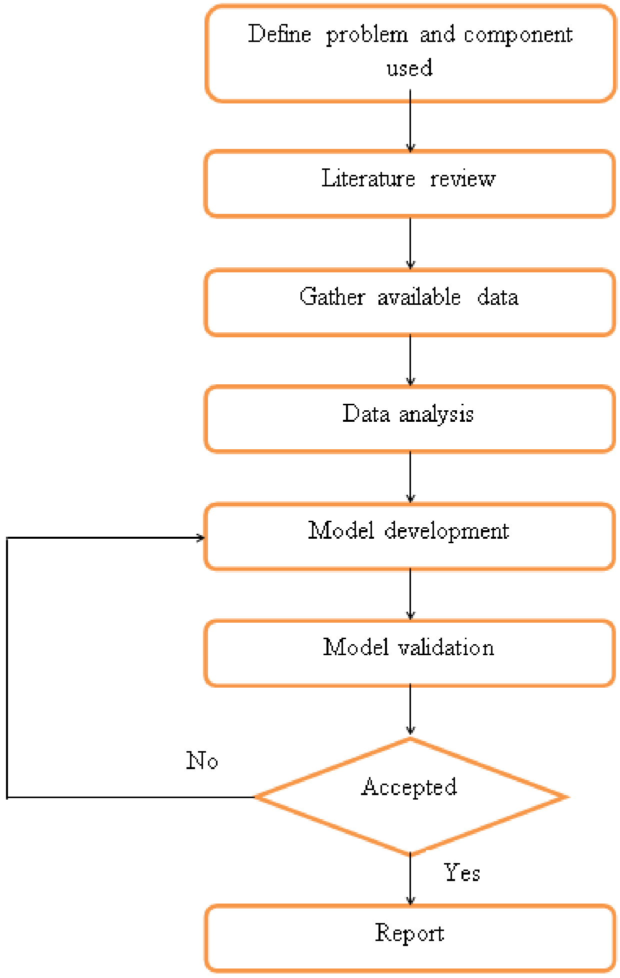


Figure 3.1: Research methodology conducted

3.1.1 Define Problem and Component Used

Identification of the problem statement is done by taking into accounts several current issues related to the extent of worldwide scope and through the problem statement, primary objectives are listed down to verify the desired end product of the project. This is followed by scoping down the scale of the project in which specific concept or devices could be identified inside the scope.

3.1.2 Literature Review

Further studies and research on the subject are conducted to not only important details of the project, but also to identify the status of the project through other people's research and studies or any current breakthrough has been done.

3.1.3 Gather Available Data

Available information or data is collected through the media in order to produce a benchmark prior to the development of the proposed project. The collected data would not only provide a guideline or reality check on the developed project, but it also produces an idea of the expected result of the project. Data to be collected would include specifications of TEG and available car system details as well as published design and structure.

3.1.4 Data Analysis

The collected data would be analyzed to identify crucial details required while developing the concept of the design. Other than that, it would also serve as a medium to validate the feasibility and functionality of the proposed design based on the extended studies.

3.1.5 Model Development

The concept generation of the design shall come first in the form of draft followed by concept evaluation to identify the best concept design to be carried onwards. The development of the concept would include simulation based on actual product and variables, generating the detailed design including dimensions and material properties as well as prototype production.

3.1.6 Model Validation

The product shall be validated through a series of experimental measures either within smaller scale or the actual condition. This process is to ensure the product is working well within specified requirements and achieving the expected result. Failure on this stage may require redeveloping of the model again.

3.1.7 Report

Documentations shall be done in which it may records all the information and activities taken from the initial steps of the proposed project. The purpose of the report would to serve as a formal and comprehensive set of proof on the development of the proposed project itself.

3.2 PROJECT ACTIVITIES

The activities of the proposed project are designed in such a way that it comprises of two phases. The first phase of the project would mainly involve with studies and investigation on related subjects while the second phase would incline towards designing the prototype.

3.2.1 Phase 1

Specification measure of TEG

Purpose:

To validate the capacity of TEG as well as other details required such as heat transfer rate and efficiency.

Method:

Experimental set up comprises of heat source, measurement meters and heat source under several pre-defined variables.

Investigate Myvi exhaust system

Purpose:

To verify the design structure and conduct thermal analysis of the exhaust pipeline and locate the critical high potential section.

Method:

Physical parametric measurement of the exhaust system and heat signature data collection along pipeline via data logger.

Study on Myvi Electrical and Cooling System

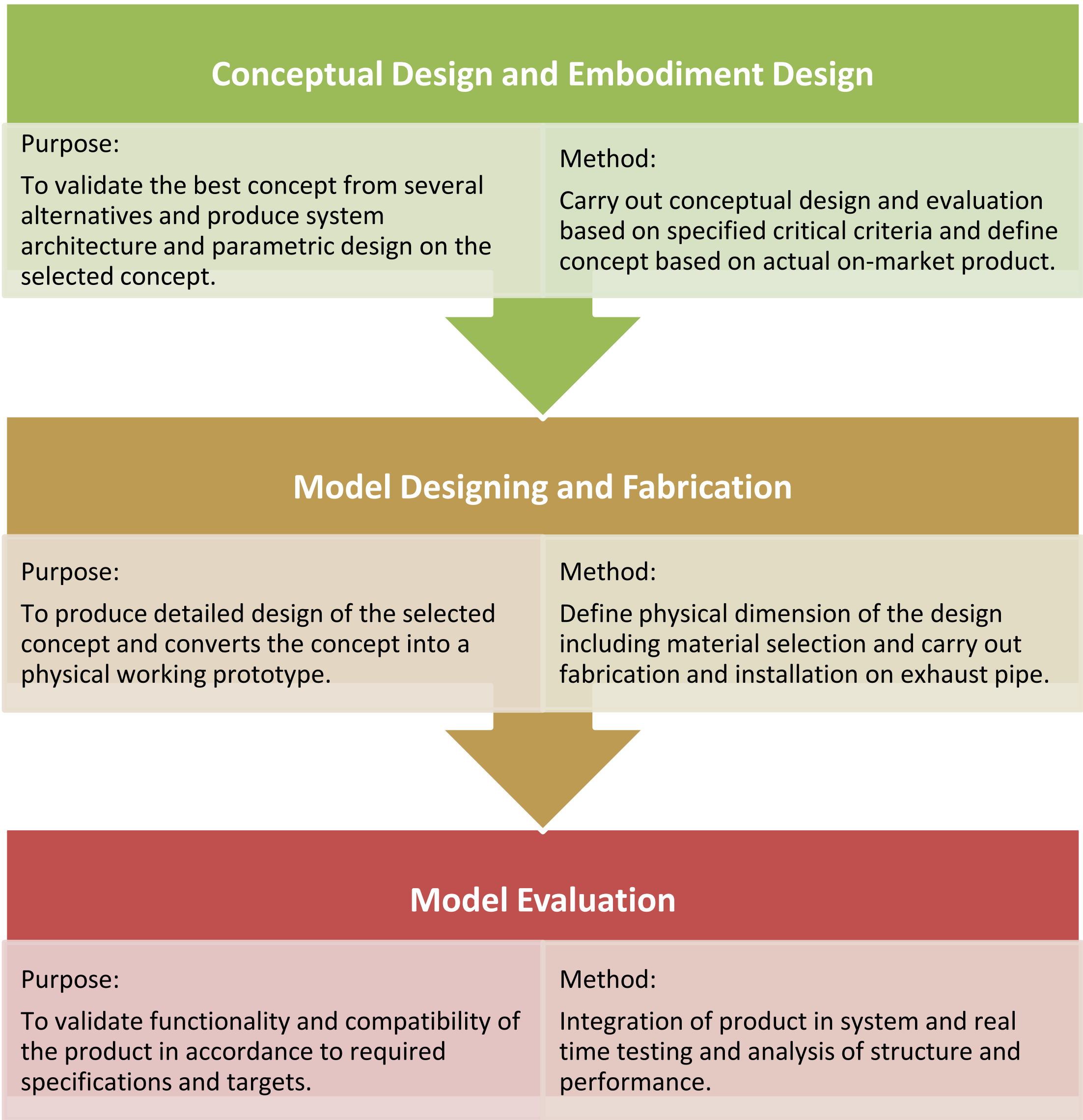
Purpose:

To validate the compatibility and functionality criteria of installed TEG as part of the integrated system.

Method:

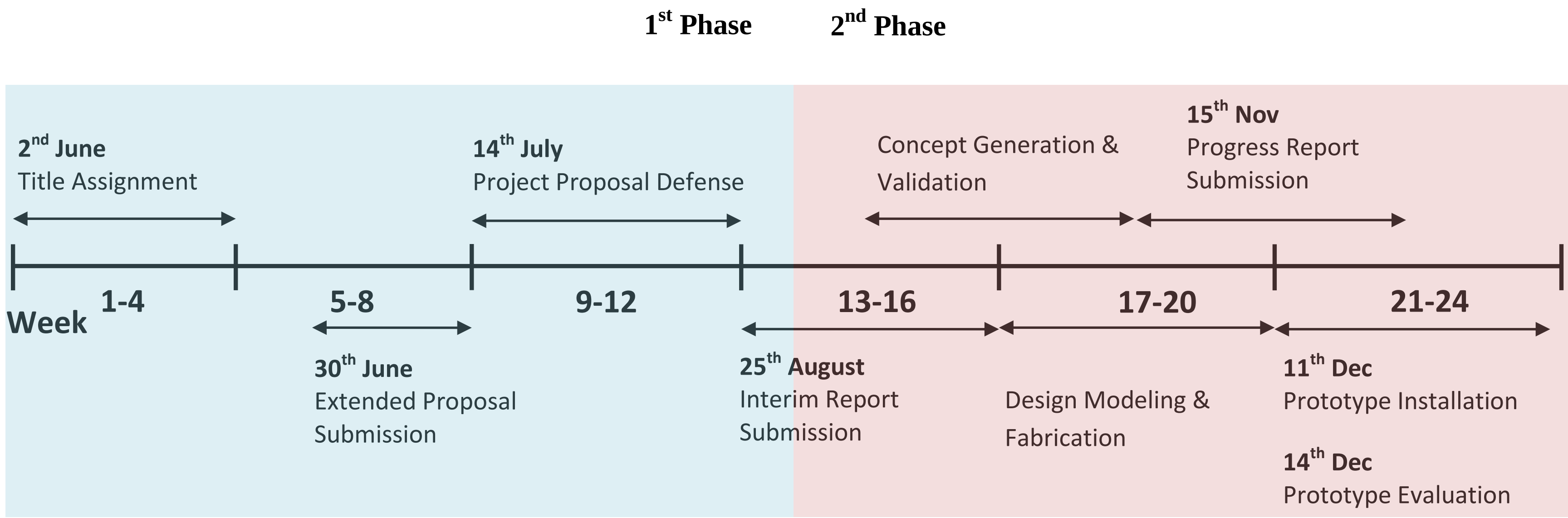
Physical and theoritical study on actual system on car and developed alternatives based on collected data.

