Power Generation From Excess Heat Using Thermoelectric Material

by

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical/Electronics)

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CERTIFICATION OF APPROVAL

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Approved by,

(Mr. Zainal Arif Burhanudin)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
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CERTIFICATION 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 as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MOHAMMAD SYAHRIZAN SHAMSUDIN)

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In the completion of this final year project, it seems that an infinite number of people provide an immeasurable amount of guidance, idea and help. While my thanks goes out to all those that helped, I can only mention a few of many supporter here.

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ABSTRACT

Thermoelectric phenomena involve the movement of heat by an electric current or the generation of electric power from a thermal gradient. For this project, analysis on car radiator excess heat or waste heat is conducted. Power generation will be implemented by using the thermoelectric module utilizing the excess heat. Two different temperatures from car radiator will be used as the parameters in order to differentiate the need of the thermoelectric module. These parameters along with other appropriate consideration in thermoelectric application will be the most important element in obtaining the best design and completing the project. The aim of the project is to demonstrate the capability of the thermoelectric materials as power generator and to show that any waste heat can be one useful resource if it is carefully consider as valuable and beneficial for any practical reason. The task flow for this project would be focusing on the foundation of the project's principles, where the overall concept of the power generation will be planned and thus, specified according to the project's requirement. All findings and the detailed analysis including key elements of the project, which is to decide the parameters, and the design procedures that should be used, will be conducted as to follow the overall concept of the project.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

From thermoelectric materials, the excess heat produced from various sources (ranging from radiator, A/C unit, flare ground structure, etc.) shows the capabilities in producing and generates power. A thermoelectric module is a manufactured solid-state device that can operate as a heat pump or as an electrical power generator. The Thermoelectric Generator (TEG) using Seebeck Effect, in which it was discovered that an electromotive force can be produced by heating a junction between two dissimilar conductors (metals), (couples) and removing this heat thereby creating a temperature difference across the device, generating electricity. Seebeck utilizes the origin of thermoelectric that was first discovered by Jean Peltier, the passage of an electric current through the junction of two dissimilar conductors could either cool or heat this junction depending on the current direction. This is the leading principles that finally discover the potential and capability of thermoelectric materials in generating electricity.

1.2 PROBLEM STATEMENT

Currently there is no adequate information regarding the excess heat from the devices (radiator, A/C unit, flare ground structure) used in generating power using thermoelectric materials. Therefore, a project will be implemented in order to show the capability of thermoelectric materials as power generator using heat as the sources. The thermoelectric module, how it works, the thermal parameters needed (at least three parameters the hot surface temperature, the cold surface temperature, and the heat load to be absorbed at the cold surface is needed in an appropriate thermoelectric application) will be the main and important element in focusing the development of the power generation using the thermoelectric materials. Therefore, a need for a good planning will be conducted, especially in deciding the devices should be used for obtaining the excess heat and suitable parameters, the designing of the thermoelectric module and focusing every aspect and important element that should be consider.

1.3 OBJECTIVES AND SCOPE OF STUDY

In order to demonstrate power generation capability of a thermoelectric material from excess heat, the fulfillment of the following objectives is important:

- To select an appropriate devices to be used when demonstrating the power generation from the thermoelectric materials. This includes the design of the thermoelectric module and the device selection that produces the waste heat.
- To verify the best coefficient in mathematical modeling in the thermoelectric modules should be used.
- To prepare a technical report about the study made which will consist of research findings and recommendation.
- To show the simulation of a thermoelectric module that capable to generate power.

Due to constraint in time frame allocated, the scope for this project will be limited within the following boundaries:

- Research/study will only focus on one device that can give the best amount of heat before the thermoelectric modules is used in generating the power.
- Analysis and study will be concentrated more on the thermoelectric generator regarding the Seebeck Effect and Coefficient.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 THERMOELECTRIC MATERIALS

A range of semi-conductor thermoelectric devices working on the Peltier Effect. When supplied with a suitable electric current they can either cool or heat. When subjected to an externally applied temperature gradient these devices will generate a small amount of electrical power.

In 1834, Jean C.A Peltier discovered that the passage of an electric current through the junction of two dissimilar conductors can either be cool or heat and this junction of cool and heat depends on the direction of the current. Heat generation or absorption rates are proportional to the magnitude of the current and also the temperature of the junction. Peltier's experiments followed by thirteen years those of Thomas Seebeck, a physicist, in which it was discovered that an electromotive force can be produced by heating a junction between two dissimilar conductors (metals), (couples) and removing this heat thereby creating a temperature difference across the device, generating electricity.

The typical thermoelectric module is manufactured using two thin ceramic wafers with a series of P and N doped bismuth-telluride semiconductor material sandwiched between them. The ceramic material on both sides of the thermoelectric adds rigidity and the necessary electrical insulation. The N type material has an excess of electrons, while the P type material has a deficit of electrons. One P and one N make up a couple, as shown in figure 1. The thermoelectric couples are electrically in series and thermally in parallel. A thermoelectric module can contain one to several hundred couples.

As the electrons move from the P type material to the N type material through an electrical connector, the electrons jump to a higher energy state absorbing thermal energy (cold side). Continuing through the lattice of material, the electrons flow from the N type material to the P type material through an electrical connector, dropping to a lower energy state and releasing energy as heat to the heat sink (hot side). Thermoelectric can be used to heat and to cool, depending on the direction of the current. In an application requiring both heating and cooling, the design should focus on the cooling mode. Using a thermoelectric in the heating mode is very efficient because all the internal heating and the load from the cold side are pumped to the hot side. This reduces the power needed to achieve the desired heating.

