# DEVELOPMENT OF THERMOELECTRIC POWER GENERATOR (TEG) BASED HI-Z THERMOELECTRIC MODULES FOR AUTOMOTIVE WASTE HEAT RECOVERY

**MOHAMAD FIRDAUS SUKRI**

**RESEARCH VOTE NO:**
**PJP/2008/FKM (13)**

**Fakulti Kejuruteraan Mekanikal**
**Universiti Teknikal Malaysia Melaka**

**2011**

**ABSTRACT**

*(Keywords: Thermoelectric Power Generators, waste heat recovery, sustainable energy)*

In automobiles, coolant system is one of the systems that producing waste heat. This waste heat is a form of energy. It is neither created nor destroyed, but it is transformed. Therefore by using TEG, it is possible to transform waste heat from engine coolant to electricity. A lot of researches have been done to investigate the potential of exhaust systems as a source of heat for TEG compared to other components. In coolant systems, lack of research in this system is due to the low temperature of the coolant itself. Nevertheless, there is no detail investigation has been done yet. The advantage of TEG being installed in this system is it can reduce work done by the engine in cooling down the coolant temperature, thus more power produce by the engine can be used for other vehicle operations. Therefore, in this project, it is proposed to investigate the potential of this system as a source of heat for TEG. In this project, a model of coolant based-TEG with eight of HZ-20 thermoelectric modules are developed and fabricated for 4G13 SOHC Mitsubishi engine. Experimental investigations are done by using thermocouples and SF-902 Engine Dynamometer. In this research, the maximum power produced by the TEG is 1.36 W (theory) and 0.82 W (experiment) at engine rpm of 4000 rpm. The efficiency of this TEG at this point is 60%. It is due to highest operating temperature of the coolant and the TEG itself providing highest temperature to hot side area of the TEG.

**Key Researchers:**

Mohamad Firdaus Sukri (Head)
Nur Rashid Bin Mat Nuri
Shafizal Bin Mat
Mohd Afzanizam Bin Mohd Rosli

E-mail : mohdfirdaus@utem.edu.my
Tel. No. : +606-2333440
Vote No.: PJP/2008/FKM (13)

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# CHAPTER I

# INTRODUCTION

## 1.1 Background

Nowadays, the demands for electric power in automobiles are growing rapidly. It is due to many electronic devices installed in modern automobiles. Due to this reason, many researchers are focusing on finding new sustainable sources of electric power. The unstable and increasing of oil prices in the world market and low utilization of gasoline powered internal combustion engines makes it is necessary to generate new sustainable sources of electric power in modern automobiles. By generating new sustainable sources of electric power, the utilization of gasoline energy can be increased.

Hybrid vehicles, solar energy panels and thermoelectric power generators (TEGs) are the main alternative in providing sustainable and clean sources of electricity for powering modern automotive system [7]. It is therefore proposed a research to develop TEGs based Hi-Z thermoelectric modules for automotive waste heat recovery.

## 1.2 Problem Statement

In gasoline powered internal combustion engines, only 25% of energy generated is fully utilized for vehicle operation, while roughly 40% of the fuel energy is wasted in gas exhaust, 30% in engine coolant, 30% in engine, 5% for friction and radiated [5].

To increase the energy utilization, TEGs application in automobiles can utilize the waste heat in the exhaust heat or/and the waste heat in engine coolant [5].

## 1.3 Objectives

The objectives of this research are

a. to increase knowledge on TEGs in term of basic principles, how its work, application and etc,
b. to design, fabricate and test the TEG based on 4G13 SOHC engine,
c. to analyze the capability of this TEG, and
d. to investigate the effect of the application of TEG to the performance of the 4G13 SOHC engine.

## 1.4 Scopes

The scopes of this research are

a. application of TEG at coolant system on 4G13 SOHC Mitsubishi engine,
b. type of thermoelectric module is *HZ-20*,
c. 8 modules are used in design (fixed),
d. materials of TEG is Al 7075,
e. cooling technique during operation of TEG is forced convection by using fins and
f. experimental study is concentrating on power produced by the TEG, coolant temperature at inlet and outlet of the TEG and effects on the engine in term of torque and power produced by the engine.