3.2.2 Phase 2


Conceptual Design and Embodiment Design
Purpose:
To validate the best concept from several alternatives and produce system architecture and parametric design on the selected concept.
Method:
Carry out conceptual design and evaluation based on specified critical criteria and define concept based on actual on-market product.
Model Designing and Fabrication
Purpose:
To produce detailed design of the selected concept and converts the concept into a physical working prototype.
Method:
Define physical dimension of the design including material selection and carry out fabrication and installation on exhaust pipe.
Model Evaluation
Purpose:
To validate functionality and compatibility of the product in accordance to required specifications and targets.
Method:
Integration of product in system and real time testing and analysis of structure and performance.

3.3 PROJECT MANAGEMENT

3.3.1 Study Plan



3.3.2 Gantt Chart and Key Milestone

Gantt Chart																								
Month	**May**		**Jun**				**Jul**				**Aug**				**Sept**				**Oct**				**Nov**	
Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Task																								
Project assignment and introduction																								
Liaison with particular parties																								
Research and acquire project details																								
Theoritical and experimental data gathering																								
Exhaust system parameters modelling																								
Data analysis and report documentation																								
Proposed conceptual working system																								
Conceptual design and validation process																								
Model design and parameters specifications																								
Design approval and material acquisition																								
Prototype fabrication and installation																								
Prototype evaluation and data gathering																								
Documentation report																								

CHAPTER 4

RESULT AND DISCUSSION

4.1 EXPERIMENTAL STUDY ON THERMOELECTRIC GENERATOR

A basic construction of TEG panel comprises of Peltier Chips sandwiched between two plates of highly heat conductive material, normally aluminum. While one side of the plate receive the energy from the heat source, the cold side releases the heat energy to the surrounding as it passes through the chips where conversion of energy takes place.

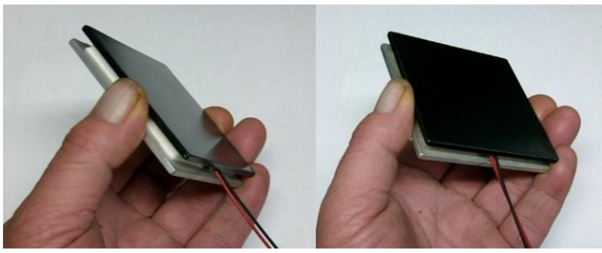


Figure 4.1: Basic construction of TEG

A simple experiment is conducted to measure the performance of the acquired TEG by applying a heat source and heat sink to allow the generation of electricity which is then measured accordingly. The main objective of the experiment is to measure the maximum power produced through an extent of temperature difference and to study the characteristics of the TEG. The result of the experiment is as below.

Table 4.1: Experimental result on TEG

T_H [^oC]	T_C [^oC]	ΔT [^oC]	V [V]	I [A]	P [W]
80	40	40	14.0	0.15	2.1
105	55	50	15.0	0.32	3.0
150	65	85	15.5	0.80	12.4
200	80	120	15.5	1.00	15.5
250	110	140	15.5	1.25	19.4

Based on the experimental result, the following can be deduced:

- The potentiometer is of adjustable type in which the voltage output can be control within the range of 0-15.5V.
- The current on the other hand remains constant as it depends on the load (temperature difference) itself whereby in this case remains constant as well.
- Since the voltage is limited, the next steps to increase the power output would be to increase the current via the load on the TEG panel.
- As the temperature increases, the current, I and the electrical power, P increases.
- The above panel temperature, T_C increases along with the bottom temperature, T_H.

The electrical power is calculated by the equation, $P=IV^2$. The increase in power is correlated to the efficiency of the TEG panel itself which is given by;

$$\eta = \left(\frac{\Delta T}{T_H}\right)\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+{}^{T_C}/_{T_H}}\right) \quad (1)$$

However the equation above is limited to certain parameters especially the Figure of Merits of the panel which is give as

$$ZT = \frac{Electrical\ \ conductivity\ \ *Seebeck\ \ coeff\ .^2}{Total\ thermal\ conductivity} . T \quad (2)$$

Therefore, the parameters of the surrounding affecting the TEG panel define the operation of the panel itself. To enhance the performance of the panel, the following recommendations are made:

i. Application of thermal grease between the hot side of the panel and the heat source to enhance flow of heat over the surface.
ii. Installation of insulator between the cold side and the hot side of the plate to optimize the flow of heat across the Peltier Chips.
iii. Installation of high thermal conductivity material at the cold side of the panel to enhance heat lost from the cold side to maintain a fairly low temperature on the plate.

These recommendations alongside with the obtained results are useful in integrating the TEG panel into functioning design. However, it is critical to study as well the conductivity behaviour of the panel. Thus, a simple experiment is conducted to measure the temperature signatures across the three layers of the TEG panel, namely hot plate, Peltier chips and cold plate. The graph below shows an alternative manifestation temperature variation according to respective layer when the heat supplied is gradually increased.

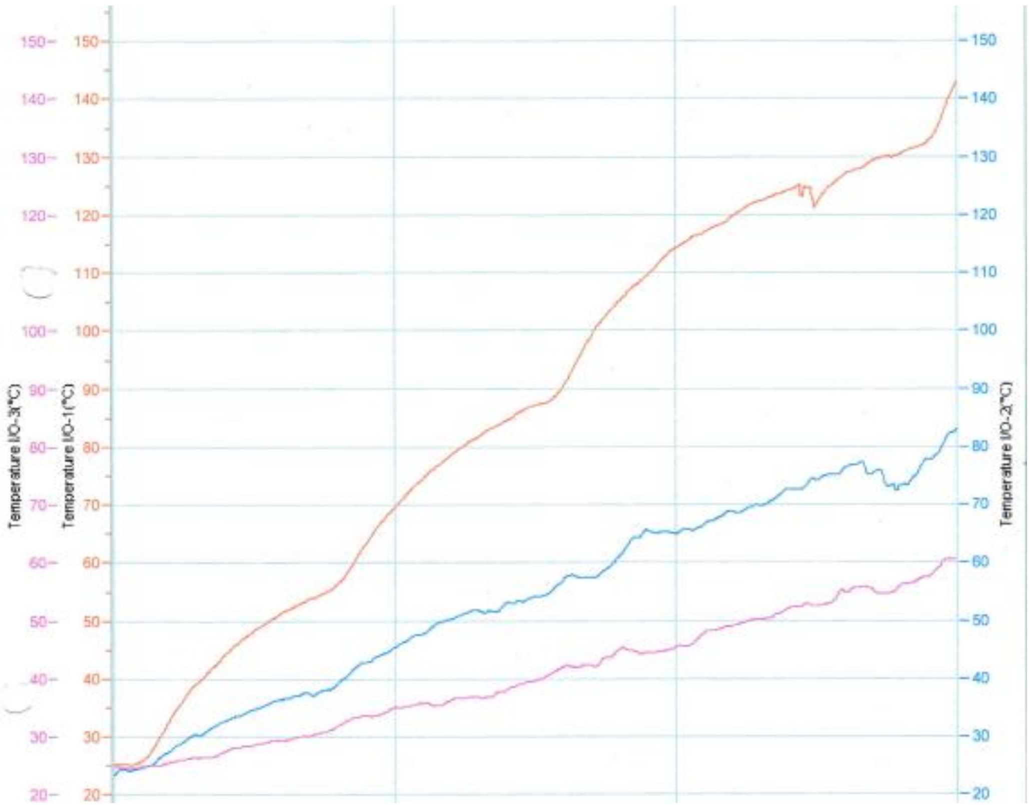
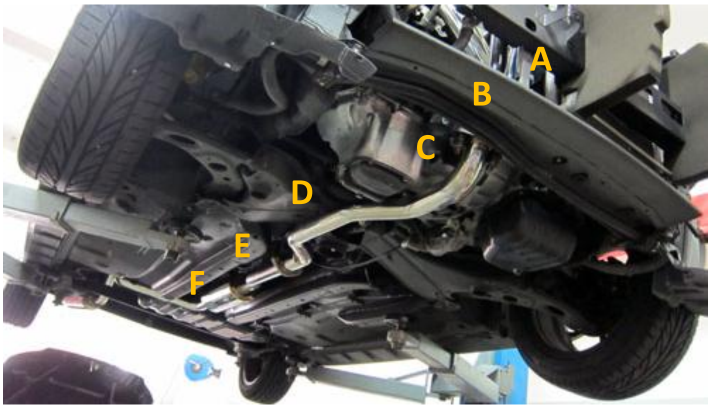


Figure 4.2: Temperature profiles across layers of TEG

As shown in the table above, as the temperature of the heat source increases, the hot plate (orange line) increases drastically as compare to the chips (blue line) and the cold plate (pink line). The temperature gap between the hot plate to Peltier Chips is significantly large which approximately 50 º C is while the temperature difference between the chips and the cold plate however is approximately 20ºC. However, due to unforeseen circumstances, the temperature of the heat source could not be raised any further thus providing fairly insufficient data on higher temperature region.

