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Mechanical Engineering Department

Graduation project

Automotive Thermoelectric Generator Design and Build

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شهادة تقييم مشروع التخرج

جامعة بوليتكنك فلسطين

الخليل – فلسطين

اسم المشروع :

Automotive thermoelectric generator design and build

فريق العمل

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عبدالله ابو عرفة

بناء على توجيهات الأستاذ المشرف على المشروع وبموافقة جميع أعضاء اللجنة الممتحنة، تم تقديم هذا المشروع إلى دائرة الهندسة الميكانيكية في كلية الهندسة والتكنولوجيا للوفاء الجزئي بمتطلبات الدائرة لدرجة البكالوريوس.

توقيع مشرف المشروع	**توقيع رئيس الدائرة**
د. زهدي سلهب	د.يوسف سويطي
.... 12/6/12	....

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Dedication

To our parents who

spent nights and days doing their best

to give us the best …

To all students and who

wish to look for

the future …

To whom like the knowledge

To whom carry candle of science

to light his avenue

of life …

To our beloved country Palestine …

To all of our friends …

Acknowledgments

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Abstract

This paper presents an experimental research using so called "Automotive Thermoelectric Generator; Design and Building" which replaces the traditional alternator as an alternative electrical energy. Other goal of such device is primarilytoreduce the amount offuelconsumed by the vehicle,throughthe exploitation ofthermal energygenerated byfuel combustionin the engineto generateelectrical energythat can be usedto power the electrical devicesin the vehicle.

To achieve the main goals of this paper, a system was builtusing58thermoelectric generators (TEG) fixed and installed around the vehicle exhaust pipe. This system converts waste thermal energyfrom the engine(relied on temperature differences) into electrical oneby 52amperesand 14.2volts. Theelectric powergeneratedis sufficientto dispense the traditionalgeneratorin most ofthe operating conditions ofthe engine and vehicle, charge the batteryand power the other vehicle electrical devices.

The measurement results indicated that the fuel consumptionwas reduced by8.85%.

ملخص

يهدف المشروع بشكل أساسي إلى تقليل كمية استهلاك الوقود في المركبة، وذلك من خلال استغلال الطاقة الحرارية الناتجة عن احتراق الوقود في المحرك في توليد طاقة كهربائية يمكن استخدامها لتشغيل الأجهزة الكهربائية في المركبة.

وبذلك يمكن الاستغناء عن المولد التقليدي والذي بدوره يستهلك جزء من طاقة المحرك كما يشكل حملاً عليه ويزيد أيضاً من استهلاك الوقود.

حيث تم تصميم نموذج النظام باستخدام ٥٨ خلية حرارية تقوم بتحويل الطاقة الحرارية الضائعة في المحرك إلى كهرباء بمقدار ٥٢ أمبير و ١٤.٢ فولت، وهذه الطاقة الكهربائية الناتجة كافية للاستغناء عن المولد التقليدي في معظم ظروف تشغيل المحرك، وشحن البطارية وتشغيل أنظمة السيارة.

وبناءا على الحسابات النظرية لهذا النظام فإن استهلاك الوقود قل بنسبة ٨.٨٨%.

أما على الصعيد العملي، فقد تم استخدام ٧٠ خلية حرارية من نوع آخر وتركيبها على أنبوب العادم بعد إعادة تصميمه لينتج ١٠.٥ امبير و ١٤.٢ فولت حيث تم الاستغناء عن المولد التقليدي بشكل جزئي ليعمل النظام بشكل هجين، وهذا أدى إلى تقليل استهلاك الوقود بنسبة ٦.٩%.

Content

Chapter One

1. Introduction

1.1 Introduction:

In light of the growing rise of oil prices, increasing demand of fuel, and the limited fuel sources, therefore the need to develop new techniques in order to improve the fuel economy becomes greater, and the efficiency of vehicle systems should be promoted to be more environmentally friendly and economic as possible.

In the recent time the scientific researches tend to utilize the wasted energy (thermal and mechanical) and convert it into another useful form.

In internal combustion engines the fuel efficiency doesn't exceed 30%, whereas around 40% of fuel energy is wasted in exhaust heat and 30% is rejected through engine coolant, figure 1.1.

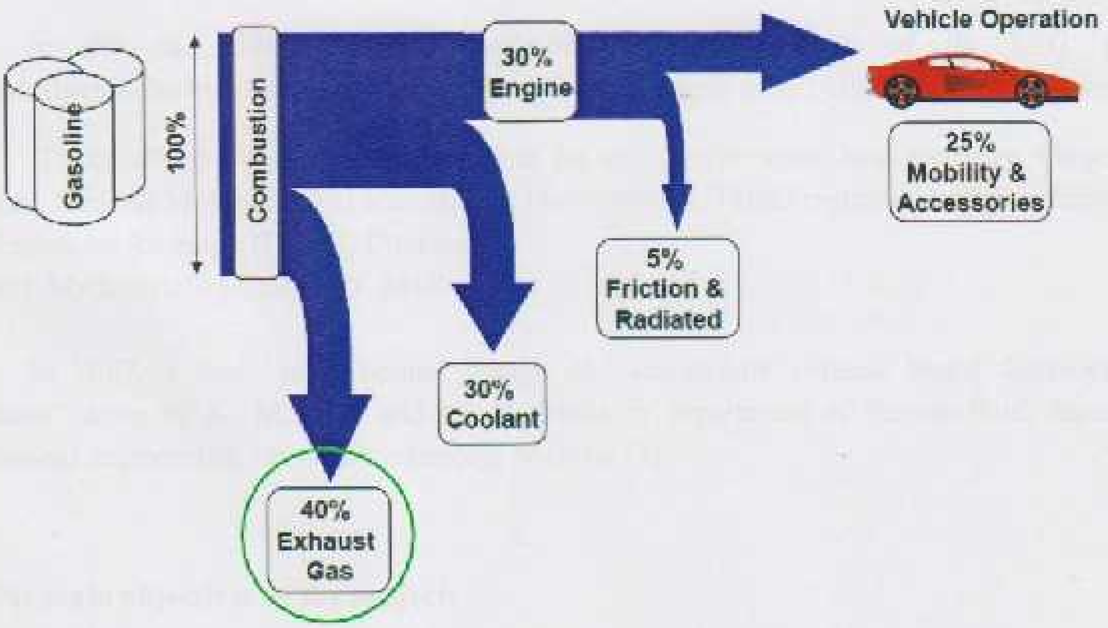

Figure 1.1: Fuel energy distribution.

After surveying the previous studies and scientific references which related to the subject of this project, it's appeared that the thermal energy can be used by converting it to electrical one using chemical properties of some materials. This generated electrical energy is used to operate electric appliances in the vehicle.

To achieve this, a device driven by the thermal energy produced from combustion can be designed and installed around exhaust pipe to generate electrical energy which can be considered an alternative to the traditional alternator in the vehicle. This device is called thermoelectric generator (TEG).

Thermoelectric generators (also called thermogenerators) are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" or "thermoelectric effect".

As it's known the traditional alternator consumes around 5% of engine power, if it can be removed or operate less, then the fuel consumption will be reduced and engine power increases.

1.2 Previous studies:

The idea of converting thermal energy into electrical started since 1820s by Thomas Johann Seebeck.

In 1963, this idea has been applied for the first time in the vehicles by Porche in "Porche 944" [1].

In the late 1990s, Nissan Motors published the results of its TEG which utilized thermoelectric materials on a 3.0 liter gasoline engine in hill-climb mode at 60.0 km/h.

Thermoelectric generator development for automotive waste heat recovery, Gregory P. Meisner, General Motors Global Research & Development, 16thDirections in Engine Efficiency and Emissions Research (DEER) Conference,
Detroit, Michigan, September 29, 2010.

In 2007, a study of "Thermal design of automobile exhaust based thermoelectric generator" done by K. M. Saqr and M. N. Musa in department of thermo-fluid, faculty of mechanical engineering, universiti teknologi Malysia [2].

1.3 The main objectives of the project:

1. The project has been mainly selected to find another source of electrical power in the vehicle which doesn't consume engine power unlike the alternator does.
2. Increasing engine power.

3. Decreasing fuel consumption.
4. Minor to decrease harmful emission.

1.4 The importance of using TEG:

The importance of using TEG in the vehicle consists in finding a potential alternative energy because of the followings,

1. Continuance increasing of fuel price.
2. Limited sources of fuel .
3. Pollution

1.5 Project description:

Building a system that converts the waste heat energy of internal combustion engine into electrical energy to be used to operate electric appliances in the vehicle, and then remove or reduce using the alternator which leads to reduce fuel consumption and emission and increase engine brake power, figure 1.2.

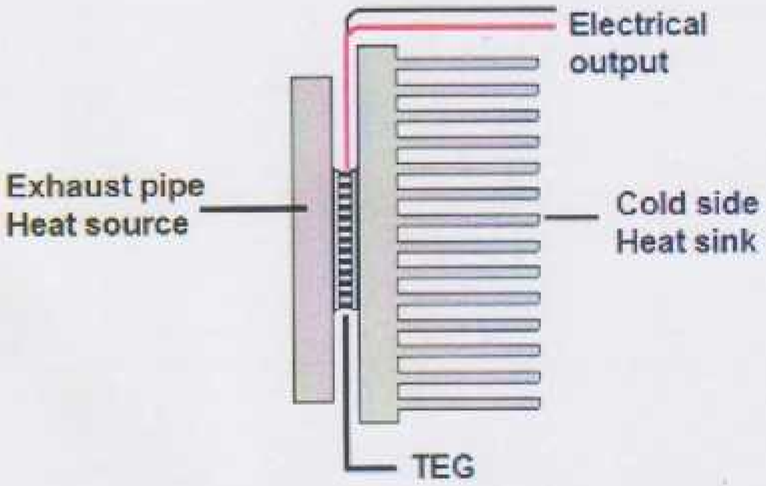

Figure 1.2: Electrical energy generation from heat.