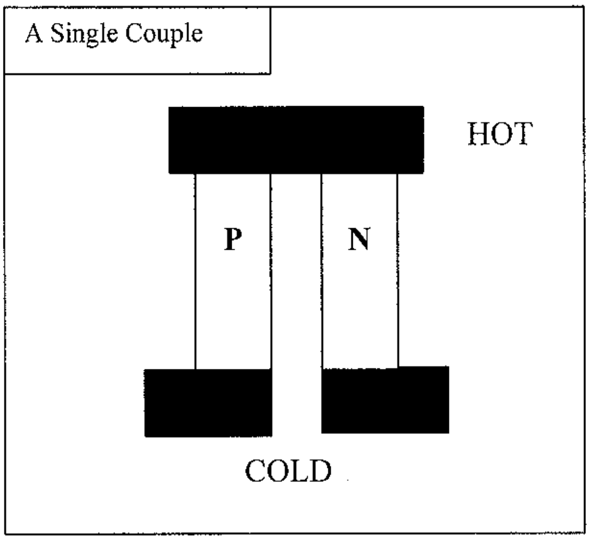

Figure 1: A single Couple

Semiconductors doped both p and n type form the elements of the couple and are soldered to copper connecting strips. Ceramic faceplates electrically insulate these connecting strips from external surfaces. The semiconductors material used is bismuth telluride as this shows the most pronounced effect at moderate operating temperatures.

The Features of the Thermoelectric Module consist of:

- Solid state, long term stability
- Capable of heating or cooling – dependent on current flow
- Generates no acoustic noise
- Capable of generating power

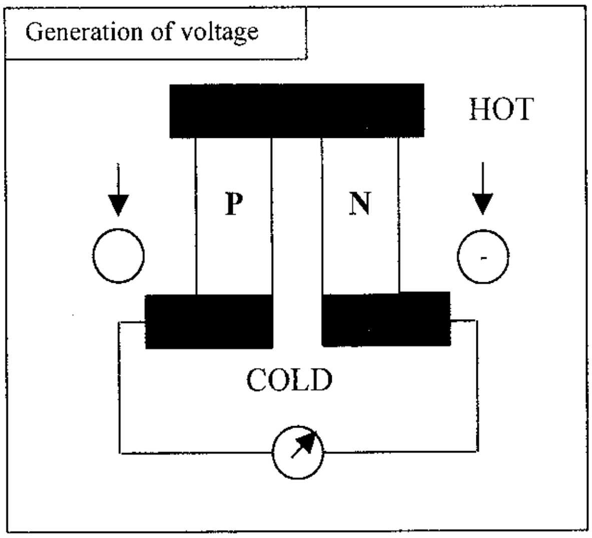

Figure 2: Generation of Voltage

At open circuit a temperature gradient maintained across the device creates a potential across its terminal proportional to the temperature difference. If the temperature difference is maintained, and if the device is connected to an electrical load power is generated.

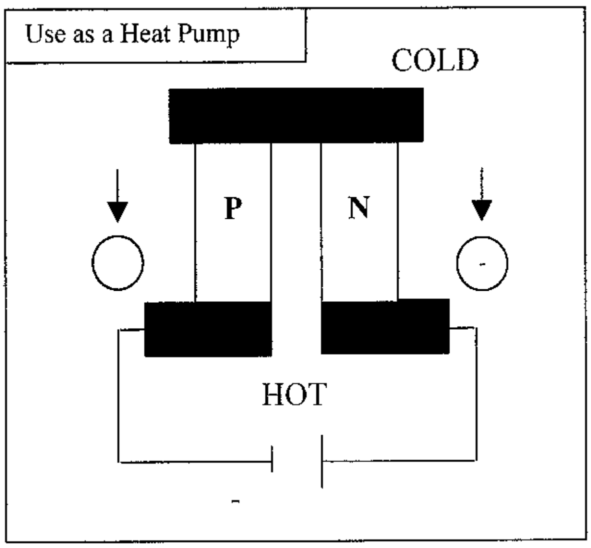

Figure 2: Heat Pump

If, instead the device is connected to a DC source, heat will be absorbed at one of the device, cooling it, while heat is rejected at the other end, where the temperature rises. Reversing the current reverses the flow of heat. Therefore the module can generate electric power or depending on how it is connected to external circuitry, heat or cool an object.

A common misconception is that the peltier device somehow absorbs heat and carries it away, perhaps with the electric current. This is simply not true. The device only transfers or pumps heat from one of its sides to the opposite side. At the hot side, the heat must be removed through the use of a heat sink or by some other means. It is important to realize that the heat delivered to the hot side of the device includes the pumped heat plus the electrical power dissipated within the devices.

The thermoelectric semiconductor material most often used in today's thermoelectric field is an alloy of Bismuth Telluride that has been suitably doped to provide individual blocks or elements having distinct "N" and "P" characteristics. Thermoelectric materials most often are fabricated by either directional crystallization from a melt or pressed powder metallurgy. Each manufacturing method has its own particular advantage, but directionally grown materials are most common. In addition to Bismuth Telluride (Bi_2Te_3), there are other thermoelectric materials including Lead Telluride (Pb-Te), Silicon Germanium (Si-Ge), and Bismuth-Antimony (Bi-Sb) alloys that may be used in specific situations.

Bismuth Telluride-based thermoelectric modules are designed primarily for cooling or combined cooling and heating applications where electrical power creates a temperature difference across the module. By using the modules "in reverse," however, whereby a temperature differential is applied across the faces of the module, it is possible to generate electrical power. Although power output and generation efficiency are very low, useful power often may be obtained where a source of heat is available.

A thermoelectric module used for power generation has certain similarities to a conventional thermocouple. Let us look at a single thermoelectric couple with an applied temperature difference as shown in figure 1 of section 1 in the appendix section.