4.2 THERMAL ANALYSIS AND FEASIBILITY STUDY ON PERODUA MYVI EXHAUST SYSTEM

Another critical part would involve the analysis of the thermal signatures along the exhaust pipe of an actual Myvi. Six critical spots were identified as having potential for TEG installation. These spots were measured in temperature and feasibility study is conducted to determine the most conducive location that having high temperature heat source as well as feasible for TEG installation.



A-Exhaust Manifold

B-Catalytic Converter

C-Extension Pipe

D-Sensors Pipe

E-Resonator

F-Muffler

Experimental setup had been conducted on these six spots to obtain the temperature behavior across the exhaust pipe as it goes from the exhaust manifold to the tailpipe. As shown in the graph below, the temperature of the exhaust pipe drops drastically as the exhaust gas travels further. As the combusted gas travels across the exhaust pipe, it experienced pressure lost and drops in temperature as the heat is lost trough the cylindrical pipe.

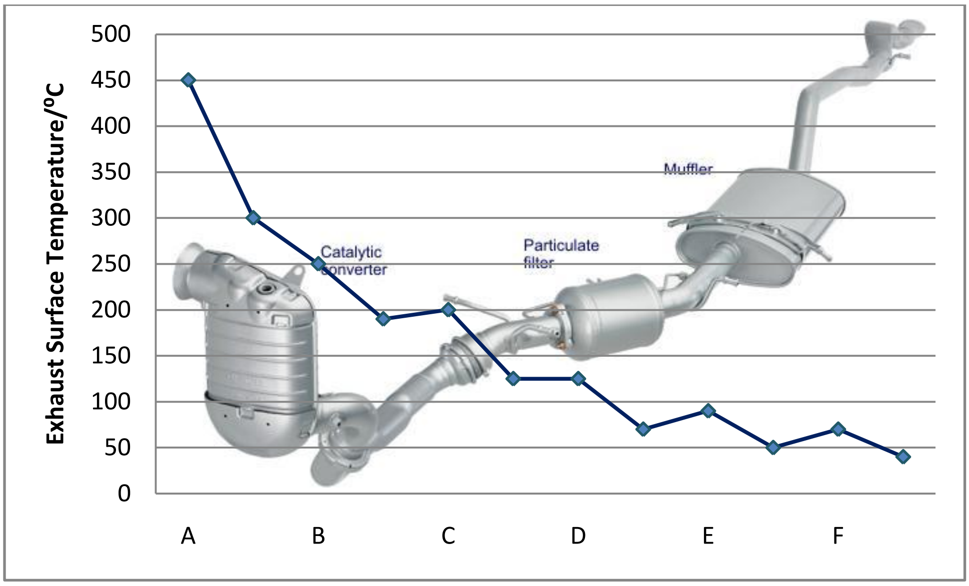


Figure 4.3: Surface temperature along exhaust system

Based on the result obtained, the ideal locations to place the TEG are across the location B to E since the optimum operation of the TEG is above 100°C for acceptable efficiency. Any temperature less than that would not produce sufficient power required. However, temperature greater than 250°C on the other hand would cause pose risk of damage to the TEG since the maximum operation temperature of the standard TEG is 300°C.

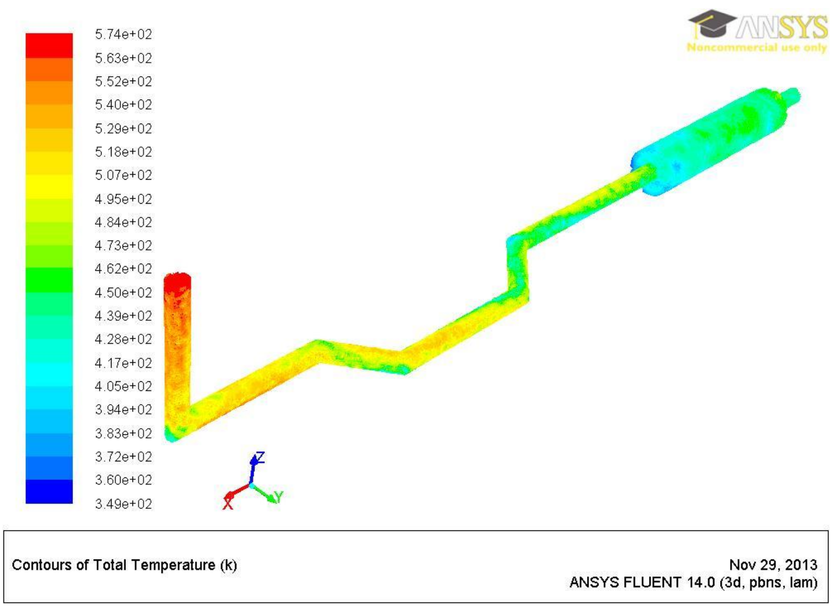


Figure 4.4: Simulated surface temperature across exhaust system

To compliment the experimental study, a simulation is conducted on ANSYS FLUENT software to validate the temperature profile across the exhaust pipeline. Geometrical setup is designed to represents the actual pipeline profiles as close as possible. A flow of hot air with 500°C temperature with a speed of 70 m/s is simulated as exhaust gas to flow across the designated pipeline. Figure 4.4 shows the temperature contour of the surface of the solid which shows a drastic drop of temperature as it travels further down the pipeline. The surface temperature records a drop of almost 200°C as the travelling fluid reaches the outlet of the solid. The simulation conducted validates the experimental study and thus provides important details of the potential locations to install the TEG.

Following that, a feasibility test is conducted to determine the suitability of each spot to host the TEG and is evaluated based on the following criteria as below.

i. Flat surface available would enhance the transfer of heat from the source to the hot plate with minimum lost to the surrounding.
ii. Possible area to mount the TEG would include any rigid or stable structure that could easily support or provide means for THE mounting.
iii. Sufficient empty space for TEG installation that maximizes the number of TEG applied.
iv. Greater heat source surface area to maximum flow of heat across to the TEG.
v. Require minimum modification either towards the exhaust pipe of TEG itself.
vi. Sufficient space for optimum design of heat sink either within the structural design of flow of cooling medium.
vii. Feasible installation and connection of electrical system for integration with the car power input.

Table 4.2: Matrix evaluation on different location of exhaust pipe

Criteria	Section of the Exhaust System					
	A	B	C	D	E	F
Flat surface area available			√	√	√	
Mounting area available	√		√	√	√	
Suitable space for TEG installment				√	√	√

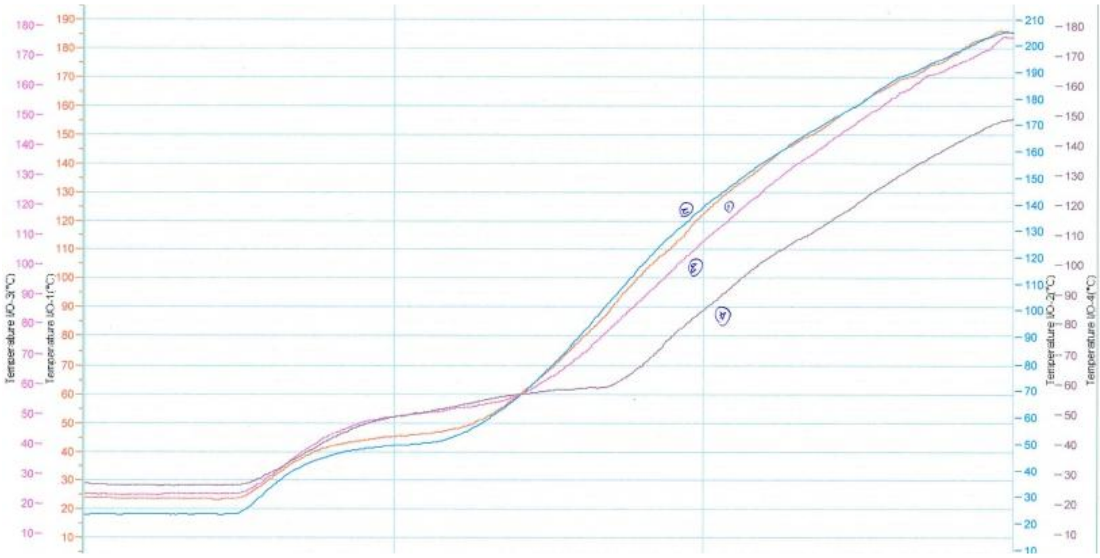
Optimum heat source surface area		√			√	√
Minimal modifications required for design	√					√
Feasible heat sink design	√	√		√		
Reasonable position for electrical system			√			

As shown in the chart above, the best ideal position to place the TEG would be across the D and E areas which are between the sensors and resonators of the exhaust pipe.