1.6 Project stages scheduling

The project stages can be summarized as follows:

- Sufficient information have been collected about the thermoelectric generator system from several references, including books, scientific papers, journals and specialized websites.
- Studying of materials and their properties has been done to choose the optimal material achieves the goals of the project.
- The vehicle electrical loads have been measured to identify the voltage, current and power required by the vehicle and which the system must supply.
- Engine power, fuel consumption and emission of a sample car have been measured when traditional charging system is used and when it's removed to simulate the project case in order to prove the claimed project goals.
- Measuring of exhaust system temperature through exhaust pipe to identify the operating temperature and the place of installing the device which provide the requirements.

Chapter Two

2. Principle of Operation of Thermocouple

2.1 Principle of operation

Consider an aluminum rod that is heated at one end and cooled at the other end as shown in Figure 2.1. The electrons in the hot region are energetic and therefore have greater velocities than those in the cold region. Consequently there is a net diffusion of electrons from the hot end toward the cold end which leaves behind exposed positive metal ions in the hot region and accumulates electrons in the cold region.

This situation prevails until the electric field developed between the positive ions in the hot region and the excess electrons in the cold region prevents further electron motion from the hot to cold end. A voltage therefore developed between the hot and cold ends with the hot end at positive potential. The potential difference (ΔV) across a piece of metal due to a temperature difference (ΔT) is called the "Seebeck effect".

To gauge the magnitude of this effect, a special coefficient is defined as the potential difference developed per unit temperature difference [3].

$$S = \frac{dV}{dT} \tag{2.1}$$

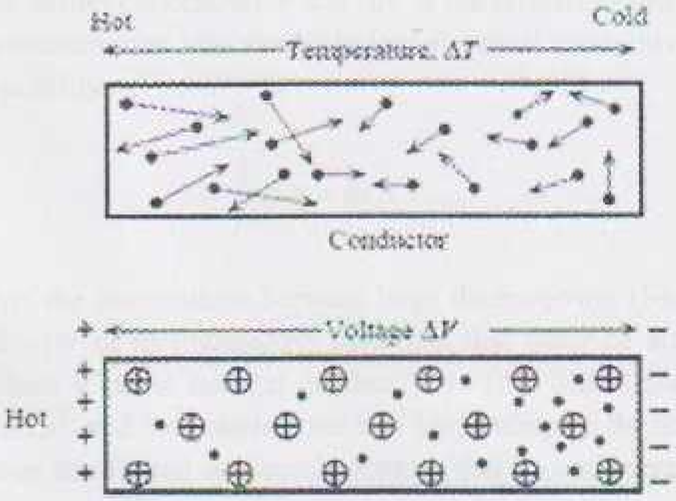

Figure 2.1: Electron motion under heat effect.

Fundamental to the field of thermoelectric materials is the need to optimize a variety of conflicting properties. To maximize the thermoelectric figure of merit (ZT), which is the performance of the thermoelectric materials and shown in equation (2.2), a large thermopower (absolute value of the Seebeck coefficient), high electrical conductivity, and low thermal conductivity are required.

$$ZT = \frac{\alpha^2 T}{\rho \kappa} \tag{2.2}$$

Where, Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ) and temperature (T) dependent materials properties.

As these transport characteristics depend on interrelated material properties, a number of parameters need to be optimized to maximize ZT such as carrier concentration and effective mass.

2.2 Carrier concentration

Low carrier concentration insulators and even semiconductors have large Seebeck coefficients: see equation (2.3).

$$\alpha = \frac{8\pi^2 \kappa_B^2}{3eh^2} mT \left(\frac{\pi}{3n}\right)^{2/3} \tag{2.3}$$

Where "n" is the carrier concentration and "m" is the effective mass of the carrier. However, low carrier concentration also results in low electrical conductivity; see equation (2.4) where μ is the carrier mobility.

$$\frac{1}{\rho} = \sigma = ne\mu \tag{2.4}$$

Figure 2.2 shows the compromise between large thermopower (Seebeck coefficient) and high electrical conductivity in thermoelectric materials that must be struck to maximize the figure of merit ZT, where κ is the thermal conductivity. This peak typically occurs at carrier concentrations between 10^{19} and 10^{21} carriers per cm^3 (depending on the material system), which falls in between common metals and semiconductors — that is, concentrations found in heavily doped semiconductors.

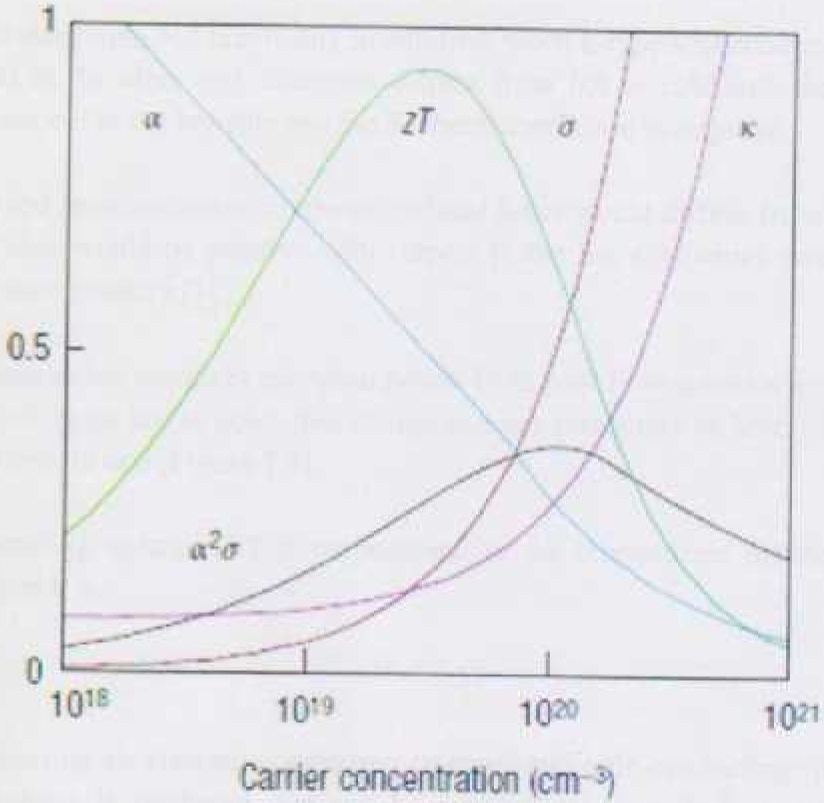

Figure 2.2: Carrier concentration effect on thermal and electrical conductivity and Seebeck coefficient.

2.3 Effective mass

large effective masses produce high thermopower but low electrical conductivity as shown in equations (2.3) and (2.4). Whereas heavy carriers will move with slower velocities, and therefore small mobilities, which in turn leads to low electrical conductivity.

A balance must be found for the effective mass for the dominant charge carrier, forming a compromise between high effective mass and high mobility. High mobility and low effective mass is typically found in materials made from elements with small electronegativity differences, whereas high effective masses and low mobilities are found in materials with narrow bands such as ionic compounds.

It is not obvious which effective mass is optimum; good thermoelectric materials can be found within a wide range of effective masses and mobilities: from low-mobility, high-effective-mass polaron conductors to high-mobility, low-effective-mass semiconductors [4].

Depending on all those, it's clear that the best type of materials is the semiconductors. Where they have an acceptable Seebeck coefficient, high electrical conductivity and low thermal conductivity, and therefore high figure of merit ZT.

Like an aluminum rod previously mentioned, when n-type semiconductor is heated at one end and cooled at the other end, electrons diffuse from hot to cold end, then the cold side is negative with respect to the hot side and the Seebeck coefficient is negative

In a p-type semiconductor, on the other hand holes would diffuse from the hot to the cold end. The cold side would be positive with respect to the hot side which would make Seebeck coefficient positive quantity [3].

A thermoelectric produces electrical power from heat flow across a temperature gradient. As the heat flows from hot to cold, free charge carriers (electrons or holes) in the material are also driven to the cold end (Figure 2.2).

The resulting voltage (V) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α.

$$V = \alpha \Delta T \tag{2.5}$$

By connecting an electron conducting (n-type) and hole conducting (p-type) material in series, a net voltage is produced that can be driven through a load. A good thermoelectric material has a Seebeck coefficient between 100 μV/K and 300 μV/K; thus, in order to achieve a few volts at the load, many thermoelectric couples of n-type and p-type thermoelectric connected electrically in series and thermally in parallel to make a thermoelectric generator. The flow of heat drives the free electrons (e-) and holes (h+) producing electrical power from heat.