# CHAPTER II

# LITERATURE REVIEW

## 2.1 Thermoelectric Module

A thermoelectric module relies on the "thermoelectric effect" to convert heat directly into electricity. Refer Figure 1.

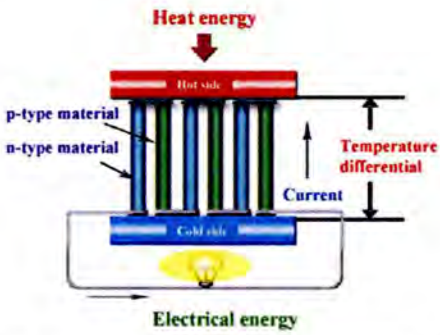


Figure 2.1: Mechanism of thermoelectric power generation [1]

The voltage produced is depending on Seebeck coefficient of the material, α and temperature difference between hot and cold side of the module as follow,

$$\Delta V = \alpha\ (T_{hot} - T_{cold}) \quad (2.1)$$

The two dissimilar legs are made of semiconductor material, one is p-type and the other one is n-type. The p and n legs are joined by an electrically conducting material at the p-n junction and are called a thermoelectric couple (TE) with p-n couples care connected electrically in series and thermally in parallel. One TE is the fundamental unit of thermoelectric module. Due to temperature difference, the negatively charged electrons in the n-leg are created and flows to the positively charged holes in the p-leg. The flow of electrons disturbs the original uniform charge carrier distribution and produces a current flow in the thermoelectric couple against the flow direction of electrons.

### 2.1.1 HZ-20

Hi-Z Technology, Inc is one of the thermoelectric module's manufacturers in the world. The products are HZ-2, HZ-9, HZ-14 and HZ-20, with capability to produce power up to 2, 9, 14 and 20 W respectively. Hi-Z modules are based on bismuth telluride semiconductor alloys and are most efficient in temperature ranges from -20°C to 300°C [4]. The bonded metal conductors enable Hi-Z modules to operate continuously for up to 10 years or longer. While Hi-Z modules are optimized as power generators the reversible thermoelectric effect allows them to be used as thermoelectric coolers.

The HZ-20 module consists of 71 thermocouples arranged electrically in series and thermally in parallel [4]. The thermocouples consists of "Hot Pressed", Bismuth Telluride based, semiconductors to give the highest efficiency at most waste heat temperatures as well as high strength capable of enduring rugged applications. The bonded metal conductors enable the HZ-20 module to operate continuously at temperatures as high as 250°C (480 F) and intermittently as high as 400°C (750 F) without degrading the module [4]. Table 1 and Figure 2 show the details properties and physical appearance of HZ-20 respectively.

Table 2.1: Properties of HZ-20 [4]

| **Physical Properties** | **Value** | **Tolerance** |
|---|---|---|
| Width & Length | 2.95" (7.5 cm) | ±0.01 (0.25) |
| Thickness<br>(Special Order) | 0.2" (0.508) | ±0.01 (0.25)<br>±0.002 (0.05) |
| Weight | 115 grams | ±3 grams |
| Compressive Yield Stress | 10 ksi (70 MPa) | minimum |
| Number of active couples | 71 couples | ---- |
| **Thermal Properties** | | |
| Design Hot Side Temperature | 230°C (450°F) | ±10 (20) |
| Design Cold Side Temperature | 30°C (85°F) | ±5 (10) |
| Maximum Continuous Temperature | 250°C (480°F) | ---- |
| Minimum Continuous Temperature | none | ---- |
| Maximum Intermittent Temperature | 400°C (750°F) | ---- |
| Thermal Conductivity* | 0.024 W/cm*K | +0.001 |
| Heat Flux* | 9.54 W/sqcm | ±0.5 |
| **Electrical Properties (as a generator)*** | | |
| Power** | 19 Watts | minimum |
| Load Voltage | 2.38 Volts | ±0.1 |
| Internal Resistance | 0.3 Ohm | ±0.05 |
| Current | 8 Amps | ±1 |
| Open Circuit Voltage | 5.0 Volts | ±0.3 |
| Efficiency | 4.5 % | minimum |