Figure 4.5: Sensor and Resonator Entry Pipe

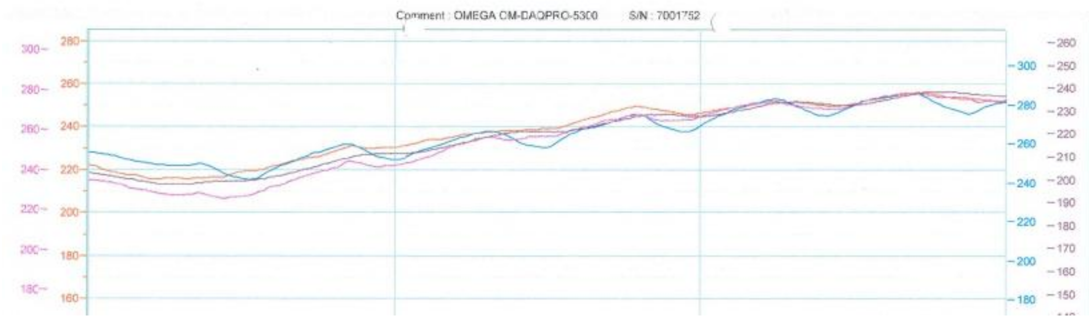
Thus, further experimental setup is conducted to analyze the temperature signatures of these locations over different engine speed. The result of the experiment is shown in the series of graphs below.

i. Engine start up (idle condition)

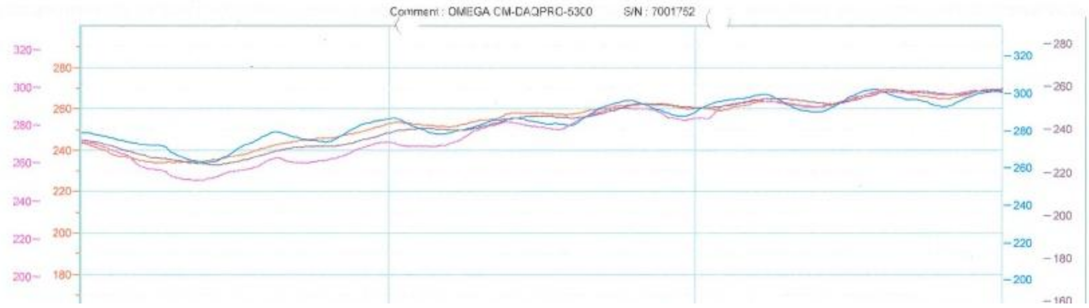


ii. Engine speed 2000 rpm

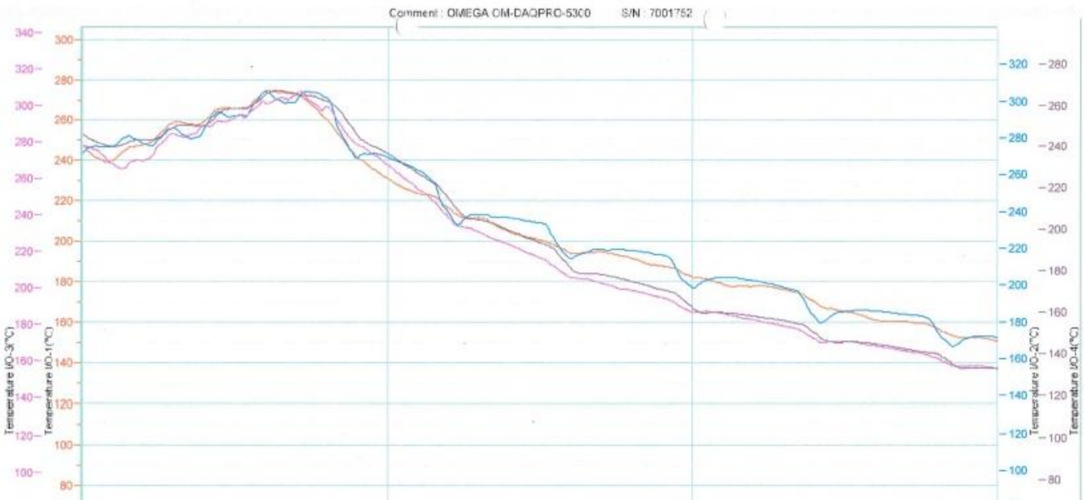
iii. Engine speed 2500 rpm



iv. Engine speed 3000rpm



v. Engine speed 3500 rpm and shut down



With respect to the graphs above, four thermocouple probes are placed at the ends of each section of the sensors and resonator of the exhaust.

- The first probe (orange line) measures the surface temperature of the front of the sensor pipe.
- The second probe (blue line) measures the surface temperature of the rear sensor pipe.
- The third probe (pink line) measures the surface temperature of the front junction of the resonator.
- The fourth probe (brown line) measure the surface temperature at the end of the resonator.

As shown in respective graphs, as the engine is started and stays idle at approximately 1000 rpm, the surface temperature of the exhaust pipe increase drastically up to an average of 190°C. As the engine speed is gradually increases, the surface temperature increases slowly up to an average maximum of 280°C. As the engine is stopped, the temperatures dropped slowly overtime as the exhaust pipe cools down. The result shows significant data of acceptable range of temperature across different engine speeds. This range of temperature determines the optimum operation of TEG. The reduction in temperature is due to energy lost in various forms especially thermal, kinetic, and chemical and latent heat.

4.3 CONCEPTUAL DESIGN OF TEG

Prior to any development phase, a conceptual drawing should be produced to ensure the proper operation of the design. Conceptual design enables the designer to draw a draft view of the actual system without constraining dimensions while being creative on the process. A conceptual design is the fundamental steps in any design which helps to remove any risk of missing element or malfunction in the integration of the components.

Four distinctive conceptual designs had been developed for the TEG which is shown in Appendix A.

Concept 2# is selected whereby it uses auxiliary blower to produce low-temperature with high-velocity flow of air across the cooling side of the TEG. This would increase the thermal conductivity of the system to removes optimum amount of heat from the TEG. However, due to constraint on the exhaust pipe, several modifications should be made on the design.

4.4 DETAILED DRAWING

Following the conceptual design is the embodiment design in which the concept is put into actual piece. This would include dimensioning, material selection and design validation. The following pages of the report show the detail drawings of the assembly and exploded design. The part design drawings could be found on the Appendix.