2.1.1 Heat Input and Generator Efficiency

With no load (RL not connected), the open circuit voltage as measured between points a and b is:

$$V = S \times DT$$

where:

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

S is the average Seebeck coefficient in volts/°K

DT is the temperature difference across the couple in °K where $DT = T_h - T_c$

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:

$$I = \frac{S \times DT}{R_C + R_L}$$

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 ohms

The total heat input to the couple (Q_h) is:

$$Q_h = (S \times T_h \times I) - (0.5 \times I^2 \times R_c) + (K_c \times DT)$$

where:

Q_h is the heat input in watts

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

T_h is the hot side of the couple in °K

The efficiency of the generator (E_g) is:

$$E_g = \frac{V \times I}{Q_h}$$

We have thus far discussed an individual thermoelectric couple, but since a complete module consists of a number of couples, it is necessary to rewrite the equation for an actual module, as follows:

$$V_o = S_M \times DT = I \times (R_M + R_L)$$

where:

V_o is the generators output in volts

S_M is the module's average Seebeck coefficient in volts/°K

R_M is the module's average resistance in ohms

It must be remembered that module Seebeck coefficient, resistance and thermal conductance properties are temperature dependent and their values must be calculated as described in section 2 of the appendix section. As an alternative to these calculations, however, generator performance may be reasonably approximated through the use of the data shown in section 3 (refer the appendix). In either case, the values of SM, RM, and KM must be selected at the average module temperature T_{avg} where:

$$T_{avg} = \frac{T_h + T_c}{2}$$

The power output (Po) from the module in watts is:

$$P_o = R_L \times \left[\frac{S_M \times DT}{R_M + R_L} \right]^2$$

It is possible, but unlikely, that the precise conditions will exist within a given generator application whereby one module will provide the exact output power desired. As a result, most thermoelectric generators contain a number of individual modules, which may be electrically connected in series, parallel, or series/parallel arrangement. A typical generator configuration is illustrated in Figure 2 (refer section 2 of the appendix section). This generator has a NT total number of modules with NS number of modules connected in series and NP number of modules connected in parallel.

The total number of modules in the system is shown as follows:

$$NT = NS \times NP$$

The current (I) in amperes passing through the load resistance R_L is:

$$I = \frac{NS \times S_M \times DT}{\frac{NS \times R_M}{NP} + R_L}$$

The output voltage (V_o) from the generator in volts is:

$$V_O = R_L \times \left(\frac{NS \times S_M \times DT}{\frac{NS \times R_M}{NP} + R_L} \right)$$

The Output Power (P_O) from the generator in watts is:

$$P_o = V_o \times I = \frac{NT \times (S_M \times DT)^2}{4 \times R_M}$$

The total heat input (Q_h) to the generator in watts is:

$$Q_h = NT \times \left[\frac{S_M \times T_h \times I}{NP} - 0.5 \times \left[\frac{I}{NP}\right]^2 \times R_M + K_M \times DT \right]$$

The efficiency (E_g) of the generator is:

$$E_g = \frac{P_o}{Q_h} \times 100\%$$

Maximum efficiency occurs when the internal resistance of the generator (R_{GEN}) equals the load resistance (R_L). The generator resistance is:

$$R_{GEN} = \frac{NS \times R_M}{NP}$$

There are a number of parameters associated with thermoelectric materials and modules that normally would have to be considered in a mathematical model. Elements that must be incorporated into the model include the module's effective Seebeck coefficient (S_M), Electrical Resistance (R_M), and Thermal Conductance (K_M).

The values of S_M, R_M, and K_M can be expressed mathematically by polynomial equations. The specified equation coefficients, applicable over a range of -100°C to +150°C, were derived from 71-couple, 6-ampere Ferrotec module. Other module configurations easily can be modeled by applying a simple correction factor table as shown in section 2 of the appendix section. Note that when using the various equations, temperature values must be stated in degrees Kelvin.

An alternative method for estimating temperature-dependent module properties, which may be useful under certain circumstances, involves the use of tabulated module data. Values representing average SM, RM, and KM characteristics for selected modules over a wide temperature range will be found in section 3 in appendix section at the end of this report. Although somewhat less accurate than using calculated values, this method provides a relatively simple approach to predicting module performance.

When a temperature differential is maintained across a thermoelectric device, a voltage can be detected at the input terminals. The magnitude of the resultant voltage, called the Seebeck emf, is proportional to the magnitude of the temperature difference. The Seebeck coefficient, as a function of temperature, can be expressed as a third order polynomial:

$$S_M = s_1 + s_2T = s_3T^2 + s_4T^3$$

where:

S_M is the Seebeck coefficient of the module in volts/°K

T is the average module temperature in °K

Coefficients for a 71-cpl, 6-amp module

$$s_1 = 1.33450 \times 10^{-2}$$
$$s_2 = -5.37574 \times 10^{-5}$$
$$s_3 = 7.42731 \times 10^{-7}$$
$$s_4 = -1.27141 \times 10^{-9}$$

The above polynomial expression represents the Seebeck coefficient when the temperature difference across the module is zero ($DT = T_h - T_c = 0$). When DT>0, the Seebeck coefficient must be evaluated at both temperatures T_h and T_c using the expressions:

$$S_{MTh} \text{ or } S_{MTc} = s_1T + \frac{s_2T^2}{2} + \frac{s_3T^3}{3} + \frac{s_4T^4}{4}$$

$$S_M = (S_{MTh} - S_{MTc}) / DT$$

where:

S_{MTh} is the module's Seebeck coefficient at the hot side temperature T_h

S_{MTc} is the module's Seebeck coefficient at the cold side temperature T_c

The electrical resistance of a thermoelectric module, as a function of temperature, can be expressed as third order polynomials for the two conditions (a) and (b):