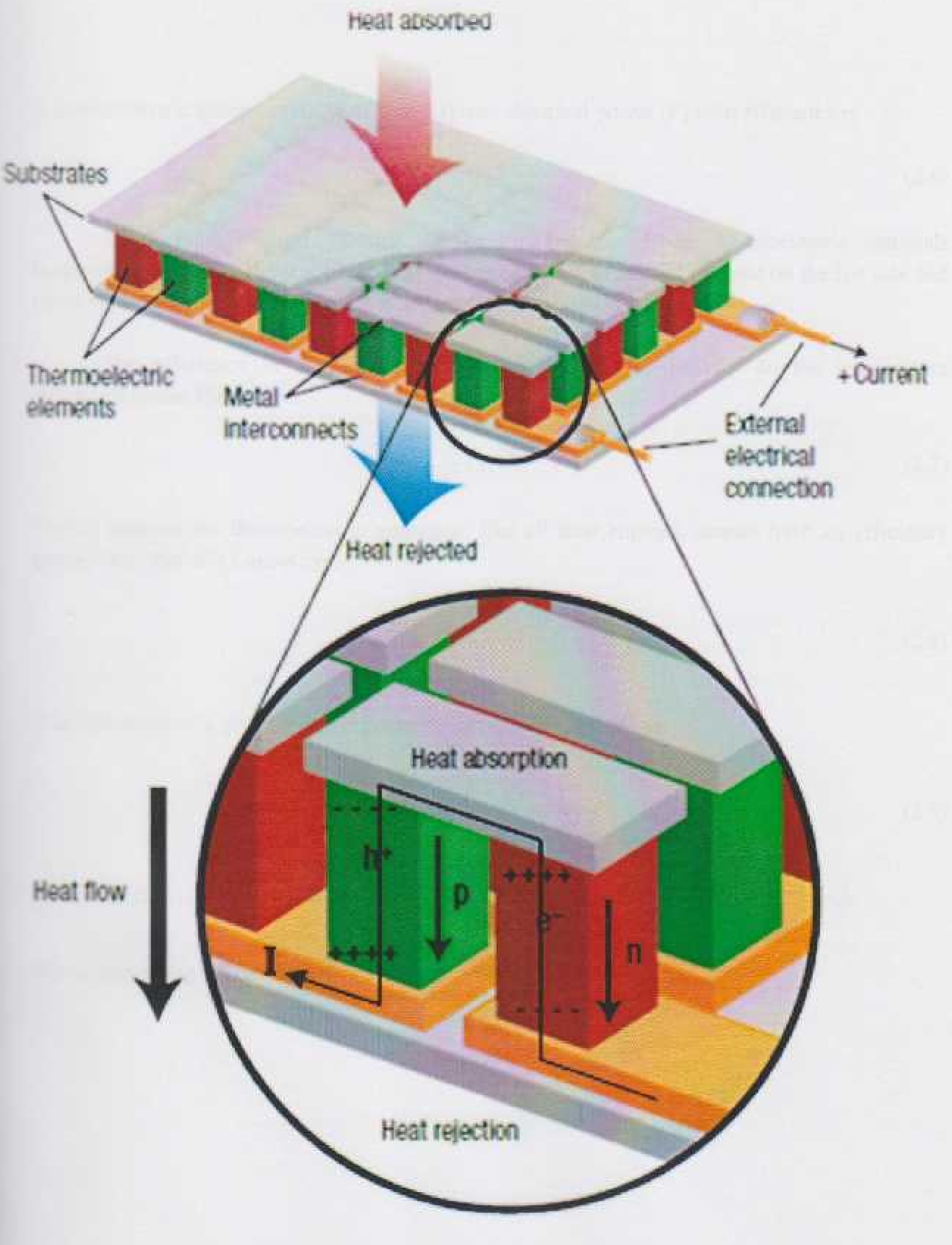

Figure 2.2: Thermoelectric generator showing heat flow, direction of electrons and holes motion, and current direction

A thermoelectric generator converts heat (Q) into electrical power (P) with efficiency η.

$$P = \eta Q \tag{2.6}$$

The amount of heat, Q, that can be directed though the thermoelectric materials frequently depends on the size of the heat exchangers used to harvest the heat on the hot side and reject it on the cold side.

The efficiency of a thermoelectric converter depends heavily on the temperature difference across the device.

$$\Delta T = T_h - T_c \tag{2.7}$$

This is because the thermoelectric generator, like all heat engines, cannot have an efficiency greater than that of a Carnot cycle.

$$\eta_{carnot} = \frac{\Delta T}{T_h} \tag{2.8}$$

The efficiency of a thermoelectric generator is typically defined as

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c / T_h} \tag{2.9}$$

Where the first term is the Carnot efficiency and ZT is the figure of merit for the device.

When calculating ZT of some semiconductors, figure 2.3 is produced.

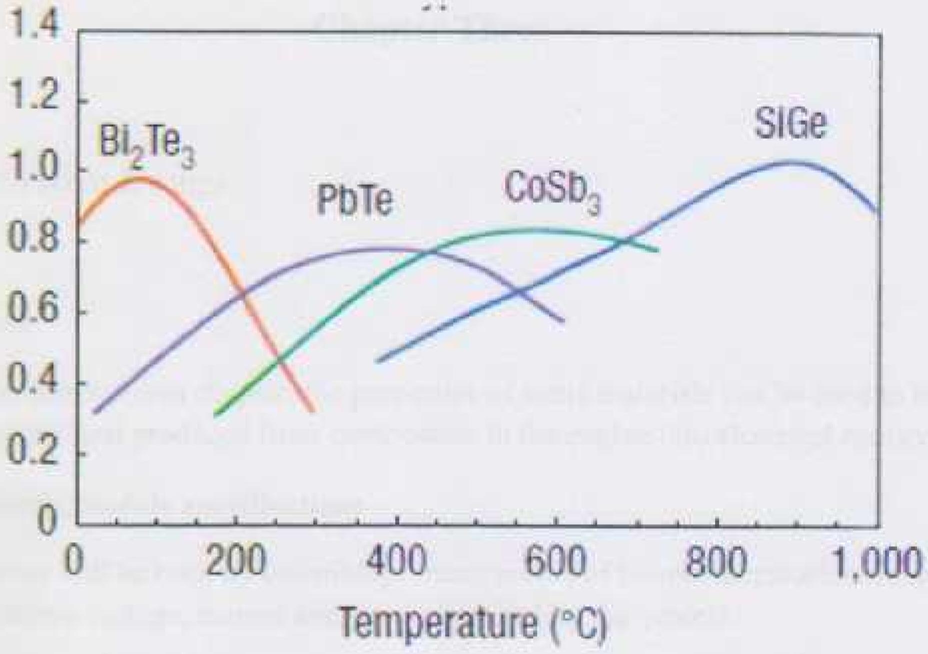

Figure 2.3: Figure of merit of some semiconductors.

It's clear from the curves that the best materials for operating temperature of the system are bismuth telluride (Bi_2Te_3) and lead telluride (PbTe), the manufacturers of thermo electric modules provide bismuth telluride thermoelectric modules. So it's will be used to build the system.

Chapter Three

3. Optimal System Design

3.1 Introduction

Based on the previous chapter, the properties of some materials can be used to build a device that converts heat produced from combustion in the engine into electrical energy.

3.2 Thermoelectric module specifications

This device will be built by assemblage many pieces of bought thermoelectric modules, figure 3.1, to achieve voltage, current and power required by the vehicle.

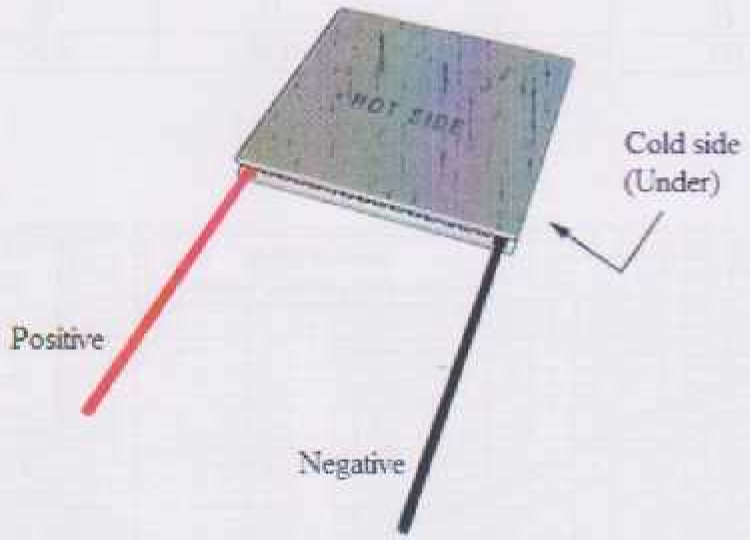

Figure 3.1: Thermoelectric module.

Each piece of this module has a weight of 60 grams, dimensions as shown in figure 3.2 and table 3.1, output voltage, current and power as shown in figures 3.3, 3.4 and 3.5 respectively [5].

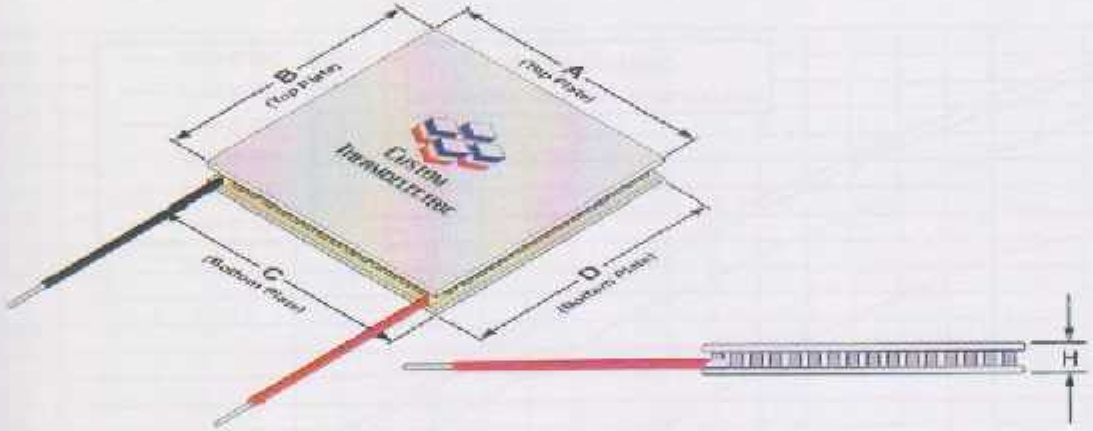

Figure 3.2: Thermoelectric module dimensions.