4.4.1 Assembly Design Drawing

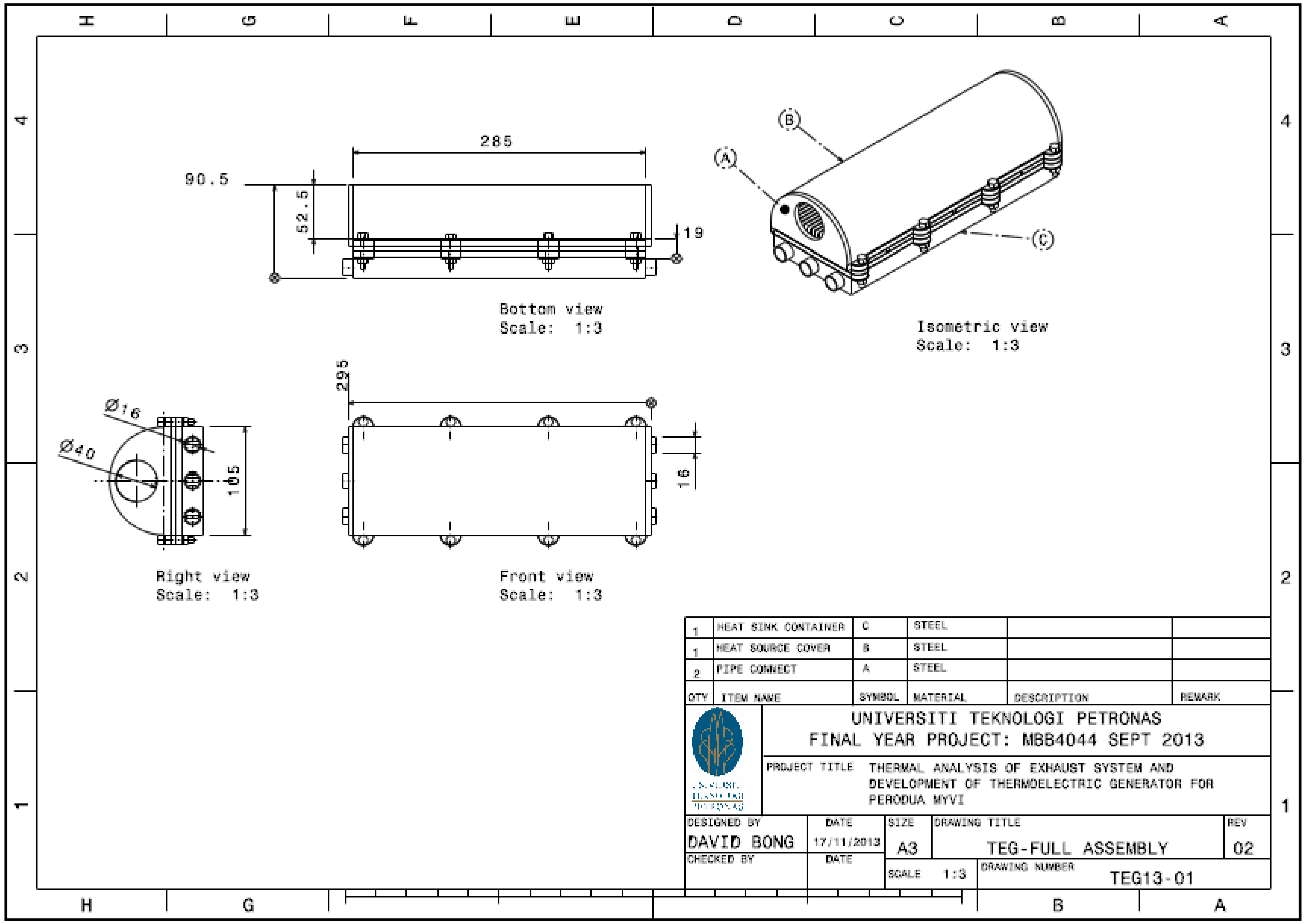


Figure 4.8: Assembly drawing of developed TEG

4.4.2 Exploded View Drawing

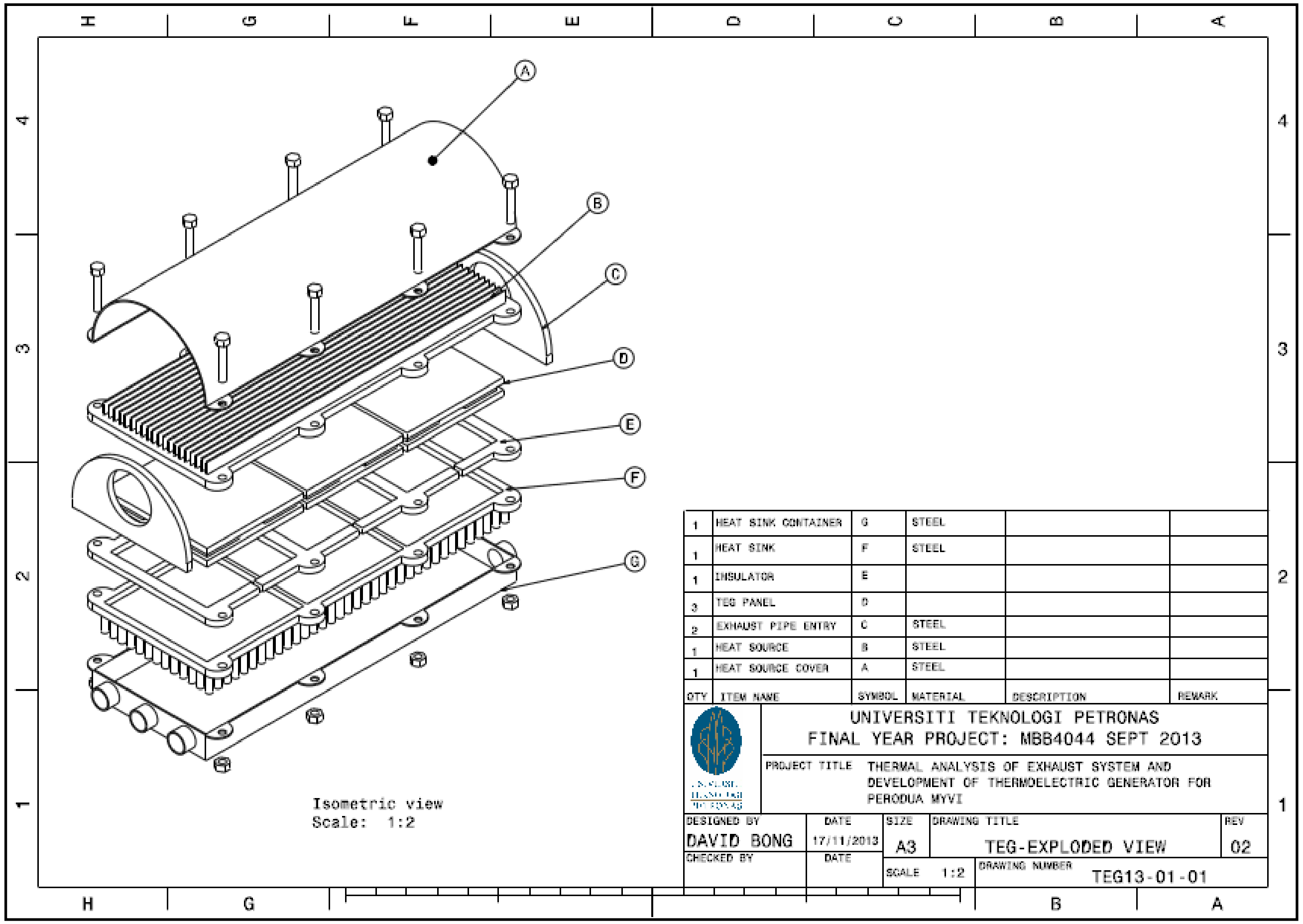


Figure 4.9: Exploded view drawing of the developed TEG

4.5 PARAMETRIC DESIGN

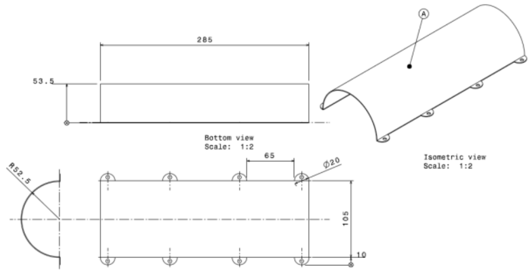
The developed TEG is designed in such a way that it could absorb heat effectively from the flowing exhaust gas while not imposing any restrictions on the flow itself. Any restrictions or irregularities on the flow of exhaust gas might cause back pressure to the engine and possibly reduce the ICE overall performance.

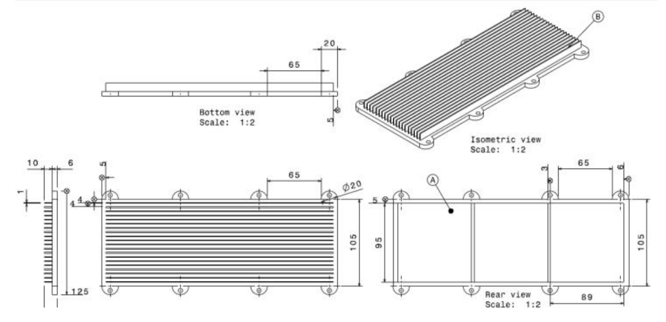
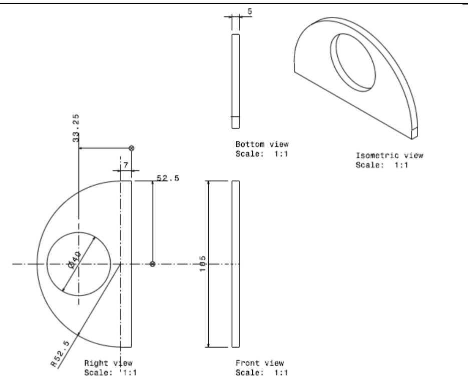
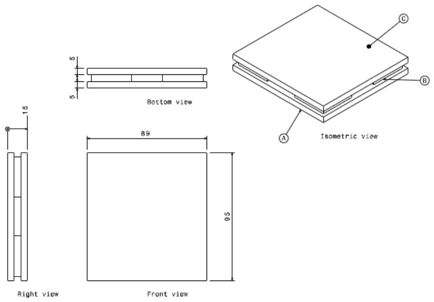
The development of TEG for Perodua Myvi comprises of three main challenges which are:

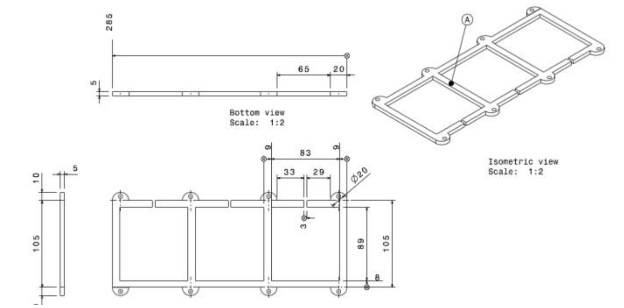
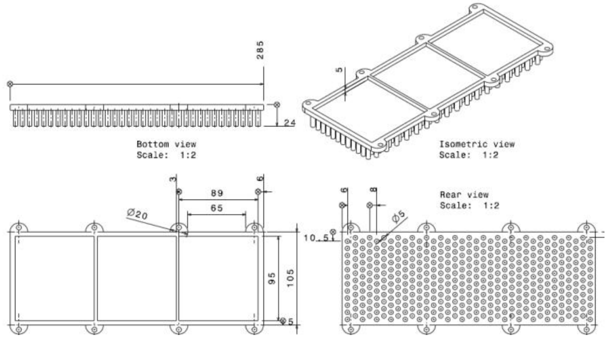
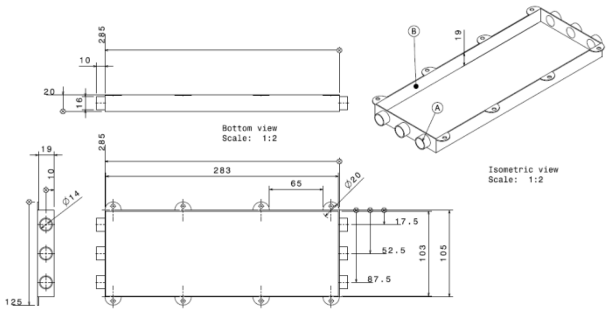
1. **Recapture waste heat** through installation on the exhaust pipeline.
2. **Transfer and remove heat efficiently** through the application of heat sink.
3. **Compact and firm structure in design** to fit on the lower floor of the car.

The designs of the TEG including its components are based on the parameters of the exhaust pipe and underneath floor profile of the car.

Table 4.3: Components of the developed TEG

No.	TEG Part Design	Function	Material	Description
1		<u>Heat Source Cover</u> Covers and contains the flowing exhaust gas.	Mild Steel	Designed semi-circle with tolerances on the radius to allow for exhaust pipe total diameter.

2		<u>Heat Source</u> Captures heat as the exhaust gas flows through the upper surface fins	Mild Steel	The heat fins are placed to increase surface area for better heat absorption with specified height and thickness to allow smooth flow of exhaust gas.
3		<u>Exhaust Gas Entry</u> Channels of input and output for exhaust gas.	Mild Steel	Semi-circle design is to allow sufficient connection for exhaust pipe. Thickness is specified to allow proper welding and leak-proof.
4		<u>TEG Panel</u> Allow flow of heat across the Peltier chips to produce electricity.	Non Specified	Four Peltier chips are sandwiched between two aluminium plates for each set of TEG panel. Three sets of the panels shall be integrated into the design.

5		<u>Insulator</u> Isolates and insulates two side of the TEG, the heat source and heat sink.	Ceramic	Low thermal conductivity of ceramic encourages heat transfer across the TEG panels. The design is such a way to fit between the layers of two sides.
6		<u>Heat Sink</u> Removes heat from the TEG panels to the surrounding or cooling medium.	Aluminium	The heat pins designed to increase heat transfer to encourage flows of heat across the panels of TEG. The pins can be fabricated via dye-sinker.
7		<u>Heat Sink Container</u> Contains and allows flow of cooling medium to removes heat from the heat sink.	Aluminium	The container not only channels flow of cooling medium but also act as a heat sink itself.