(a) when DT = 0: $R_M = r_1 + r_2T + r_3T^2 + r_4T^3$

[redacted]

$R_M = (R_{MTh} - R_{MTc}) / DT$

where:

R_M is the module's resistance in ohms

R_{MTh} is the module's resistance at the hot side temperature Th

R_{MTc} is the module's resistance at the cold side temperature Tc

T is the average module temperature in °K

Coefficients for a 71-cpl, 6-amp module

$$r_1 = 2.08317$$
$$r_2 = -1.98763 \times 10^{-2}$$
$$r_3 = 8.53832 \times 10^{-5}$$
$$r_4 = -9.03143 \times 10^{-8}$$

The thermal conductance of a thermoelectric module, as a function of temperature, can be expressed as third order polynomials for the two conditions (a) and (b):

(a) when DT = 0: $K_M = k_1 + k_2T + k_3T^2 + k_4T^3$

[redacted]

$$K_M = \frac{K_{MTh} - K_{MTc}}{DT}$$

where:

K is the module's thermal conductance in watts/°K

K_{MTh} is the thermal conductance at the hot side temperature T_h

K_{MTc} is the thermal conductance at the cold side temperature T_c

T is the average module temperature in °K

Coefficients for a 71-cpl, 6-amp module

$$k_1 = 4.76218 \times 10^{-1}$$
$$k_2 = -3.89821 \times 10^{-6}$$
$$k_3 = -8.64864 \times 10^{-6}$$
$$k_4 = 2.20869 \times 10^{-8}$$

There are five variable parameters applicable to a thermoelectric module that affects its operation. These parameters include:

I - the input current to the module expressed in amperes

V_{in} - the input voltage to the module expressed in volts

T_h - the hot side temperature of the module expressed in °K

T_c - the cold side temperature of the module expressed in °K

Q_c - the heat input to (or heat pumped by) the module expressed in watts

In order to calculate module performance it is necessary to set at least three of these variables to specific values. Two common calculation schemes involve either (a) fixing the values of T_h, I, and Q_c or, (b) fixing the values of T_h, I and T_c. For the computer-oriented individual, a relatively straightforward calculation routine can be developed to incrementally step through a series of fixed values to produce an output of module performance over a range of operating conditions.

There are many other properties of thermoelectric devices that can be described mathematically.

a) The maximum heat pumping capacity (Q_{max}) in watts of a thermoelectric module is given by the following expression. Note that DT =0 at the maximum Q_c condition and, therefore, $T_c = T_h$.

$$Q_{max} = \frac{S_M^2 \times T_C^2}{2 \times R_M}$$

b) The maximum temperature differential (DT_{max}) in °K may be expressed as shown below. To obtain an accurate DT_{max} value, however, it will be necessary to perform an iterative series of calculations comparing T_c to DT_{max} at a fixed value of T_h.

$$DT_{max} = \frac{S_M^2 \times T_C^2}{2 \times R_M \times K_M}$$

c) The Figure-of-Merit (Z) is a measure of the overall performance of a thermoelectric device or material. Z always is higher for raw thermoelectric semiconductor material than for an actual module functioning within a thermal system. Since an operating module is affected by interface, conductive, convective, and other losses, the effective Figure-of-Merit is less than that of the raw material. The Figure-of-Merit may be expressed:

For Raw Material

$$Z = \frac{A^2}{p \times k}$$

For a TE Module

$$Z = \frac{S_M^2}{R_M \times K_M}$$

where:

A is the Seebeck coefficient of the material in v/°K

p is the electrical resistivity of the material in ohm-cm

k is the thermal conductivity of the material in w/cm-°K

d) The optimum current (I_{opt}) in amperes required to produce the maximum heat removal rate (Q_{max}) is:

For Raw Material

$$I_{opt} = \frac{a \times T_c \times a}{p \times l} = \frac{a \times T_c}{R}$$

For a TE Module

$$I_{opt} = \frac{S_M \times T_c}{R_M}$$

where:

a is the cross-sectional area of an individual thermoelectric element in centimeters.

l is the length (height) of an individual thermoelectric element in centimeters

R is the resistance of an individual thermoelectric element in ohms.

2.2 RADIATOR

Basically, engine cooling is a very crucial system of an engine. Without proper cooling, an engine would be ineffective and would not work properly. Taking the whole cooling system into perspective, the engine heat is rejected to the coolant usually water, by means of conduction and convection heat transfer. The coolant that circulated throughout the engine would carry the stored heat and pumped into the radiator. The radiator is a heat-exchanging device that consists of fins and tubes. The coolant that circulates within the tubes is cooled by the passing air. Heat is transferred to the air by convection.

A radiator will dissipate the maximum heat when the airflow is uniform. Efficiency will be reduced in proportion to the air misdistributions on the cooling. Sometimes, the coolant is not evenly distributed due to loss of fluid by expansion, fluid aeration, poor water-pump inlet conditions, possible cavitations that reduces the pump output, or perhaps the life of the pump itself.

Radiator is a device for holding a large volume of coolant in close contact with a large volume of air. This allows heat to transfer from the coolant to the air. The radiator core is divided into two separate and intricate compartments. Coolant passes through one, and air passes through the other. There are several types of radiator core. Two of the more commonly used types are tube-and-fin and the ribbon cellular. The tube- and-fin type consists of a series of long tubes extending from the top to the bottom of the radiator (or from upper to lower tank). Fins are placed around the tubes to improve heat transfer. Air passes around the outside of the tubes, between the fins, absorbing heat from the coolant in passing.