* At Design Temperatures

** At Matched Load, refer to the graphs for properties at various operating temperatures and conditions.

Figure 2.2: HZ-20 (cold side view) [4]

## 2.2 Thermoelectric Power Generator (TEG)

TEG is a solid state 'heat engine' capable of converting heat to electricity (Seeback effect) or alternatively capable of converting electricity into cooling effect (Peltier effect). TEGs are constructed base on the three factors that are source of heat, type of cooling system, and required electric power. The source of heat included radioactive materials, fossil fuels and waste heat. In space applications, radioisotope TEG has been used since 1960s, while fossil fuel powered TEGs has been used in military applications [3].

Application of TEGs in automotive, sometimes called Automotive Thermoelectric Power Generator (ATEG) can increase the efficiency of an internal combustion engine due to it recover waste heat in the engine to electricity. This electricity can be used to power electronic devices on the automobile, charging battery or even possible to power alternator of the engine. There are two types of TEG; exhaust-based TEGs and coolant-based TEGs [6]. The exhaust-based TEGs convert heat lost in the exhaust whereas the coolant-based TEGs convert heat lost in the coolant engine to electricity. A TEG consists of three main components; hot side heat exchanger, cold side heat exchanger and thermoelectric materials (TEMs) [6].

The function of hot side heat exchanger is to extracting waste heat and delivering this heat to the surface of TEM. The cold-side heat exchanger is responsible for dissipating heat from TEM to prevent damage on TEM due to high temperature and providing the possible lowest temperature of cold side area of the TEM for generating higher voltage.

### 2.2.1 Development History of TEG

Up to now, the development of TEG is too concentrating on exhaust-based TEG. It is due to high operating temperature of exhaust compared to coolant operating temperature, thus providing opportunities to produce higher voltage. According to Wong [6], exhaust system temperature can go up to 900°C whereas the operating fluid in radiator reaches maximum 120°C only.

The first TEG was built by Neild in 1963 [6]. In 1988, Birkholz published the results that describe an exhaust-based TEG which integrating Fe based thermoelectric materials between a carbon steelhot-side heat exchanger and an aluminium cold side heat exchanger in collaboration with Porsche. The TEG had produced multiple tens of watts out of a Porsche 944 exhaust system.

In early 1990s, an exhaust-based TEG designed by Hi-Z Inc could produce 1 kW from a 14 liter Cummins NTC 350 engine [2]. As shown in Figure 2.5, this generator uses seventy-two of Hi-Z's 13 Watt bismuth-telluride thermoelectric modules for energy conversion [2].

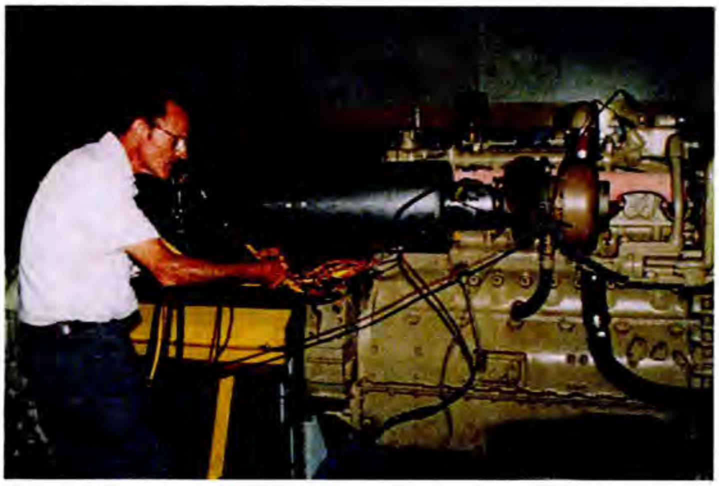

Figure 2.5: 1 kW generator mounted on Cummins NTC 350 engine [2]

## 2.3 Automobile Coolant Systems

A vehicle's cooling system is designed to protect the engine from the destructive forces of too much heat. The basic cooling system consists of liquid coolant being circulated through the engine, then out to the radiator to be cooled by the air stream coming through the front grill of the vehicle. If this system is not working properly, simple tasks such as sitting idle in rush-hour traffic can cause a vehicle to overheat even when temperatures drop below the freezing mark.