4.6 DESIGN OPTIMIZATION

Design optimization is carried out to identify necessary changes or modifications upon original design. This changes or modifications may be due to limited fabrication alternatives, the availability of material required or complications on system design.

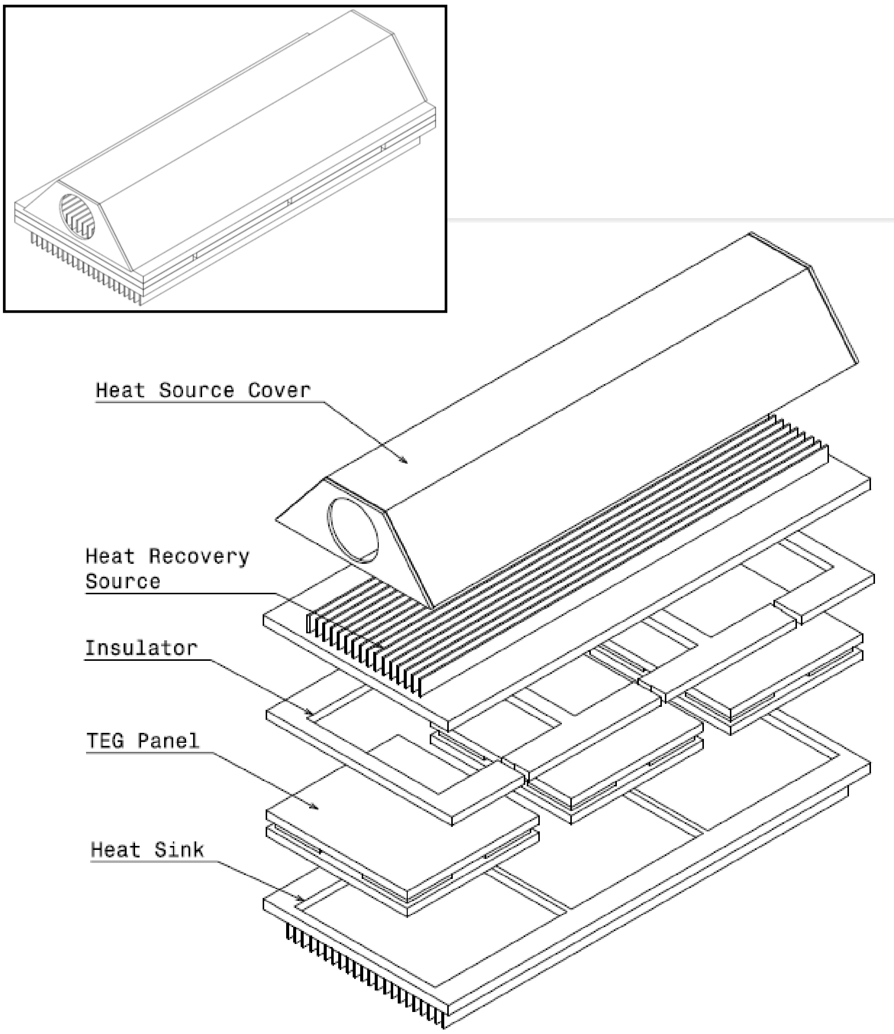


Figure 4.10: TEG Optimized Design

4.6.1 Optimized Heat Source Cover

The heat source cover is designed to be semi-hexagonal in shape instead of semi-circle. This is due to limited machinery equipment to roll into the required shape. Semi-hexagonal however is easily bend and fabricated from a sheet of metal. The parameters of the original design remain the same as to accommodate the exhaust pipe assembly. This includes the total length, width and height.

4.6.2 Optimized Heat Recovery Source

The features of the design are kept from the original with the addition of heat fins to allow more heat recovery. However, following the change of the cover, the height and distance between the fins are modified which resulted in decrease in height and arranged in a more-inwards manner.

4.6.2 Optimized Insulator

The insulator is installed to isolate the two distinctive layers of the TEG which are the hot and cold side. Thus, changes in features of the layers require changes in the insulator as well. Fabricated from ceramics, it is difficult to drill holes through the insulator. Thus, a new connecting mechanism is required to seal and secure all the layers in place including the insulator.

4.6.3 TEG Panel

There is no modification required on the TEG panels. Three sets of these panels shall be installed in place while ensuring proper orientation of the plates and connecting wires.

4.6.4 Optimized Heat Sink

The design shall utilized natural flowing air as the cooling medium to removes heat from the panels. This is due to complications and possibly further required additional auxiliary system to be installed to support other alternatives such as cooling water or forced flowing air. Heat fins are utilized instead of pins to ease fabrication process.

4.6.5 Optimized Assembly Mechanism

To hold all the layers in place, metal strap band with the addition of sealant is use instead of connecting bolts. The utilization of bolts may provide more secure assembly however the nature of different materials across the layers may causes complications such as thermal expansion and difficulty in assembly. Thus, a metal band is utilized instead.

4.7 FABRICATION AND INSTALLATION

The fabrication of the TEG is done according to the optimized design in which various methods are conducted to ensure proper finish and functionality. Once completed, the TEG is installed on an actual Perodua Myvi for further development.

4.7.1 Heat Source and Cover

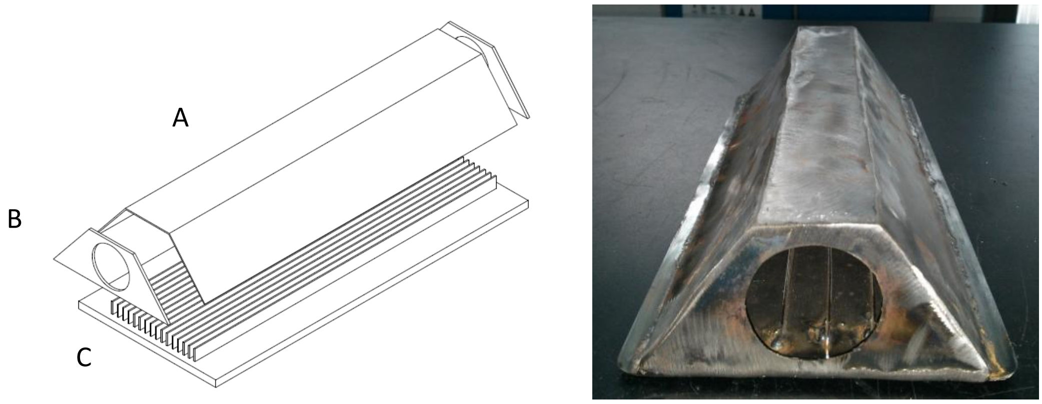


Figure 4.11: Heat Source Part

A sheet of mild steel of thickness 2mm is cut according to the designated shapes using metal sheet shear cutter. The upper part which is the cover (A) is marked and bent so as to produce a semi-hexagonal shape. A hole is drilled with a radius of 20mm at the centre of the heat source entry (B). Series of fins is welded on the foundation layer of the design (C). All the three components are welded accordingly and checked to ensure no cavities or faulty that may causes the exhaust gas to leak.

4.7.2 Insulator and TEG Panels

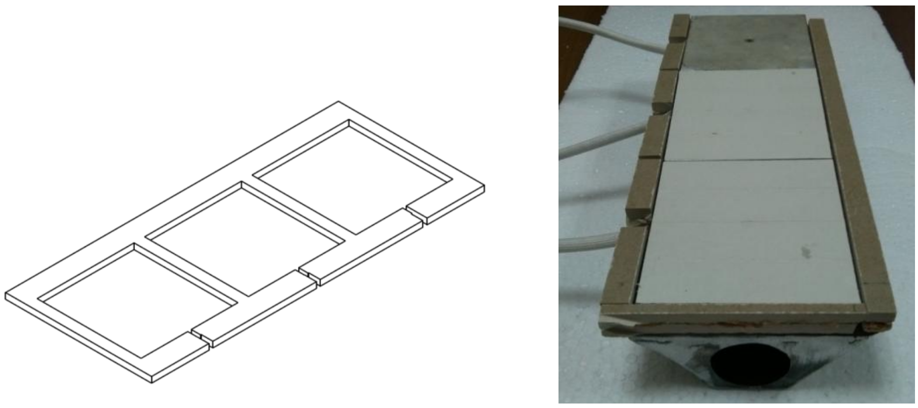


Figure 4.12: Installed insulator and TEG panel

The insulator is fabricated from a ceramic tile of thickness 5mm in which it is cut into several pieces resembling puzzles using tile cutter. These puzzles are arranged accordingly along the TEG panels while providing three gaps to accommodate for the output electrical wires. The ceramics are placed together using thermal resistant ceramic sealant. In addition, the two plates of the TEG panels are soaked with thermal paste to enhance thermal conductivity across the different layers as well as to fill in any cavities due to irregularities in shape or faulty.

4.7.3 Heat Sink

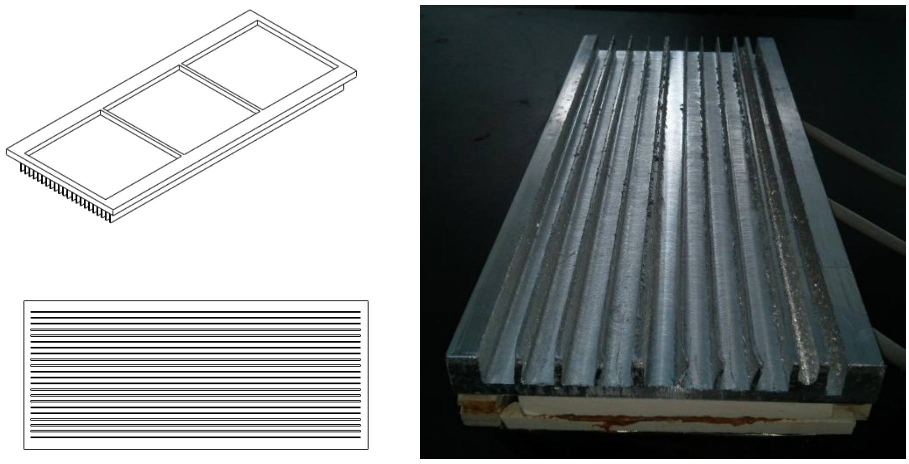


Figure 4.13: Heat sink

Using a conventional milling machine, the heat sink is fabricated by simply removing pieces from an aluminium plate of thickness 20mm. However, the aluminium plate must first be cut into the required length and width using the metal cutter tool. To increase accuracy and consistency in the fabrication process, the series of fins including necessary parameters are marked accordingly.