The ribbon cellular radiator core is made up of a large number of narrow coolant passages. The passages are formed by pairs of thin metal ribbons soldered together along their edges, running from the upper to the lower tank. The edges of the coolant passages which are soldered together form the front and back surfaces of the radiator core. The coolant passages are separated by air fins of metal ribbon, which provide air passages between the coolant passages. Air moves through these passages from front to back, taking heat from the fins. The fins, in turn, absorb heat from the coolant moving downward through the coolant passages. As a consequence, the coolant is cooled.

Radiators can be classified in another way, according to the direction of coolant flow through them. In some, the coolant flows from top to bottom (down-flow type). In others, the coolant flows horizontally from an input tank on one side to another tank on the other side (cross-flow type). The coolant tank situated above or to the side of the radiator serves two purposes. It provides a reserve supply of coolant. It also provides a place where the coolant can be separated from any air that might be circulating in the system. The tank has a filter cap which can be removed for addition of coolant as necessary.

For the first design of the thermoelectric module, the upper and lower hose of the car radiator is chosen (as shown in figure 3, section 1 of the appendix section). The hot surface of the module will be attached to the upper hose while the cold one is connected to the lower hose. For second design, the cold part of the thermoelectric module will be connected to the ambient temperature replaces the lower hose. The second design is chosen for this project because it produces larger difference temperature, thus smaller module that are reasonable is implemented. This is the relation between the car radiator and thermoelectric materials. The radiator supply heat, while thermoelectric materials utilize it in order to generate power.

CHAPTER 3

METHODOLOGY / PROJECT WORK

This final year project will be going on for duration of two semesters. Therefore, it will be divided into four sections, where the distribution of the main tasks could be listed as below: -

1. *First quarter : Literature Review / Data gathering*
2. *Second quarter: Data Gathering / Calculation*
3. *Third quarter : Practical / Data Analysis*
4. *Fourth quarter: Overall Analysis and Finalization of Project*

The task flow for this project would be based on the timeframe that has been allocated, which is two semesters. For the first semester, the focus of the project will be on the foundation of the project's principles, where the overall concept of the power generation will be planned and thus, specified according to the project's requirement. Therefore, the flow of methodology would be as follows: -

1. *Literature Review (reference on projects of related interests through the internet and journals)*

   - Before doing the project, literature review and research should be done to seek information through books, journals and the Internet. The findings should focus on thermoelectric materials and any sources of waste or excess heat.

2. *Data gathering and acquisition on the related subject for the purpose of doing power generation from excess heat using thermoelectric material.*

   - Relevant and important data obtained from the research are gathered. These findings should be use for later stages.

3. *Identification of the best techniques to be used*

   - From the study made, all the method that should be consider for the project will be focused before the best is chosen. The purpose of the study is to get a suitable technique that is appropriate for the project. The identification is important in obtaining the thermoelectric module and selecting the devices that produce excess heat. Temperature selection will be the crucial part because it determines the size of the module. The module also studied, in order to specify whether the module can stand the temperature and which module is suitable for the range of temperature. .

4. *Compilation on all the findings obtained for the next step of detailed analysis.*

   - All the data and information that is important for the project will be compiled before detail analysis is done. The analysis will be done during the second semester, which it will be the first task should be performed in that semester.

For the second semester, as mentioned before, the project will continue with detailed analysis of the findings which will include the key elements of the project which is to decide the parameters and the design procedures that should be used as to follow the overall concept of the project. The important considerations for the project will be confirmed during this semester in order to accomplish the aim.

1. *Continue with more detailed findings.*

   - Although the detail analysis should be done, research will be still in progress as to find more data that can be decisive and crucial for the project. New module from other manufacturer of thermoelectric materials is study until decision is made.

2. *Decision made.*

   - From the considerations that have been analyzed, selection is made for the thermoelectric module should be used. From many modules studied, the Ferrotec module is used for this project. Car radiator is selected for their excess heat that are seen suitable to be used to shows the capability of the thermoelectric to generate electricity.

3. *Finalization of the project*

- Overall analysis should be done to achieve the objectives of the project. Compilation will be made and all the data will be include in the final report.

Power generation from excess heat will be performed using thermoelectric materials. The thermoelectric module should be used in this project is from Ferrotec America Corporation. Bismuth Telluride based thermoelectric is applied to the module. The design of the module is discussed in the results and discussion section where all the parameters needed and calculation for the module is shown. Heat gained that is seen suitable for the project is from car radiator.

For the first design, the temperature along both the upper and lower hose of the car radiator is chosen. The results from the design analysis shown that, big module will be needed due to the small temperature difference between the hose. A study is made in order to find a better design, and the ambient temperature is chosen along with the upper hose. The design of the module with all the important considerations is shown in next section. The module obtained is better than the first design where a smaller module is designed. All the features follow the attributes that are chosen for the module during the design stages.

CHAPTER 4

RESULTS AND DISCUSSION

Power generation will be performed using thermoelectric material, which converts heat into power. The heat that will be going to use is from a car radiator. The heat, with two differential temperatures will be connected with the thermoelectric generator to produce electricity. The bigger the differential temperature, the best coefficient is produced. From the radiator, about 10 ^{0}C to 20 ^{0}C differential temperatures can be obtained. This temperature is determined from the lower and upper hose of the radiator (as shown in figure 3, section 1 of the appendix section). For the first design, the two temperatures are selected and the result shows that a huge module will be needed. Some consideration should be made in order to produce smaller module. The temperature difference has been focused and another design is implemented. The new temperatures that are chosen come from the upper hose of the car radiator and the ambient temperature. From the study made, the new design produce around 50 ^{0}C differential temperatures and the size of the module is reasonable.

The illustration of the design process will be shown below. A 12-volt, 1.5-ampere thermoelectric power generator will be implemented. To begin the design process the system parameters and some preliminary calculations is shown below.