Cooling system must maintain the engine at a constant temperature in any surrounding conditions by transferring the heat from the coolant to the surrounding air. If the engine temperature is too low, fuel economy will suffer and emissions will rise. If the temperature is allowed to get too hot for too long, the engine will self destruct.

In automobiles with a liquid-cooled internal combustion engine, a radiator is connected to channels running through the engine and cylinder head, through which a liquid (coolant) is pumped. This liquid may be water or a mixture of water and antifreeze. Radiators are typically mounted in a position where they receive airflow from the forward movement of the vehicle, such as behind a front grill. Where engines are mid- or rear-mounted, it is common to mount the radiator behind a front grill to achieve sufficient airflow, even though this requires long coolant pipes. Alternatively, the radiator may draw air from the flow over the top of the vehicle or from a side-mounted grill.

In general, cooling system is made up from the passages inside the engine block and heads, a water pump to circulate the coolant a thermostat to control the temperature of the coolant, a radiator to cool the coolant, a radiator cap to control the pressure in the system, and some plumbing consisting of interconnecting hoses to transfer the coolant from the engine to radiator. The typical automotive components of cooling system are shown in Figure 2.6. This system works by continuously pumping a liquid coolant through passages in the engine block and heads. As the coolant flows through these passages, it absorbs heat form the engine. The heated fluid then travels through a hose to the radiator. As it flows through the thin tubes in the radiator, the hot liquid is cooled by the air stream. After the fluid is cooled, it returns to the engine to absorb more heat.

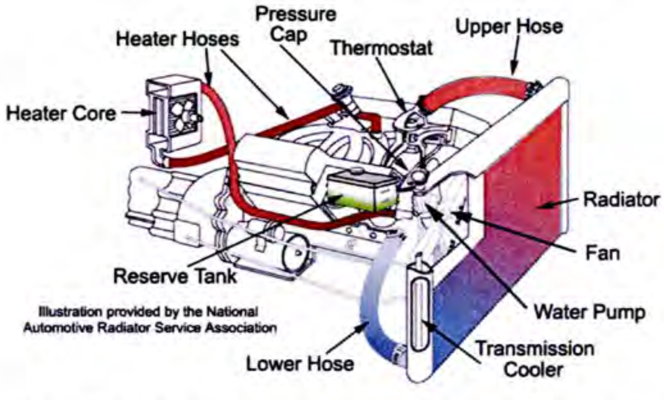


Figure 2.6: Typical automotive components of cooling system [6]

A thermostat is placed between the engine and the radiator to control the coolant stays above a certain pre-set temperature. It only allows the coolant flow to the radiator if the coolant temperature above this temperature. Otherwise the thermostat blocks and forcing the fluid directly flow back to the engine. The coolant will continue to circulate like this until it reaches the design temperature where the thermostat will open its valve and allow the coolant pass to the radiator.

# CHAPTER III

# RESEARCH METHODOLOGY

## 3.1 Introduction

In general, the process flow of this project is shown in Figure 3.1. Project will starts with literature review and ended with final report. During project, there were three (3) major activities. These are,

a. theoretical study,
b. designing process of TEG, and
c. experimental study.

## 3.2 Project Flow Chart

The project flow chart of this research is shown in Figure 3.1. The activity of manufacturing process in this project is done out source since this project is not looking at the manufacturing aspects.