Table 3.1: Thermoelectric module dimensions.(All dimensions in mm)

Top plate		Bottom plate		Height
A	B	C	D	H
56.0	56.0	56.0	56.0	5.0

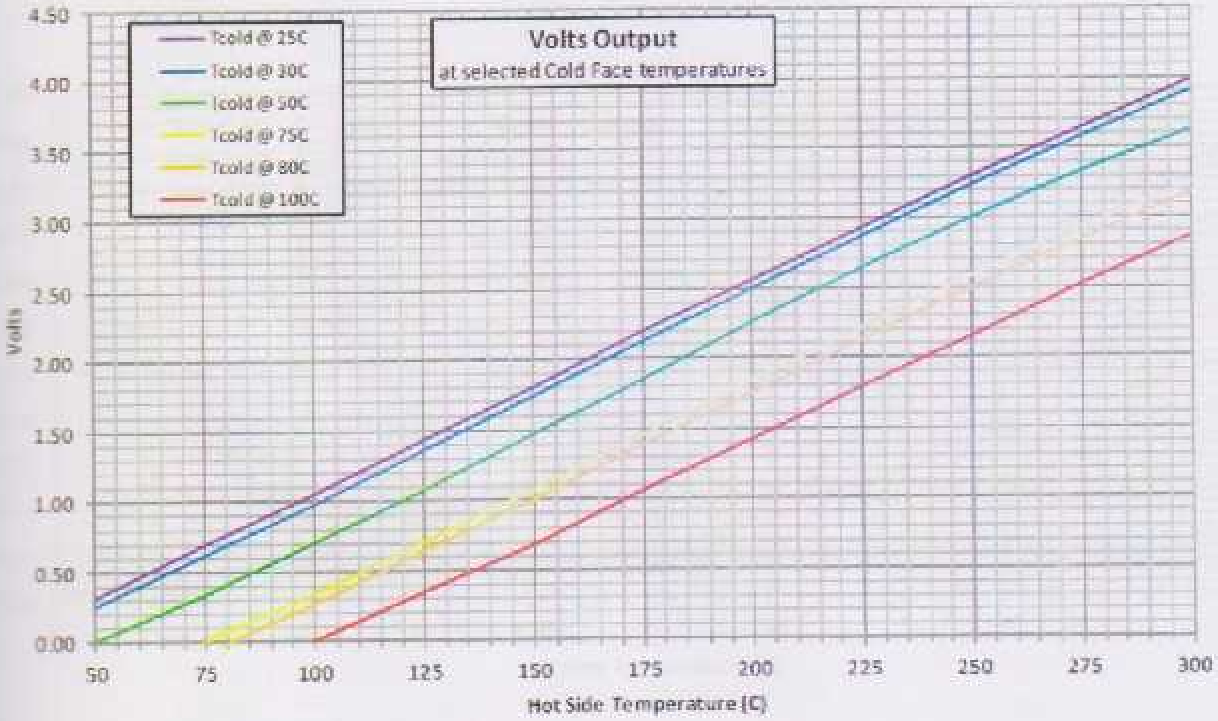

Figure 3.3: TEG output voltage.

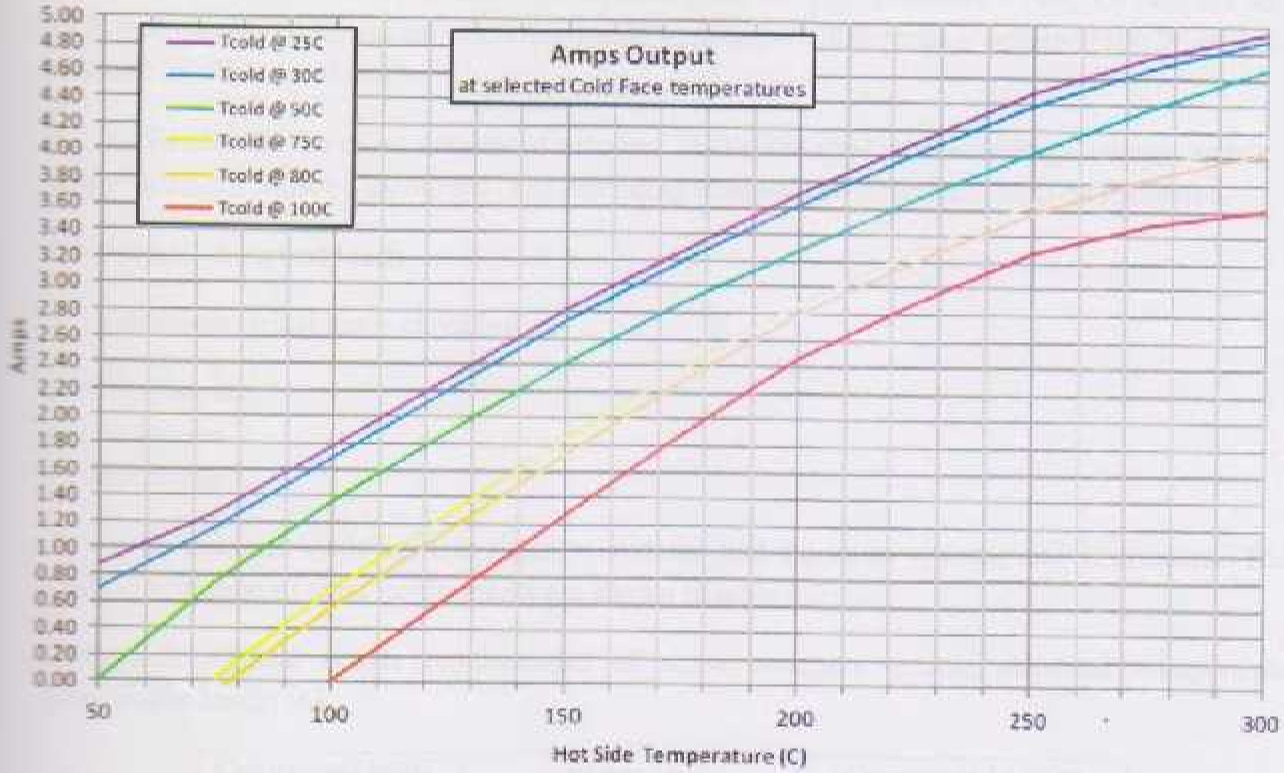

Figure 3.4: TEG output current.

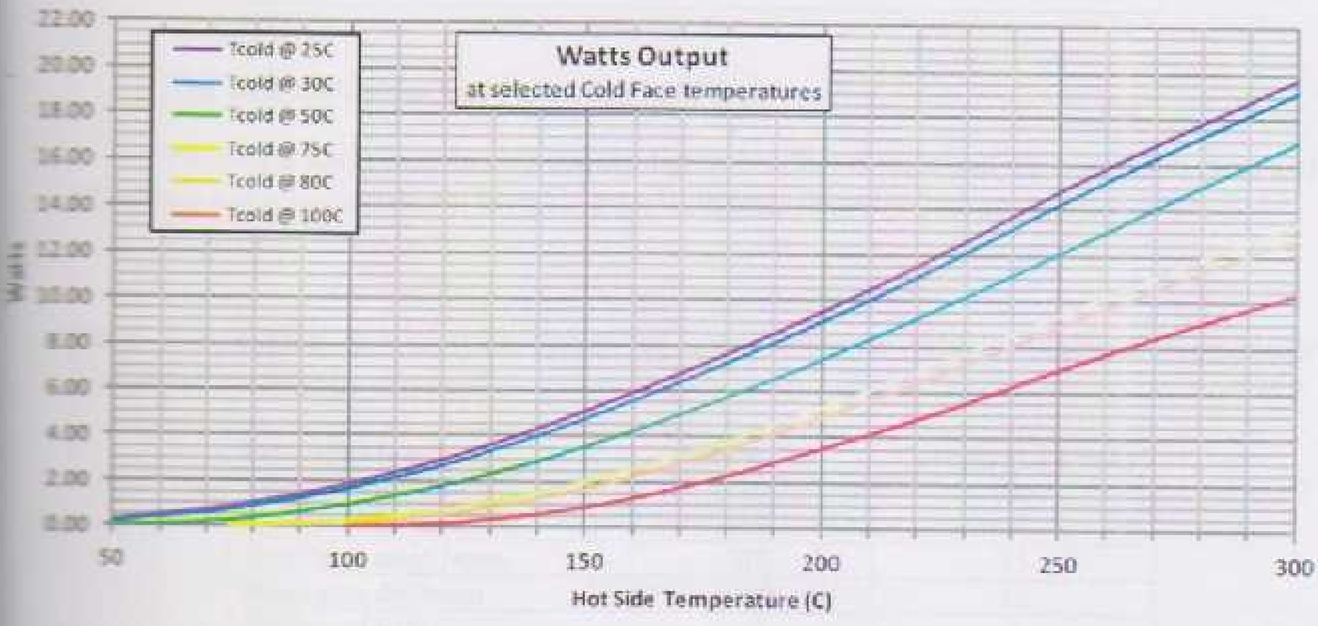

Figure 3.5: TEG output power.

As it was shown in previous figures, each piece of TEG produces 4Volt, 4.9 Ampere and 19.6 Watt as maximum values when maximum temperature difference is applied (300 °C on hot side and 25 °C on cold side).

To identify the exact number of required TEG's, the total vehicle voltage, current and power demands must be identified , and operating temperature difference must be measured.

3.3 Vehicle electrical loads

Vehicle electrical loads classified as:

1. Continuous.
2. Prolonged.
3. Intermittent.

Continuous loads contain ignition system, fuel injection system, and instrument. The loads distribution of these components are shown in table 3.2.