Given:

$T_h = +80°C = 353.2K$

$T_c = +30°C = 303.2K$

$V_o = 12$ volts

$I = 1.5$ amperes

Therefore:

$$T_{avg} = (T_h+T_c)/2 = (353.2+303.2)/2 = 328.2K$$

$$R_L = V_o/I = 12 / 1.5 = 8.0 \text{ ohms}$$

$$P_o = V_o \times I = 12 \times 1.5 = 18 \text{ watts}$$

$$DT = T_h-T_c = 353.2 - 303.2 = 50K$$

It is usually desirable to select a relatively "high power" thermoelectric module for generator applications in order to minimize the total system cost. For this reasons a Ferrotec 127 couple, 6-ampere module is chosen in this design.

From the 127-couple, 6 ampere selected module, the following values are obtained at T_{avg} = 328.2K from the data shown in Table 3 (section 3) included in the appendix section:

$$S_M = 0.05519 \text{ volts/K}$$

$$R_M = 2.8556 \text{ ohms}$$

$$K_M = 0.5903 \text{ watts/K}$$

The required power for the load has been calculated as 18 watts. It is now necessary to determine the minimum number of modules needed to meet this load requirement. The maximum output power from one module is:

$$P_{max} = \frac{(S_M \times DT)^2}{4 \times R_M} = \frac{(0.05519 \times 50)^2}{4 \times 2.8556} = 0.6667 \text{ watts}$$

The minimum number of modules needed is:

$$NT_{min} = \frac{P_o}{P_{max}} = \frac{18}{0.6667} = 26.9 \text{ » } 27 \text{ » } 28$$

With a group of 28 modules, the most logical connection configuration is two parallel strings of four modules, i.e., NS = 7 and NP = 4. Generator resistances for this configuration are thus:

$$R_{GEN} = \frac{NS \times R_M}{NP} = \frac{7 \times 2.8556}{4} = 4.9973 \text{ ohms}$$

While 4.9973 ohm R_{GEN} value does not exactly match the 8.0 ohm load resistance, this value normally would be considered as being within the satisfactory range. In any event, this is the closest resistance match that can be obtained with the selected module type. The voltage for this arrangement (11.9 volts) is calculated as follows:

$$V_o = R_L \times \left[\frac{NS \times S_M \times DT}{\frac{NS \times R_M}{NP} + R_L} \right] = 8.0 \times \left[\frac{7 \times 0.05519 \times 50}{\frac{7 \times 2.8556}{4} + 8.0} \right] = 11.89 \text{ volts}$$

We can now see that V_o is quite close to the desired value and it is apparent that we have obtained the optimum series/parallel configuration. If "fine tuning" of V_o is required, it will be necessary to accomplish this either by some form of electronic voltage regulation or by externally altering the applied temperature differential (DT). In certain instances it will be found that the output voltage is significantly out of range despite trying all possible series/parallel combinations. In this event it may be necessary to use an alternate thermoelectric module having a different current rating and/or number of couples.

It is now possible to complete the design analysis by determining power levels and efficiency. Since V_o has been established, output power (P_o) can be simply calculated:

$$P_o = \frac{(V_o)^2}{RL} = \frac{(11.89)^2}{8.0} = 17.7 \text{ watts}$$

The total heat input (Q_h) to the generator is:

$$Q_h = NT \times \left[\frac{S_M \times T_h \times I}{NP} - 0.5 \times \left[\frac{I}{NP}\right]^2 \times R_M + K_M \times DT \right]$$

$$= 28 \times \left(\frac{0.05519 \times 353.3 \times 1.5}{4} - 0.5 \times \left(\frac{1}{4}\right)^2 \times 2.8556 + 0.5903 \times 50 \right) = 860.46 \text{ watts}$$

The generator efficiency (E_g) is:

$$E_g = \frac{P_o}{Q_h} \times 100\% = \frac{17.7}{860.46} \text{X } 100\% = 2.06\%$$

The heat transferred to the cold-side heat sink (Q_c) is:

$$Q_c = Q_h - P_o = 860.46 - 17.7 = 842.76 \text{ watts}$$

For any thermoelectric generator design it is always desirable to maximize the applied temperature differential in order to minimize the total number of modules in the system. For the first case, from a study concerning car radiator, the differential temperature can be gained is only around 20 ^{0}C. This value is quite small; therefore the total number of modules needed is big. In order to minimize this number, some consideration will be taken which is to analyze other sources of temperature from a car that can give bigger value of differential temperature. A very large number of modules are needed when the cold side temperature (T_c) is high and the temperature differential, therefore, is small. Performance of the cold-side heat sink is of the utmost importance and its thermal resistance must be extremely low. The second design is implemented by using the ambient temperature replaces the lower hose of the radiator. This is done in order to obtain bigger value of temperature difference. The temperature difference now, gained between the upper hose of the car radiator and ambient temperature is 50 ^{0}C. All the parameters concerning the thermoelectric module for the second design are discussed above.

CHAPTER 5
CONCLUSION

As a conclusion, from the study and researches that have been done, the power generation that is going to be performed from excess heat using the thermoelectric material will be conducted using the module discussed. The excess heat gained should be used for the thermoelectric generator has been decided and it came from car radiator. The upper hose of the car radiator and the ambient temperature will be the main parameters selected for the design. The designing illustration, which is to determine the parameters, needed in this thermoelectric application and the total number of module needed has been confirmed. This is the best designed implemented since many considerations has been studied and taken care off. The efficiency obtained for the power generator is 2.06%. This is a reasonable value since normal thermoelectric generator produce low efficiency when it comes to generating power. Still, by good planning and development the thermoelectric power generator is one worthy application. The design illustrate that waste heat are practically useful if it is consider as a valuable sources for any reason.