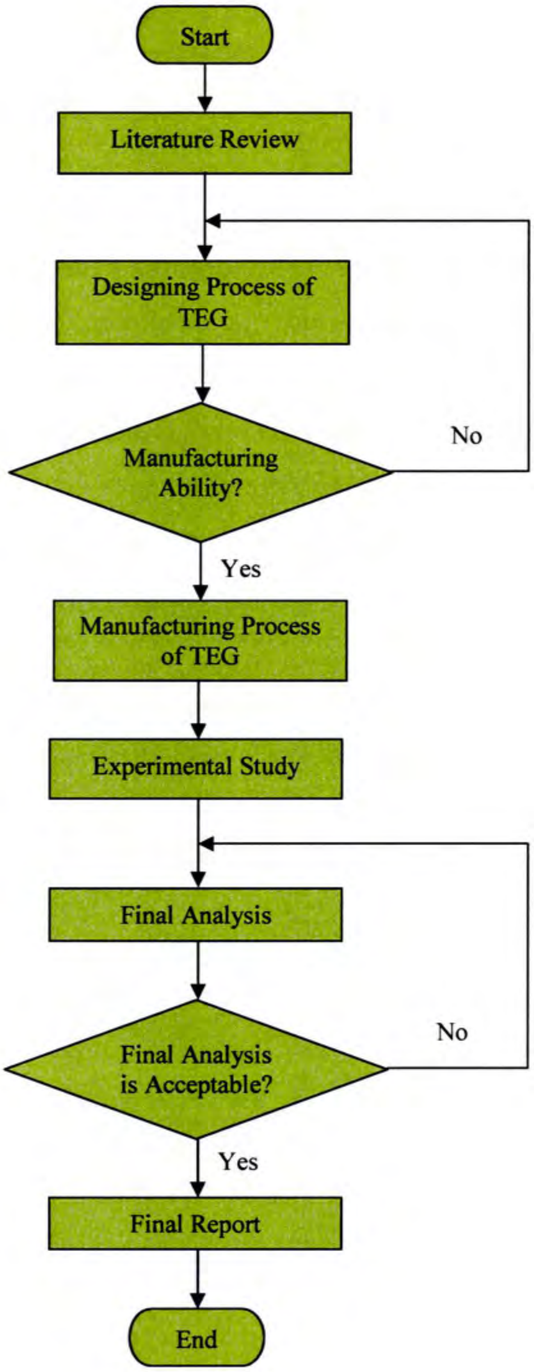


Figure 3.1: Project flow chart

The aim of designing process is to design the TEG based on few constrains. The length of the TEG is based on 4 modules of HZ-20 with connected by fins in the top and bottom. Solidwork is used for designing process.

The material of this TEG is 100% from Aluminimum 7050 series. It is efficient as a heat conductor and cheaper compared to Copper. This type of aluminium is also chosen due to its hardener properties make it available for wide range of manufacturing process.

The critical process in manufacturing process is during producing fins. The fin is expected to as much as possible along the length of the TEG in order to provide maximum area for cooling process. Therefore, wire cut machine is used to produce fins with gap 2 mm for each 2 mm-fin.

Experimental study is done by using SF-902 Engine Dynamometer. This testing is done by installing the TEG between outlet flow of coolant from engine and inlet flow of coolant to radiator. This testing is conducted at Advance Technology Training Center (ADTEC) Taboh Naning, Alor Gajah Melaka.

# CHAPTER IV

# EXPERIMENTAL STUDY

## 4.1 Introduction

The experimental study was conducted into two categories. First is without TEG as shown in Figure 4.1 and second is with TEG as shown in Figure 4.2. Result from the first experimental study is used to justify result from the second experimental study in term of the effect of the TEG to the performance of the engine. During the second experimental study, few data for the TEG are also being taken and calculated to investigate its performance as shown in Table 4.4 and 4.5.

## 4.2 Dyno Testing for 1.3L 4G13 Mitsubishi Engine

In this experimental study, SF-902 Engine Dyno as shown in Figure 4.1 is used to measure power, *P* and torque, *T* produce by the engine. During experiment being conducted, the running crankshaft of the engine is attached to a system and special software called WinDyn Software is used to measure the power, *P* and torque, *T*. WinDyn has the capability to configure the units of measurement for horsepower, torque, vehicle speed, and all automatic atmospheric condition measurements. Procedures of SF-902 Engine Dyno can be referred to Appendix A.