Table 3.2: Typical power requirements of some common vehicle electrical components (continuous loads) [6].

Continuous loads	Power (w)	Current at 14 V(A)
Ignition	30	2
Fuel injection	70	2.5
Fuel pump	70	2.5
Instruments	10	1
Total	180	13

The total continuous loads are around 180 watt.

Prolonged loads contain side and tail lights, headlights main and dip beam, and radio and CD player and others as shown in (table 3.3). With total power of 260 watt.

Table 3.3: Typical power requirements of some common vehicle electrical components (prolonged loads) [6].

Prolonged loads	Power (w)	Current at 14 V(A)
Side and tail lights	30	2
Number plate lights	10	1
Headlights main beam	200	15
Headlights dip beam	160	12
Dashboard lights	25	2
Radio\cassette\CD	15	1
Total (Av. main & dip)	260	19

Intermittent loads include front and rear wipers, interior lights, horn, reverse light and others. Its average power is calculated by summing of all loads power and then multiply it by a factor of 0.1 (table 3.4).

Table 3.4: Typical power requirements of some common vehicle electrical components (intermittent loads) [6].

Intermittent loads	Power (w)	Current at 14 V(A)
Heater	50	3.5
Indicators	50	3.5
Brake lights	40	3
Front wipers	80	6
Rear wipers	50	3.5
Electric windows	150	11
Radiator cooling fan	150	11
Heater blower motor	80	6
Heater rear window	120	9
Interior lights	10	1
Horns	40	3
Rear fog lights	40	3
Reverse lights	40	3
Auxiliary lamps	110	8
Cigarette lighter	100	7
Headlight wash wipe	100	7
Seat movement	150	11
Seat heater	200	14
Sun-roof motor	150	11
Electric mirrors	10	1

The average intermittent loads when the factor is applied equals around 170 watt.

The sum of all these loads is :

$$180 + 260 + 170 = 610 \text{ watt}$$

From these tables, the vehicle needs 43 ampere at 14 volt in addition to the current required to recharge the battery [6].

To insure that these values are correct actually, voltage-ampere measuring test has been made to the car project which identified in appendix A, with maximum possible electrical load is applied. The test shows around 50 Ampere current demand with 14 Volt.

3.4 Operating temperature measuring

To identify operating temperature, exhaust pipe temperature is measured under different conditions. After measuring the new exhaust pipe temperature at different positions as shown in figure 3.4, figures 3.5 and 3.6 for idle speed and 3000 RPM respectively are produced.

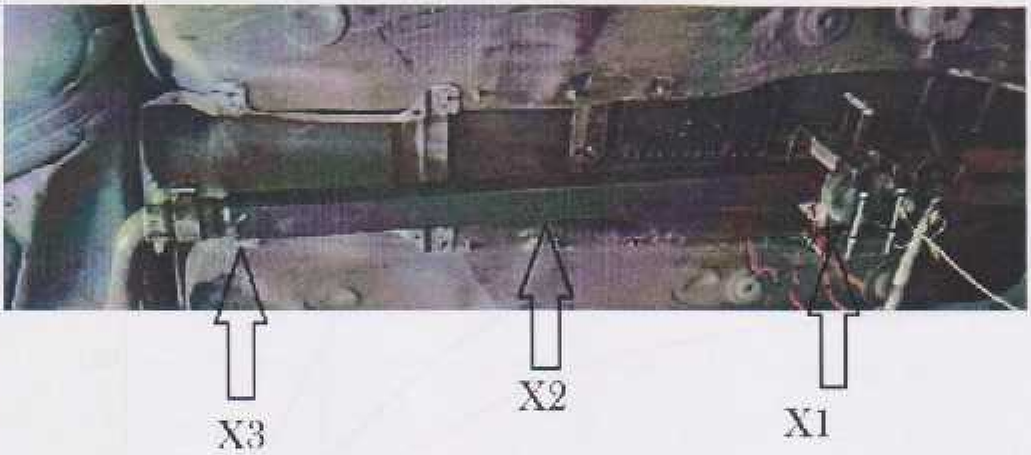

Figure 3.4: Measuring temperature positions on new exhaust pipe.

Knowing that the distance between X_1 and X_2 is 60 cm and between X_1 and X_3 is 100 cm.

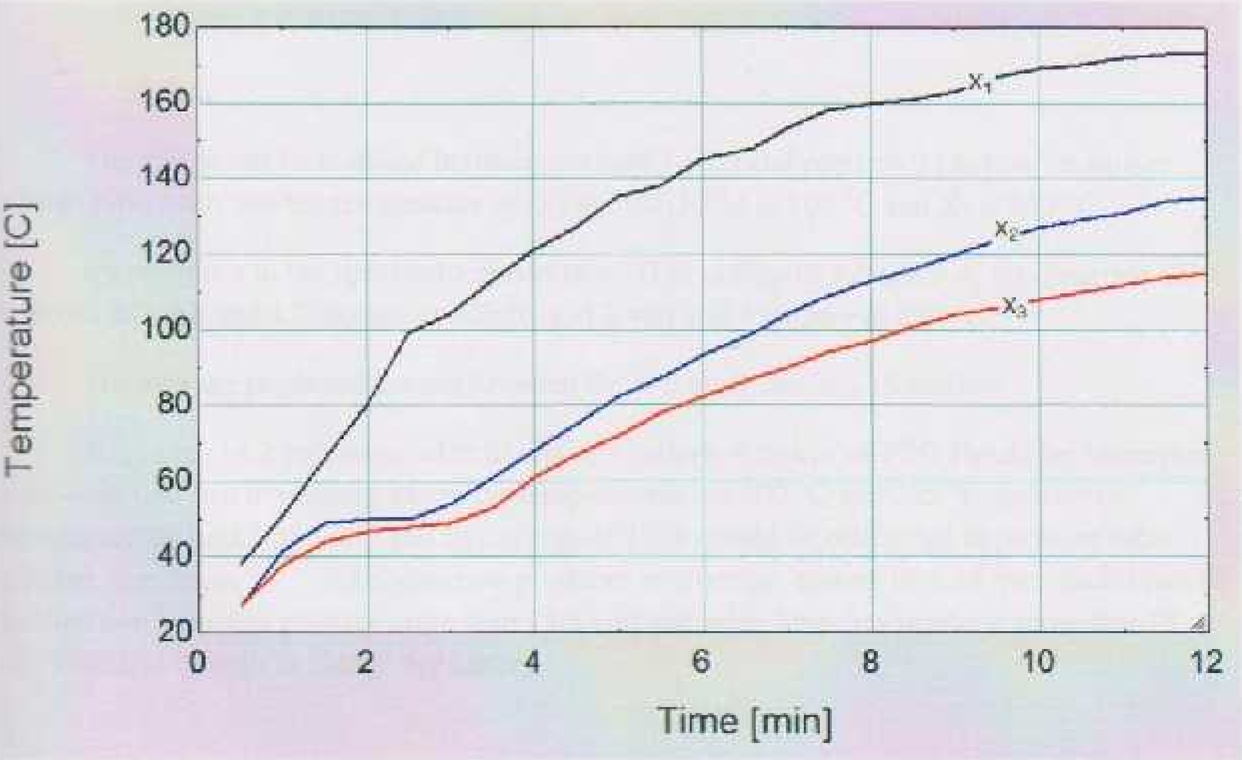

Figure 3.5: Exhaust pipe temperature at various positions at idle speed.

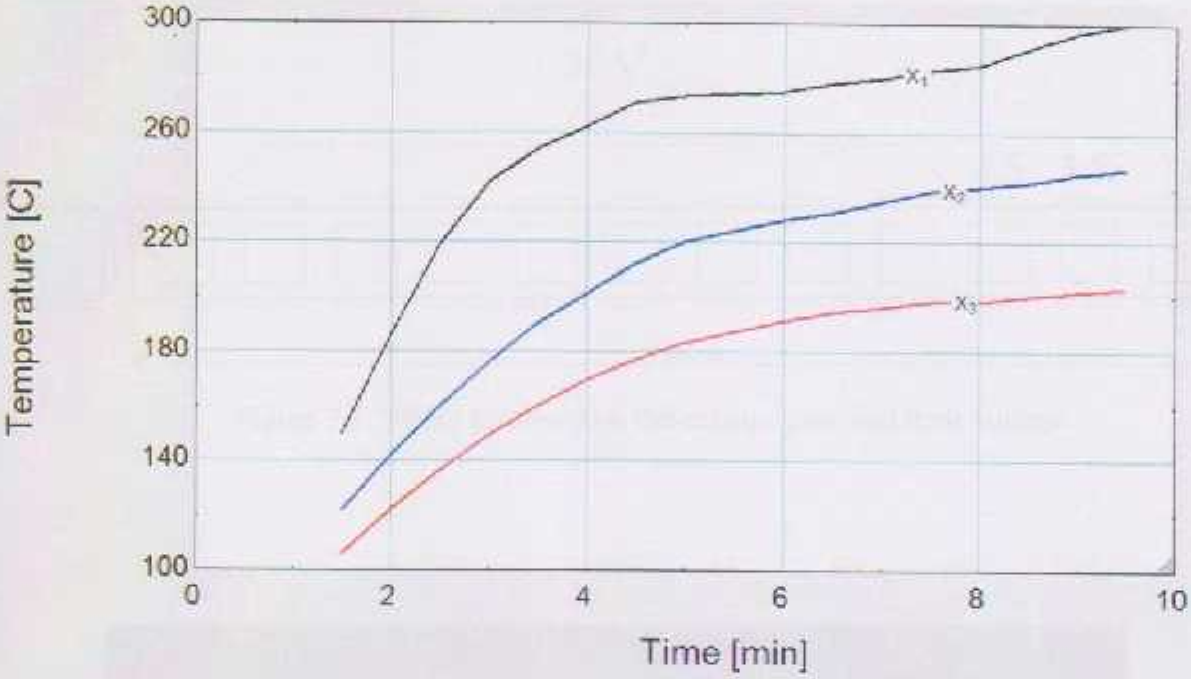

Figure 3.6: Exhaust pipe temperature at various positions at 3000 rpm.