Generally, the project shows only the design illustration. Real capability of thermoelectric materials work as power generator could not be implemented and shown practically due to the cost of the module itself and availability. The cost is quite high, thus only the illustration can be done for this project.

Although the study will be not as comprehensive and thorough as the one conducted by a third party professional consultant, the content of the material and ways of presenting data will be done in the most affordable condition from a student's perspective.

For the recommendations, the author would like to suggest that this project should be continued by next year student. The subjects that can be concentrating are about doing some improvement study and finding elements in the car that can be powered by the thermoelectric generator.

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APPENDICES

SECTION 1

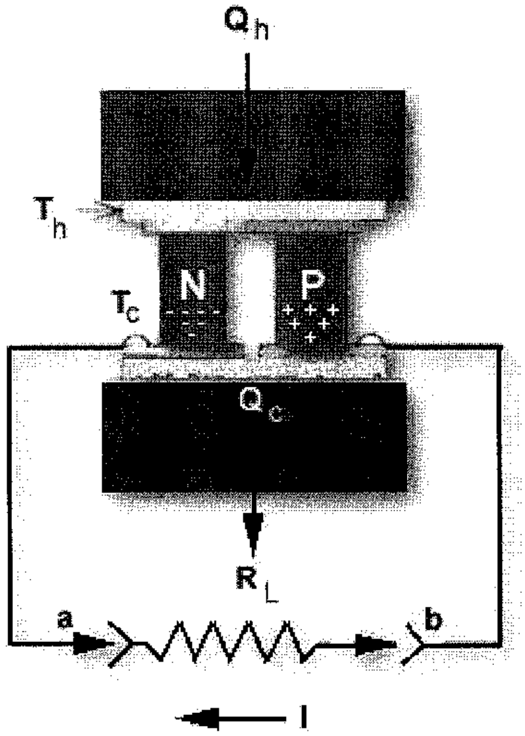

Figure 1

Single Thermoelectric Couple where Th > Tc

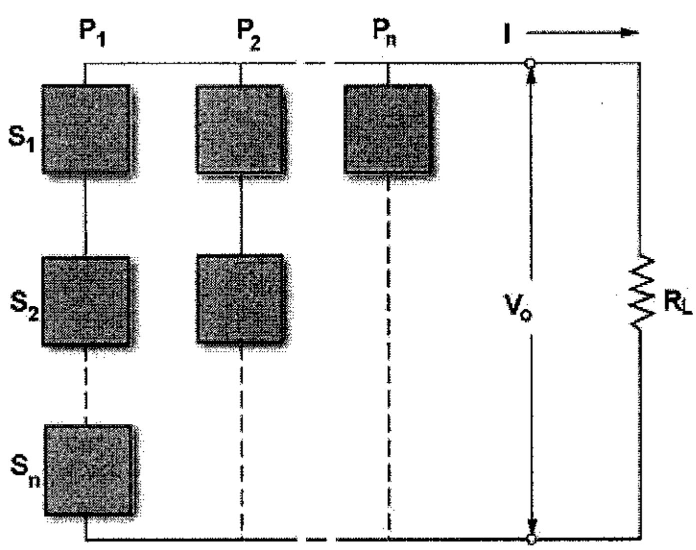

Figure 2

Typical Thermoelectric Generator with a Series-Parallel Arrangement of Modules

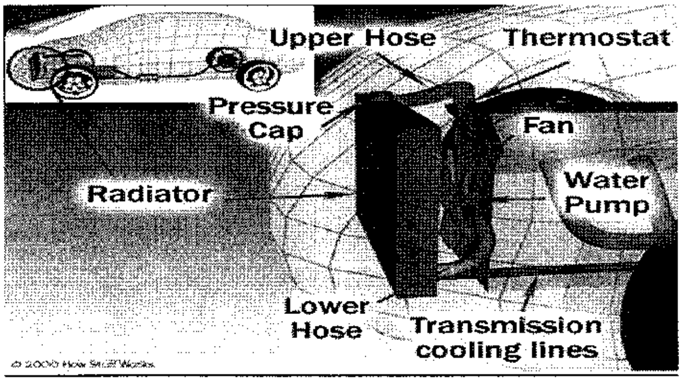

Figure 3

The engine cooling system of a modern car

SECTION 2

PARAMETER CONVERSIONS FOR OTHER MODULE CONFIGURATIONS:

[redacted]

$$R_{new} = R_M \times \frac{6}{I_{new}} \times \frac{N_{new}}{71}$$

[redacted]

Where:

Snew is the Seebeck coefficient for the new module
Rnew is the electrical resistance of the new module
Knew is the thermal conductance of the new module
Nnew is the number of couples in the new module
Inew is the optimum or maximum current of the new module