Figure 4.1: SF-902 Engine Dyno

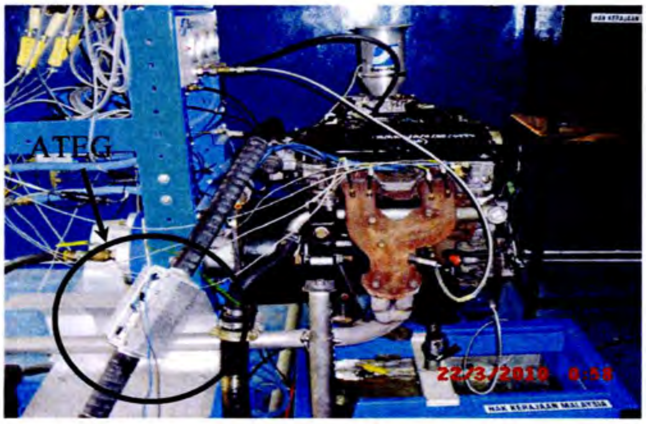


Figure 4.2: SF-902 Engine Dyno with TEG

## 4.3 Coolant Based-Thermoelectric Generator (TEG)

The TEG used in this research is shown in Figure 4.3. Detail drawings are shown in Appendix B. The physical properties of the TEG and fins are shown in Table 4.1 and 4.2 respectively.

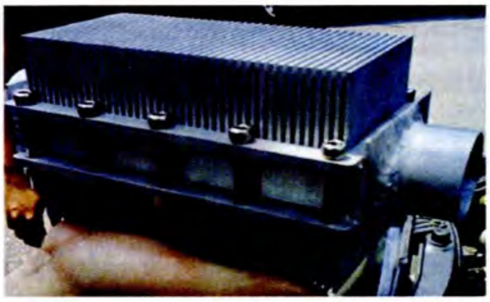

Figure 4.3: Coolant based-TEG

Table 4.1: Physical properties of coolant based-TEG

| Physical Properties | Dimension (mm) |
|---|---|
| Length | 246 |
| Width | 100 |
| High | 115 |

Table 4.2: Descriptions of the fin and modules for TEG

| Characteristics | Description |
|---|---|
| Material | Aluminum 7050 |
| Number of fins | 42 |
| Spacing between Fins (mm) | 2 |
| Thickness of each fin (mm) | 2 |
| Core depth (mm) | 35 |
| Number of HZ-20 module required | 4 |

## 4.4 Data of Experimental Study

Data generated from the SF-902 Engine Dyno is automatically saved onto the computer hard drive. Refer Appendix C. It is shown in Table 4.3 and 4.6.

### 4.4.1 First Experimental Study (Without TEG)

Table 4.3: Raw data of power and torque (without TEG)

| Engine speed (rpm) | Power (kW) | Torque (Nm) |
|---|---|---|
| 1275 | 2.2 | 16.2 |
| 1863 | 4.4 | 22.3 |
| 2090 | 21.7 | 99.0 |
| 2225 | 20.8 | 89.3 |
| 2855 | 24.7 | 82.6 |
| 3004 | 30.5 | 96.9 |
| 3346 | 32.8 | 93.6 |
| 3611 | 36.2 | 95.8 |
| 3915 | 38.1 | 93.0 |
| 4201 | 40.7 | 92.4 |
| 4476 | 42.1 | 89.9 |
| 4781 | 43.5 | 86.8 |
| 5060 | 45.3 | 85.5 |
| 5338 | 46.8 | 83.7 |
| 5568 | 48.1 | 82.6 |
| 5907 | 47.2 | 76.4 |