The pieces can be installed between position 1 (X_1) and position 2 (X_2) on the square exhaust pipe, such that the temperature of X_1 at 3000 RPM is 300 °C and X_2 is 250 °C.

By reference to the specification curves of TEG in figures 3.3 and 3.4, it's clear that TEG produces 3.6 volt and 4.7 ampere at 300 °C and 3 volt and 4 ampere at 250 °C.

The average produced current between the two positions is 4.35 ampere.

To get the 14.2 volt required to charge the battery, 4 pieces of TEG should be connected in series in first two branches (where the temperatures are 300 °C and 295 °C and output voltages are 3.6 and 3.55 volt), and five pieces of TEG should be connected in series in other branches, see figure 3.7. This connection produces an average current of 4.35 from each branch. The first two branches produce more than 14.2 volt and other branches produce more than15 volt. Which is enough to charge the battery.

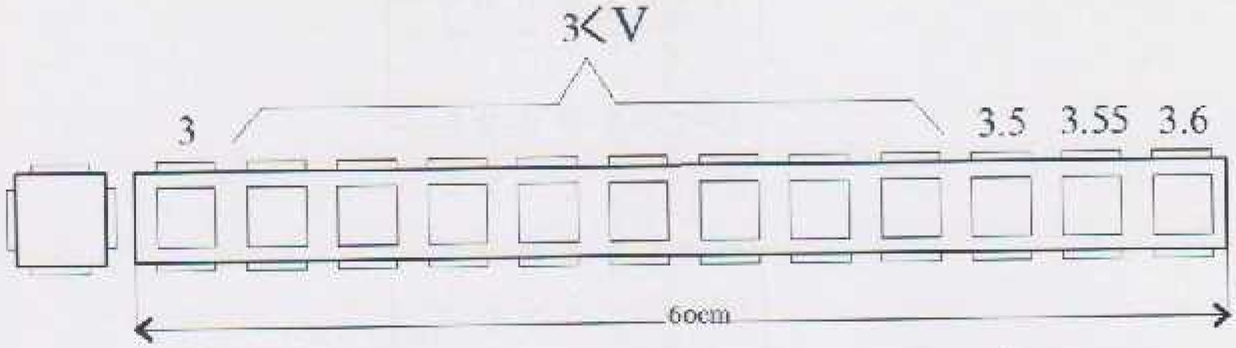

Figure 3.7: TEG's positions on the exhaust pipe and their voltage.

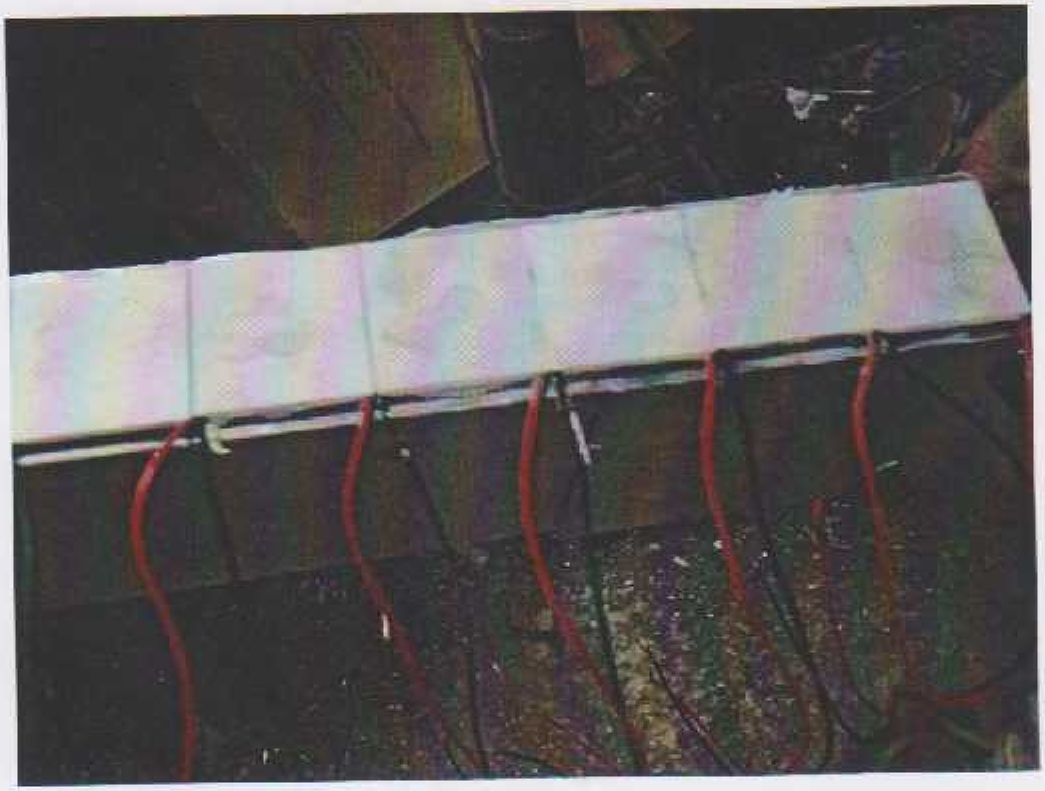

Figure 3.8:Installation of TEG's on exhaust pipe.

To get the 50 ampere demanded by vehicle electrical loads, 12 branches are required to connect in parallel as shown in figure 3.9, with total number of TEG's of 58 Piece .

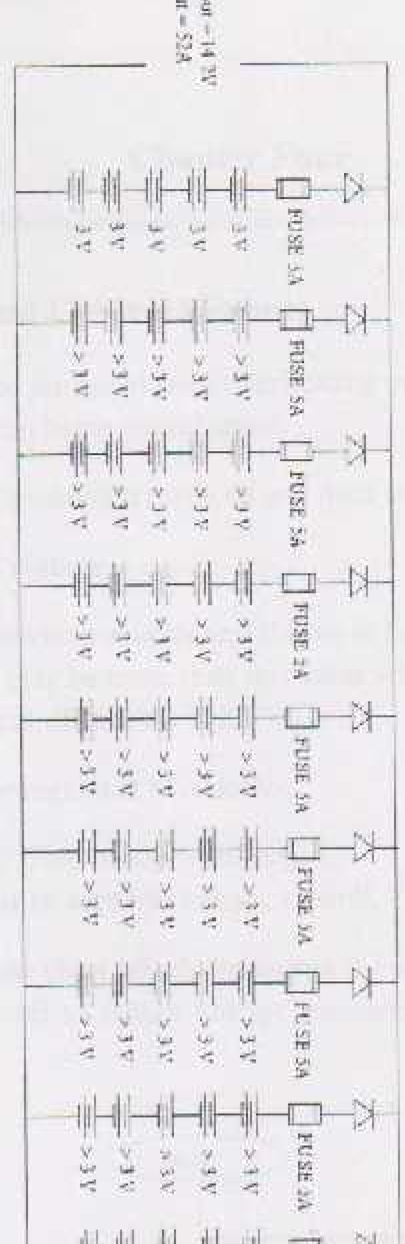

Figure 3.9: TEG's connection circuit.

Chapter Four

4. Protection Systems and Control Circuits

TEG network should be protected from overheating on both sides, hot and cold, and the battery should be protected from being overcharged.

This chapter discusses protection methods and their control circuits.

4.1 Regulation of the output voltage

As it's mentioned in previous chapter and shown in figure 3.8, the voltage of each branch is larger than 14.2 volt, and it may be more than this value when the temperature increases. So the branch voltage should be cut off to 14.2 volt.

TEG voltage should be regulated in order to:

1. Prevent the vehicle battery from being overcharged.
2. Supply electronic system with accurate voltage control.

Figure 4.1 shows a flow chart which represents the action of the regulator, showing how the TEG voltage is switched off as output voltage increases and then back on again as output voltage falls.

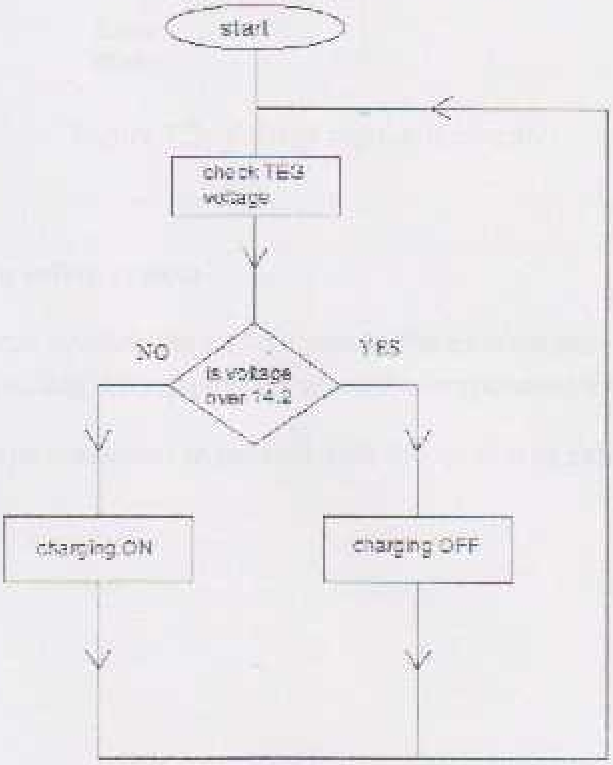

Figure 4.1: Flow chart of voltage regulator action.