SECTION 3

Averaged Module Material Parameters at Various Temperatures

31-Couple Modules

Table 1

Temperature			9-Ampere Module		15-Ampere Module	
		S_M	R_M	K_M	R_M	K_M
°C	°K	V/K	Ohms	w/K	ohms	w/K
-100	173.2	0.00859	0.2130	0.2103	0.1278	0.3504
-90	183.2	0.00898	0.2186	0.2086	0.1312	0.3477
-80	193.2	0.00938	0.2263	0.2056	0.1358	0.3427
-70	203.2	0.00978	0.2360	0.2018	0.1416	0.3364
-60	213.2	0.01017	0.2474	0.1976	0.1484	0.3293
-50	223.2	0.01056	0.2604	0.1933	0.1562	0.3221
-40	233.2	0.01094	0.2748	0.1892	0.1649	0.3153
-30	243.2	0.01130	0.2906	0.1857	0.1743	0.3096
-20	253.2	0.01165	0.3075	0.1831	0.1845	0.3052
-10	263.2	0.01198	0.3253	0.1816	0.1952	0.3027
0	273.2	0.01229	0.3440	0.1815	0.2064	0.3024
10	283.2	0.01257	0.3634	0.1828	0.2180	0.3047
20	293.2	0.01282	0.3833	0.1858	0.2300	0.3096
30	303.2	0.01304	0.4035	0.1905	0.2421	0.3176
40	313.2	0.01323	0.4239	0.1971	0.2544	0.3286
50	323.2	0.01337	0.4444	0.2057	0.2666	0.3428
60	333.2	0.01347	0.4647	0.2162	0.2788	0.3602
70	343.2	0.01353	0.4848	0.2286	0.2909	0.3809
80	353.2	0.01353	0.5044	0.2428	0.3026	0.4047
90	363.2	0.01349	0.5234	0.2589	0.3140	0.4316
100	373.2	0.01338	0.5417	0.2768	0.3250	0.4613
110	383.2	0.01322	0.5590	0.2961	0.3354	0.4936
120	393.2	0.01300	0.5753	0.3169	0.3452	0.5282
130	403.2	0.01271	0.5904	0.3389	0.3542	0.5649
140	413.2	0.01235	0.6041	0.3619	0.3624	0.6032
150	423.2	0.01192	0.6162	0.3856	0.3697	0.6426

71-Couple Modules

Table 2

Temperature			4-Ampere Module		6-Ampere Module	
		S_M	R_M	K_M	R_M	K_M
°C	°K	V/K	Ohms	w/K	ohms	w/K
-100	173.2	0.01968	1.0980	0.2140	0.7318	0.3210
-90	183.2	0.02058	1.1270	0.2123	0.7511	0.3185
-80	193.2	0.02148	1.1663	0.2093	0.7775	0.3140
-70	203.2	0.02239	1.2159	0.2054	0.8106	0.3082
-60	213.2	0.02329	1.2746	0.2011	0.8498	0.3017
-50	223.2	0.02418	1.3417	0.1967	0.8945	0.2951
-40	233.2	0.02505	1.4162	0.1926	0.9441	0.2889
-30	243.2	0.02588	1.4974	0.1891	0.9983	0.2836
-20	253.2	0.02668	1.5844	0.1864	1.0563	0.2796
-10	263.2	0.02744	1.6766	0.1849	1.1177	0.2773
0	273.2	0.02814	1.7729	0.1847	1.1819	0.2771
10	283.2	0.02879	1.8727	0.1861	1.2485	0.2791
20	293.2	0.02937	1.9751	0.1891	1.3167	0.2837
30	303.2	0.02987	2.0793	0.1939	1.3862	0.2909
40	313.2	0.03029	2.1845	0.2007	1.4564	0.3010
50	323.2	0.03062	2.2899	0.2094	1.5266	0.3140
60	333.2	0.03085	2.3947	0.2200	1.5965	0.3300
70	343.2	0.03098	2.4980	0.2326	1.6654	0.3490
80	353.2	0.03100	2.5991	0.2472	1.7327	0.3708
90	363.2	0.03089	2.6971	0.2636	1.7981	0.3954
100	373.2	0.03066	2.7913	0.2817	1.8608	0.4226
110	383.2	0.03029	2.8807	0.3015	1.9205	0.4522
120	393.2	0.02977	2.9647	0.3226	1.9765	0.4839
130	403.2	0.02911	3.0423	0.3450	2.0282	0.5175
140	413.2	0.02828	3.1129	0.3684	2.0753	0.5526
150	423.2	0.02729	3.1755	0.3925	2.1170	0.5887

127-Couple Modules

Table 3

Temperature			4-Ampere Module		6-Ampere Module	
		S_M	R_M	K_M	R_M	K_M
°C	°K	V/K	Ohms	w/K	ohms	w/K
-100	173.2	0.03520	1.9634	0.3828	1.3089	0.5742
-90	183.2	0.03680	2.0152	0.3798	1.3435	0.5697
-80	193.2	0.03843	2.0862	0.3744	1.3908	0.5616
-70	203.2	0.04005	2.1749	0.3675	1.4500	0.5512
-60	213.2	0.04166	2.2800	0.3597	1.5200	0.5396
-50	223.2	0.04325	0.3999	0.3519	1.6000	0.5278
-40	233.2	0.04480	2.5332	0.3445	1.6888	0.5168
-30	243.2	0.04630	2.6784	0.3382	1.7856	0.5073
-20	253.2	0.04773	2.8341	0.3335	1.8894	0.5002
-10	263.2	0.04908	2.9989	0.3307	1.9993	0.4961
0	273.2	0.05034	3.1713	0.3304	2.1142	0.4956
10	283.2	0.05150	3.3498	0.3328	2.2332	0.4992
20	293.2	0.05253	3.5329	0.3383	2.3553	0.5074
30	303.2	0.05343	3.7193	0.3469	2.4796	0.5204
40	313.2	0.05418	3.9075	0.3590	2.6050	0.5384
50	323.2	0.05477	4.0961	0.3745	2.7307	0.5617
60	333.2	0.05519	4.2835	0.3936	2.8556	0.5903
70	343.2	0.05542	4.4683	0.4161	2.9789	0.6242
80	353.2	0.05544	4.6491	0.4422	3.0994	0.6632
90	363.2	0.05525	4.8244	0.4715	3.2163	0.7072
100	373.2	0.05483	4.9928	0.5039	3.3285	0.7559
110	383.2	0.05417	5.1528	0.5392	3.4352	0.8088
120	393.2	0.05325	5.3030	0.5771	3.5354	0.8656
130	403.2	0.05206	5.4419	0.6171	3.6280	0.9257
140	413.2	0.05059	5.5681	0.6589	3.7121	0.9884
150	423.2	0.04882	5.6801	0.7021	3.7867	1.0531