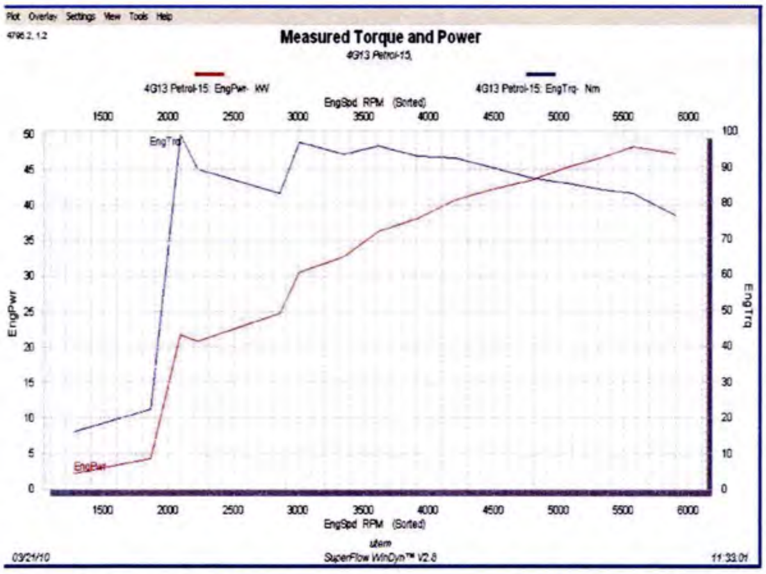


Figure 4.4: Graph of power versus speed (without TEG)

From the Figure 4.4, the maximum engine power for experimental study is 48.1 kW occurs when the engine speed is 5568 rpm. Meanwhile, the maximum engine torque is 99.0 N · m occurs when the engine speed is 2090 rpm.

### 4.4.2 Second Experimental Study (With TEG)

Table 4.4: Coolant temperature and theoretical power

| Engine Speed, $N$ (rpm) | Mass flow rate, $\dot{m}$ (kg/s) | Average Fin Temperature, $T_f$ (°C) | Coolant Temperature (°C) | | | | Theoretical Power (W) | |
|---|---|---|---|---|---|---|---|---|
| | | | [illegible] | [illegible] | [illegible] | $\Delta T$ | Power per Module | [illegible] |
| 1500 | 0.1023 | 56 | 65 | 60 | 62.5 | 5 | 0.03 | 0.12 |
| 2000 | 0.1129 | 58 | 73 | 69 | 71.0 | 4 | 0.10 | 0.40 |
| 2500 | 0.3273 | 64 | 89 | 83 | 86.0 | 6 | 0.29 | 1.16 |
| 3000 | 0.3425 | 67 | 94 | 87 | 90.5 | 7 | 0.33 | 1.32 |
| 3500 | 0.3710 | 68 | 96 | 88 | 92.0 | 8 | 0.34 | 1.36 |
| 4000 | 0.3988 | 69 | 98 | 88 | 93.0 | 10 | 0.34 | 1.36 |

Table 4.5: Experimental table for resistance and voltage

| Engine Speed, N (rpm) | Resistance, R (Ω) | Voltage, V (V) | [illegible] |
|---|---|---|---|
| 1500 | 0.27 | 0.13 | 0.06 |
| 2000 | 0.35 | 0.25 | 0.18 |
| 2500 | 0.58 | 0.54 | 0.50 |
| 3000 | 0.69 | 0.67 | 0.65 |
| 3500 | 0.89 | 0.84 | 0.81 |
| 4000 | 0.90 | 0.86 | 0.82 |

Table 4.6: Raw data of power and torque (with TEG)

| Engine Speed, N (rpm) | Power, [illegible] (kW) | Torque, [illegible] (Nm) |
|---|---|---|
| 1263 | 2.2 | 16.3 |
| 2162 | 13.2 | 58.5 |
| 1933 | 19.5 | 96.6 |
| 2301 | 20.3 | 84.3 |
| 2860 | 25.5 | 85.1 |
| 2993 | 30.0 | 95.8 |
| 3335 | 33.1 | 94.6 |
| 3615 | 36.0 | 95.1 |
| 3918 | 38.1 | 93.0 |
| 4204 | 40.4 | 91.7 |
| 4477 | 42.2 | 90.0 |
| 4788 | 43.4 | 86.5 |
| 5067 | 45.4 | 85.5 |
| 5342 | 46.7 | 83.4 |
| 5588 | 48.4 | 82.7 |
| 5884 | 47.0 | 76.3 |