Voltage regulator

Voltage regulator can be made to:

1. Sense the battery voltage.
2. Sense the TEG output voltage.
3. Combination of the two.

It's selected to sense TEG's output voltage. The regulator circuit and its components are shown in figure 4.2.

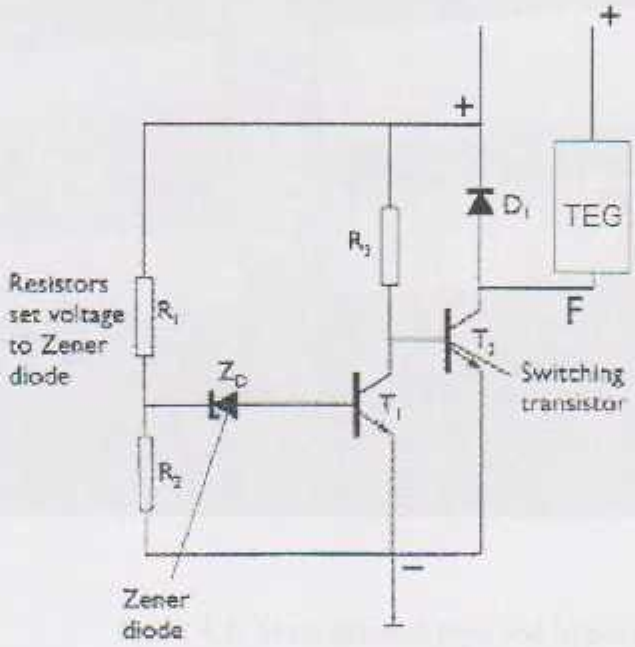

Figure 4.2: Voltage regulator circuit.

4.2 Overheat preventing safety system

To save TEG's from overheating and damaging, the exhaust gases can be prevented passing along them and passing through bypass when the temperature exceeds 300 °C.

The bypass is a pipe connected in parallel with the section of exhaust pipe that contains TEG pieces, figure 4.3.

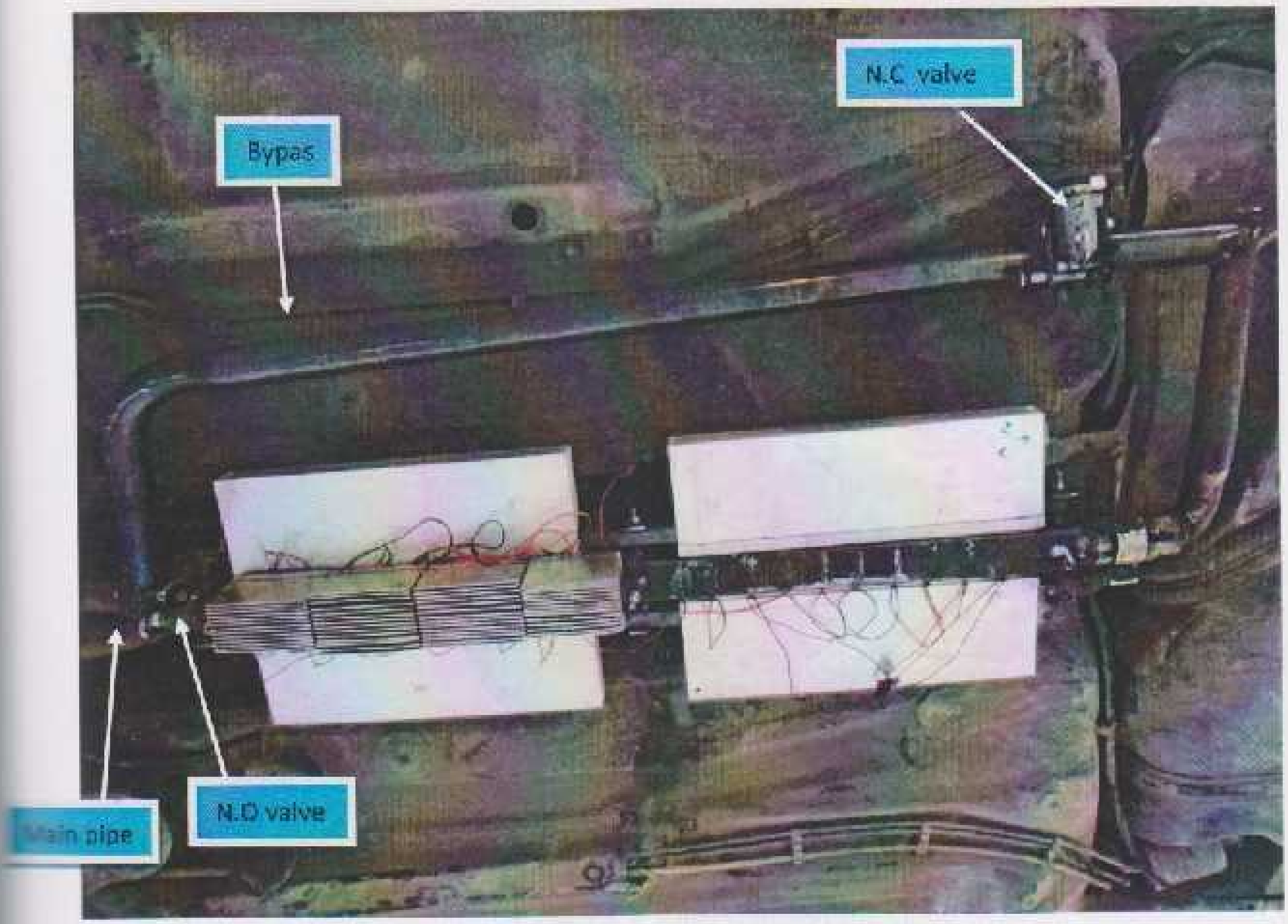

figure 4.3: Main exhaust pipe and bypass.

This bypass should have two throttle valves, one is normally open and the other is normally closed, to control gas flow in main pipe and bypass, figure 4.4.

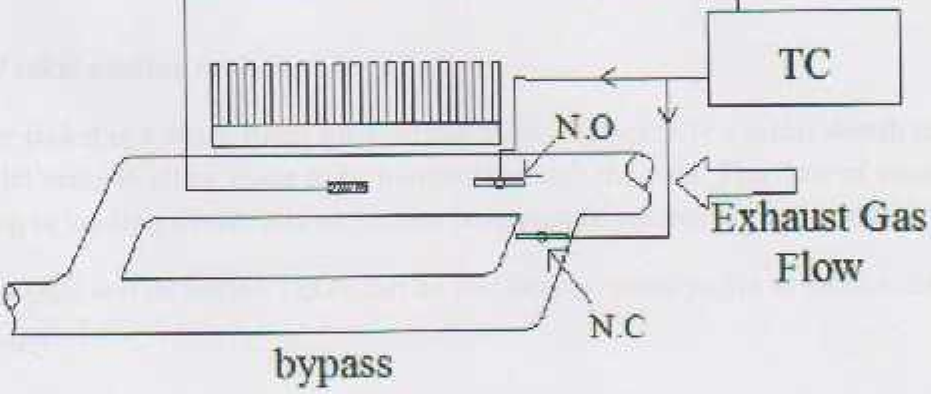

Figure 4.4: Exhaust gas bypass schematic diagram and hot side temperature monitoring.

The bypass valves are operated by temperature controller (TC), identified in appendix B, which measures exhaust pipe temperature using a thermocouple connected on the pipe and sends signals to the valve motor.

Throttle valves are a throttling plate connected to electrical motor which is operated by 5 volt received from temperature controller, figure 4.5.

Figure 4.5: Electronic throttle valve.

On the other hand, the cold side temperature of TEG mustn't exceed 180 °C or it will be damaged. But in this system, cold side temperature is preferred to be lower than 100°C in order to guarantee high performance.

To achieve that, cold side must be provided by cooling system which may be a water jacket around the TEG's or an air cooling system.

4.2.1 Water Jacket cooling system

A water jacket is a water-filled surrounding a device, typically a metal sheath having intake and outlet vents to allow water to be pumped through the void. The flow of water to an external heating or cooling device allows precise temperature control of the device[8].

Exhaust pipe and its settled TEG's can be shielded by water jacket to reduce cold side temperature, figure 4.6.

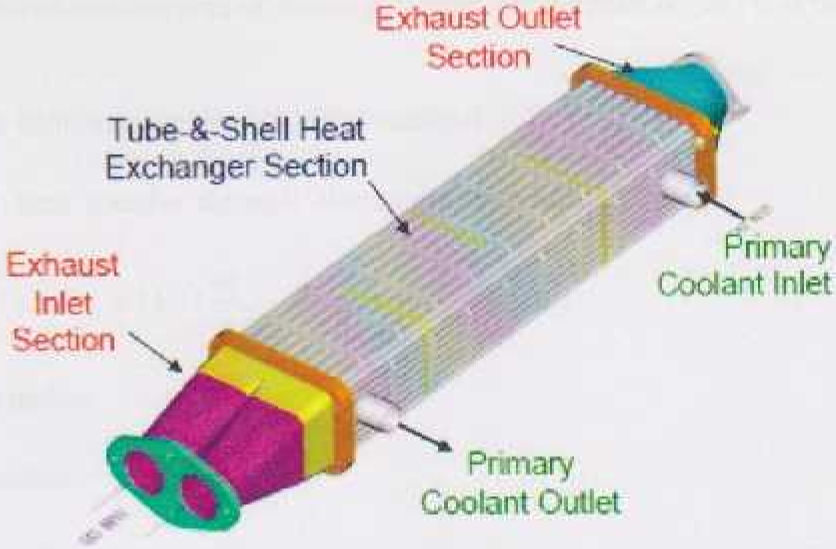

Figure 4.6: water jacket cooling system.