4.7.4 TEG Assembly and Installation on Exhaust Pipe

The TEG are inspected for proper assembly and measured in terms of specifications.

Table 4.4: TEG specifications

Thermoelectric Generator (TEG)			
Height (mm)	75.5	Length (mm)	295
Width (mm)	105.5	Weight (kg)	5.75
Material	Top part mild steel and bottom aluminium plate with ceramic in between		
Exhaust Pipe Connection	Inlet and outlet hole of diameter 40mm at both ends		
Power Output	Electrical cable of three DC output to controller at right side		

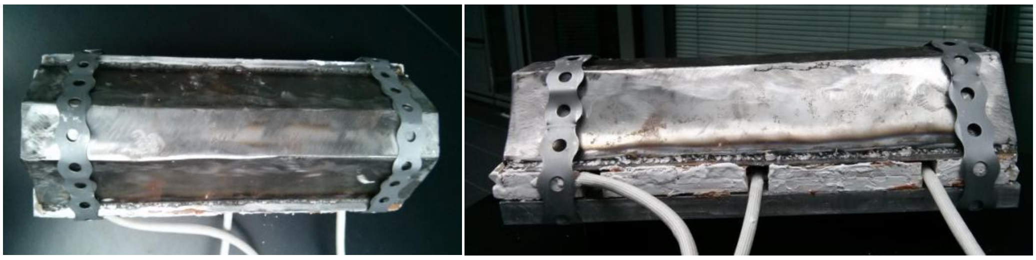


Figure 4.14: Full assembly of TEG

The components of the TEG are placed together using a galvanized metal strap. The connections of the strap as well as several critical spots on the strap such as the sharp bending edges are welded to the cover of the heat source to further secure the assembly. This is to ensure the full assembly would not fall off against natural challenges such as wind and thermal degradation as well as mechanical forces such as vibrations and aerodynamic drag.

Figure 4.15: Installation of TEG on exhaust pipe

The TEG is installed on the exhaust pipeline ahead of the resonator as per previous experimental study. To fit the assembly, the exhaust pipeline is removed from the car and cut at specified location. The TEG is placed on that particular location by welding the pipe on the heat source entry and exit of the design. The exhaust pipeline is then installed back to the car with additional support via exhaust hanger.

4.7.5 TEG Power Output and Electrical Connection

Figure 4.16: Connecting electrical output of TEG

The electrical output of the TEG is connected to the voltage regulator placed at the compartment part of the car. The voltage regulator monitors and regulates the voltage from the TEG to ensure consistent power supply to the car system as to not pose any risk of overload. The connection from the TEG is done by extending the output wiring through the gearbox console.

4.8 INTEGRATION INTO PERODUA ECO-CHALLENGE (PEC) 2013

The Perodua Eco-Challenge is an annual event as an initiative by the Malaysian Automotive Company to challenge higher learning institutions' engineering prowess and innovations as part of their Corporate Responsibility programme (CSR). As for

2013 in which the programme takes place at Shah Alam Go-Cart Circuit on December 2013, the challenge includes enhancement on current Perodua Myvi car to improve its fuel efficiency through endurance and its dynamics by time attack. In addition to that, the learning institutions are also to participate in the marketing challenge in which every team has to place efforts into promoting and induce publicity into their developed car.

Universiti Teknologi PETRONAS (UTP) along with eight other team participated in PEC 2013 in which the UTP team has developed Perodua Libero, a futuristic automobile which utilizes the urban lifestyle with fuel economy. The Libero is a new generation of Myvi which utilizes only the platform of the original car while the othe parts are developed from scratch.

Figure 4.17: UTP Team with Perodua Libero

Some of the main features of the Libero are two scissors door with adjustable front seats as well engineering products such as Solar Panel, TEG and electric pump to increase fuel efficiency of the car. As for PEC 2013, the UTP team had managed to grab two awards which are:

- First Runner-Up in Time Attack
- Second Runner-Up in Engineering Challenge

As part of the objective design of the competition, the integrated TEG into the car is hoped to not only increase fuel performance of the car, but also to further intensive research on better and more effective energy recovery system in a car

4.9 TEG MODEL VALIDATION

The installed TEG on Perodua Libero is placed into experimental testing to determine its actual performance. Two expected parameters of the testing are:

- Temperature across the layers of TEG
- Power output from the system

TEG functions through a temperature gradient across the layers and the aluminium fins at the bottom layer act as a heat sink to release heat to the surrounding. Thus, thermocouples are attached at both the heat source surface and the aluminium fins to determine the effectiveness of the heat flow across the layers. The voltage and current output on the other hand are measured using an oscilloscope which records the output over time. The setup of the experiment is shown in Figure 4.18.

Figure 4.18: Experimental setup to determine the performance of TEG

Due to several circumstances, the vehicle could not be placed on road testing. Thus, the vehicle is placed upon idle engine of 1000 rpm without any load to simulate stalling condition of a car. The data is collected for approximately 15 minutes until the steady high temperature achieved. The summary of the collected data is shown in Table 4.5.

Table 4.5: Experimental result summary

TEG Performance Testing			
Steady-State Cold Temperature, T_C	42.0^{o}C	Max. Voltage, V	14.2 V
Steady-State Hot Temperature, T_H	135.0^{o}C	Max. Current, I	2.6 A
Temperature Gradient, ΔT	93.0^oC	Max. Power, P	36.4 W

Upon idle condition, the temperature profiles of the TEG are shown in Figure 4.19 where the hot (red line) and cold (blue line) temperatures rise gradually with the cold side having a slightly lower rate. Both the temperature slowly reached a steady state at 135°C and 42°C after 10 minutes of idle engine condition.

Figure 4.19: Temperature profiles of TEG on idle condition

With respect to the power output, the voltage and current produced increase gradually and reached maximum of 14.2V and 2.6A which give a maximum power output of 36.4W. Figure 4.20 shows the profiles of the output.

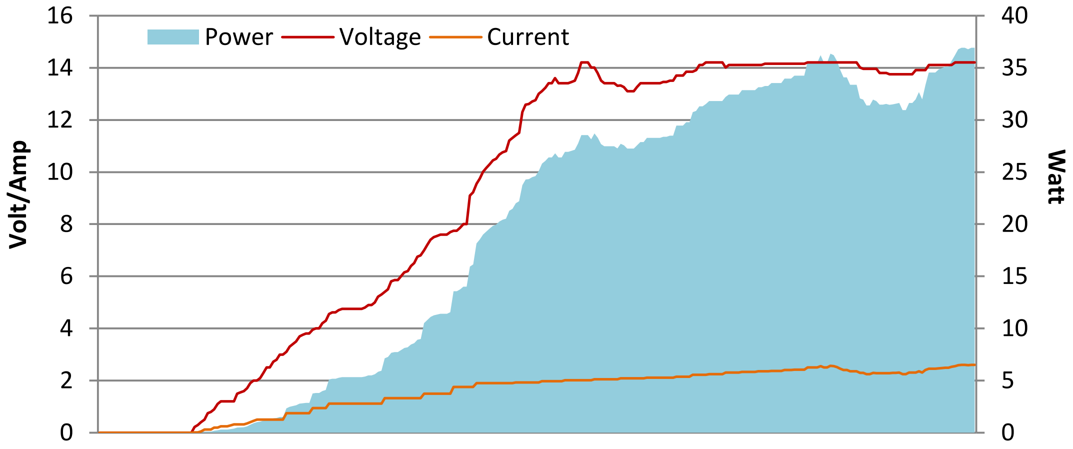


Figure 4.20: Power output of TEG

The above result has validates the functionality of the designed TEG on integration within the Perodua Libero. However, the performance itself could be improved as part of the future work of the project.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Development of a TEG on a Perodua Myvi requires various research and studies on mainly two different components of the design which are the exhaust system as well as the thermoelectric devices. Experimental studies and simulation had been conducted on the exhaust system to acquire two crucial data. The first one would be the temperature range along the exhaust pipeline while the later is the feasibility study of TEG installation. The exhaust pipe ahead of the resonator is identified as the most ideal locations as it bear significant range of operational temperature as well as feasible in terms of space. The thermoelectric panels on the other hand are lack of data thus requires further studies to identify its true potential. Thus, experimental result suggested these panels capable of producing up to 20 watts of power.

These two critical components provide necessary information to further building a design for the prototype. The design however should not only comply with the requirements or maximum potential of the device, but also in terms of ease in fabrication and material acquisition. Thus, the design had undergone several changes over the project period and finally be fabricated and installed on Perodua Libero. Final testing has shown the designed TEG capable of producing 36.4W of power while harnessing heat energy through a temperature difference of almost 100°C. Further studies on the design may increase the energy density production.

By the above, the project has achieved its objectives and manages to validate the concept of waste energy recovery by capturing heat energy from the exhaust system and produces electrical power output. The result is hoped to bring an impact towards engineering an efficient car through waste energy recovery system. In addition, it would also open doors to greater opportunities and advancement in the technology which could provide more values and better performance.

5.2 RECOMMENDATIONS

Developed in less than six months, the TEG is not finite in performance and several modifications are identified which are seen as a possible improvements to increase the power output in particular.

5.2.1 Forced Fluid Cooling System

The power output a TEG depends on the temperature difference between its two plates. The greater the temperature difference, the more power it could produce. While the hot temperature due to exhaust gas is relatively constant, the temperature of the cold side however could be reduce further by introducing fluid with higher heat capacity such as water or coolant. This could be complimented with better cooling system such as multiple entry and auxiliary pump to increase fluid flow.

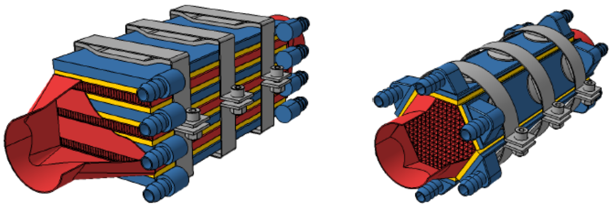


Figure 5.1: Conceptual designs of TEG

5.2.2 Arrays of Peltier Chips

The developed TEG utilizes a panel consisting of only four Peltier chips which responsible for the energy conversion. Reducing spaces and demonstrating an array of those chips would therefore provide greater potential for energy conversion and thus improving the power output produce.

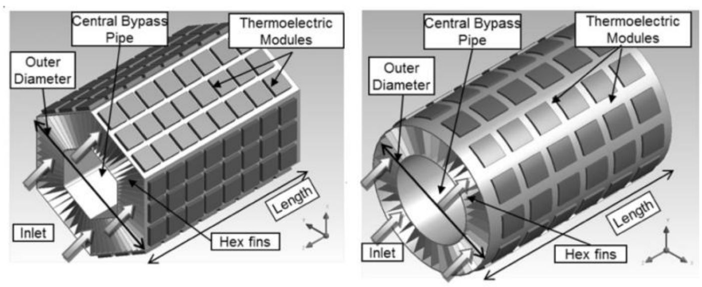


Figure 5.2: Arrays of Peltier chips on different orientations

5.2.3 Further Development of TEG system

With respect to its function, the developed TEG could be improvised in terms of several aspects which would not only improve its performance, but also from a marketing perspective.

- Fuel efficient concept
  Investigating the concept of harnessing waste heat energy to reduce fuel consumption of a car.
- Architecture
  Producing design which could increase power density and feasible for mass production and operation.
- Energy output
  Improvement on the overall system in steady states and dynamical states within driving cycles which could result in higher consistent power output.
- Hardware
  Utilization of materials which can withstand extreme temperature for optimum TEG operation.
- Improvement of overall system on conventional vehicles, hybrid or range extended vehicles.

REFERENCES

[1] Wang, Y., Dai, C. & Wang. S., 2012, "Theoritical analysis of a thermoelectric generator using exhaust gas of vehicle as heat source," Applied Energy Journal **(3):** 118-132

[2] Snyder. G. F. 2008 < http://www.electrochem.org/dl/interface/fal/fal08/fal08_p54-56.pdf>

[3] Kober. M., Hafele. C. & Friedrich. H. 2012, "Methodical concept development of automotive thermoelectric generators (TEG)" *in 3rd International Conference, Thermoelectrics goes automotive*

[4] 2010 <http://www.formula1.com/inside_f1/understanding_the_sport/8763.html>

[5] Lim, A. 2011<http://paultan.org/2011/06/16/2011-perodua-myvi-full-details-and-first-impressions/>

[6] 2012< http://www.khulsey.com/automotive-cutaway-generic-sedan.html>

[7] Stabler. F. 2012, "Automotive Thermoelectric Generator (TEG) Controls". *DOE Thermoelectric Workshop*

[8] Fairbanks. J. W. 2012, "Automotive Thermoelectric Generators and HVAC". *Department of energy conference*

[9] Vazquez. J., Palacios. R. & Arenas. A. 2012. *State of the art of thermoelectric generators based on heat recovered from the exhaust gases of automobiles.* University of Pontificia Comillas, Spain.

[10] Kumar. S., Heister. S. D., Xu. X. & Salvador. J. R. 2013, "Thermoelectric Generators for Automotive Waste Heat Recovery System Part 1: Numerical Modeling and Baseline Model Analysis," *Journal of Electronic Materials* **42(4)**

[12] Meisner. G. P. 2011, "Advanced Thermoelectric Materials and Generator Technology for Automotive Waste Heat" *GM. Thermoelectric Applications Workshop*

[13] Casano. G. & Piva. S. 2010, “Experimental investigation of the performance of a thermoelectric generator based on Peltier cells,” *Journal of Experimental Thermal and Fluid Science* **35:** 660-669.

[14] Lau. P. G. & Buist. R. J. 2010 <http://www.tetech.com/publications/pubs/ICT97PGL.pdf>

[15] Karri. M. A., Thacher. E. F. & Helenbrook. B. T. 2011, “Exhaust energy conversion by thermoelectric generator: Two case studies,” *Journal of Energy Conversion and Management* **(62):**1596-1611.

[16] Weng. C. & Huang. M. J. 2013, “A simulation study of automotive waste heat recovery using a thermoelectric power generator,” *International Journal of Thermal Sciences* **71:** 302-309.

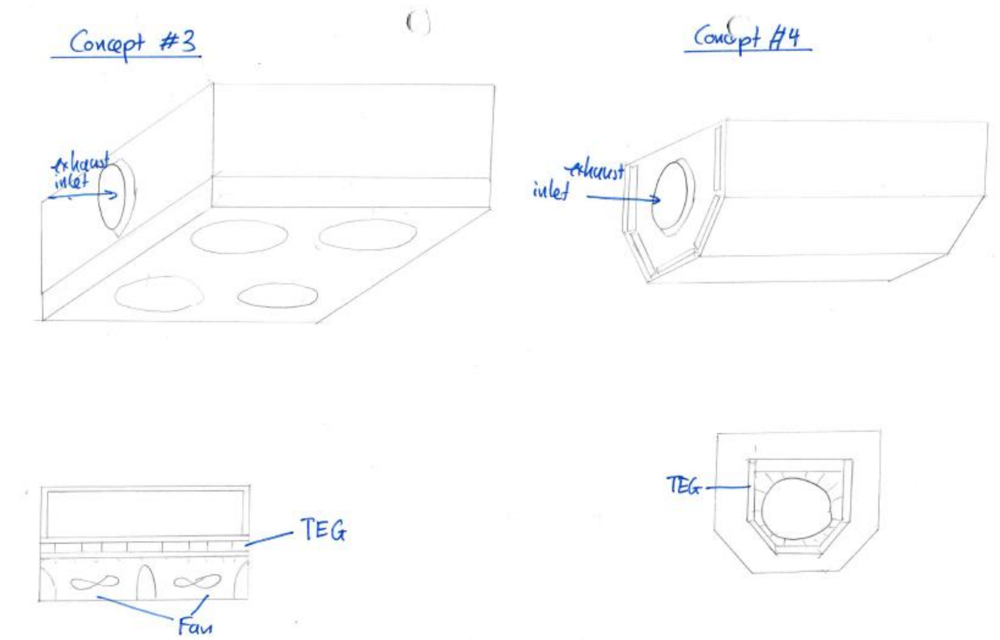
[17] 2009 <http://www.firestonecompleteautocare.com/cf/batteries/your-cars-electrical-system>

[18] 2008 <http://www.shoptireworld.com/exhaust.htm>

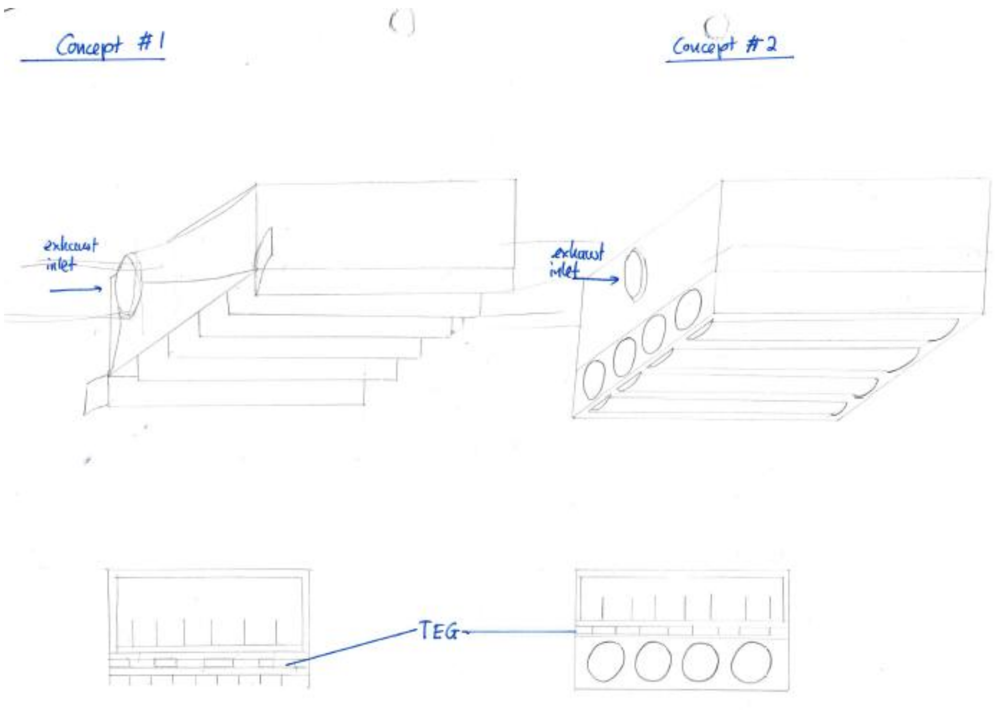
APPENDIX A

SKETCHES OF CONCEPTUAL DESIGN

Sketches #1 & #2



Sketches #3 & #4



APPENDIX B

PART DESIGN DRAWING