Using this system needs an additional radiator (heat exchanger) to cool water from 90 °C (engine coolant temperature) to 25 °C, which is very difficult to be achieved. As well as adding extra amount of coolant creates an additional load to the water pump thus to the engine. So this cooling method will be neglected.

4.2.2 Air cooling system

The environmental air can be used to cool the other side of the TEG's, but it's necessary to increase the surface area of TEG's cold side in order to increase cooling efficiency. That can be achieved by using a heat exchanger which may be aluminum fins settled on the TEG's cold side, figure 4.7.

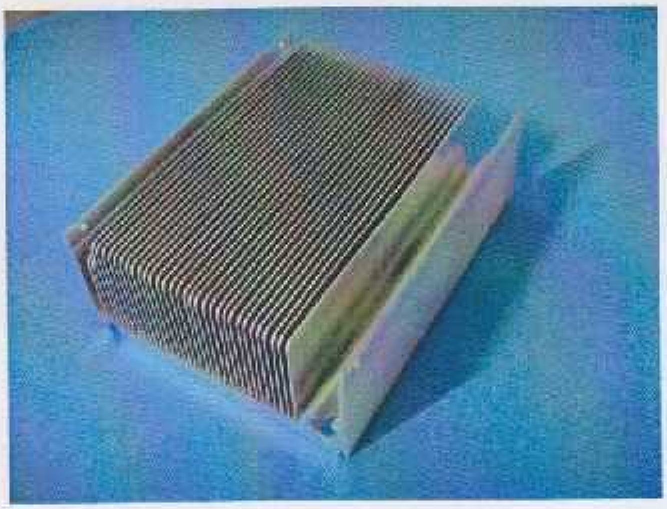

Figure 4.7: fins heat exchanger.

The required surface area of fins to guarantee temperature of 25 °C is calculated as follow:

Q_t : Conduction heat transfer through TEG material.

Q_c : Convection heat transfer through aluminum material.

U_c: Velocity of air. $U_c = 11.11 \frac{m}{s}$.

R_e: Reynolds number.

N_u: Nusselt number.

H_c : Coefficient of heat convection.

P_r : Prandtl number.

$$Q_t = Q_c \tag{4.1}$$

$$Q_t = -\frac{K_{teg} \times A \times \Delta T}{\Delta X} = -\frac{1.5 \times 4 \times 80 \times 10^{-4} \times -250}{4 \times 10^{-3}} = 3000\ watt \tag{4.2}$$

$$\text{Re} = \frac{Uc \times D}{\upsilon} = \frac{11.11 \times 6.36 \times 10^{-2}}{2.7 \times 10^{-4}} = 2617.28 \tag{4.3}$$

$$Nu = 0.3 + \frac{\left(0.62 \times \text{Re}^{0.5} \times \text{Pr}^{0.33}\right)}{\left(1 + \left[\frac{0.4}{\text{Pr}}\right]^{0.66}\right)^{0.25}} \times \left[1 + \left(\frac{\text{Re}}{282000}\right)^{0.5}\right] = 27.25 \tag{4.4}$$

$$h_c = \frac{K \times Nu}{D} = \frac{0.024 \times 27.25}{6.36 \times 10^{-2}} = 10.28 \frac{w}{m\ c} \tag{4.5}$$

$$\begin{aligned} Q_c &= h_c \times A_f \times \Delta T \\ 3000 &= 10.28 \times A_f \times 225 \\ A_f &= 1.29 m^2 \end{aligned} \tag{4.6}$$

These calculations show that the required area is 1.29 m^2, so the actual used area is 2 m^2 of aluminum fins.

These calculations based on air speed of 50 Km/h (11.11 m/s), the average driving speed, but when the speed decreases or when the vehicle stops the efficiency of cooling decreases, so the TEG's should be prevented from cold side overheating.

When temperature of cold side increases and exceeds 100 °C, the bypass valve operates by temperature controller (TC) to prevent the gas flowing along the TEG's and allow it to flow through bypass pipe, figure 4.8.

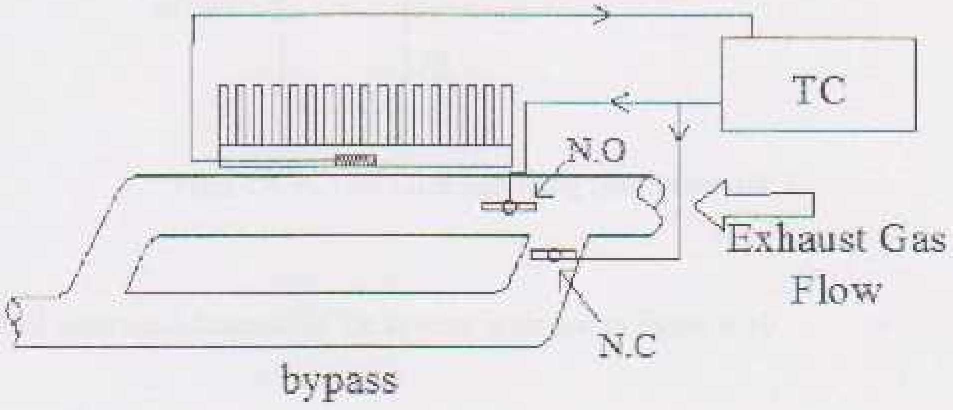

Figure 4.8: Exhaust gas bypass schematic diagram and cold side temperature monitoring.

4.3 Hybrid system

Hybrid system is used to compensate TEG shortage when low temperature difference is applied by using the traditional alternator to provide the rest voltage and current.

The alternator operation can be controlled by an electrical control unit depending on TEG's output voltage, figure 4.9.

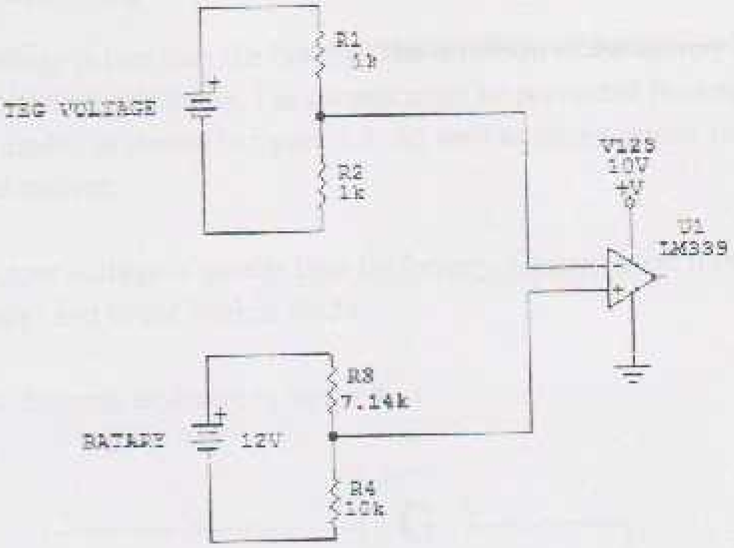

Figure 4.9: Alternator operating control circuit.

The overall schematic diagram of the system is shown in figure 4.10.

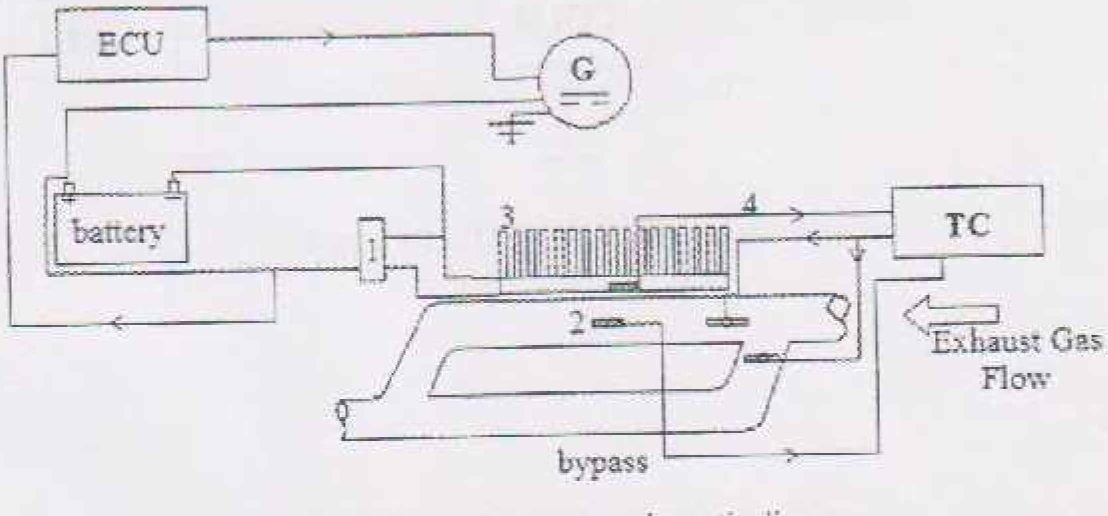

Figure 4.10: Overall system schematic diagram.

Where:

1. Voltage regulator.
2. Exhaust pipe temperature sensor.
3. Thermoelectric generator.
4. TEG cold side temperature sensor.

4.4 Charging system operating modes

1. When the TEG voltage is less than the battery. The direction of the current flow must be from the battery to the vehicle loads. The current must be prevented flowing from the battery to the TEG using diodes as shown in figure 3.8. As well as the alternator must share providing required current.

2. When the TEG output voltage is greater than the battery. Current must flow from TEG to the battery (if necessary) and to the vehicle loads.

Control schematic diagram is shown in figure 4.11.

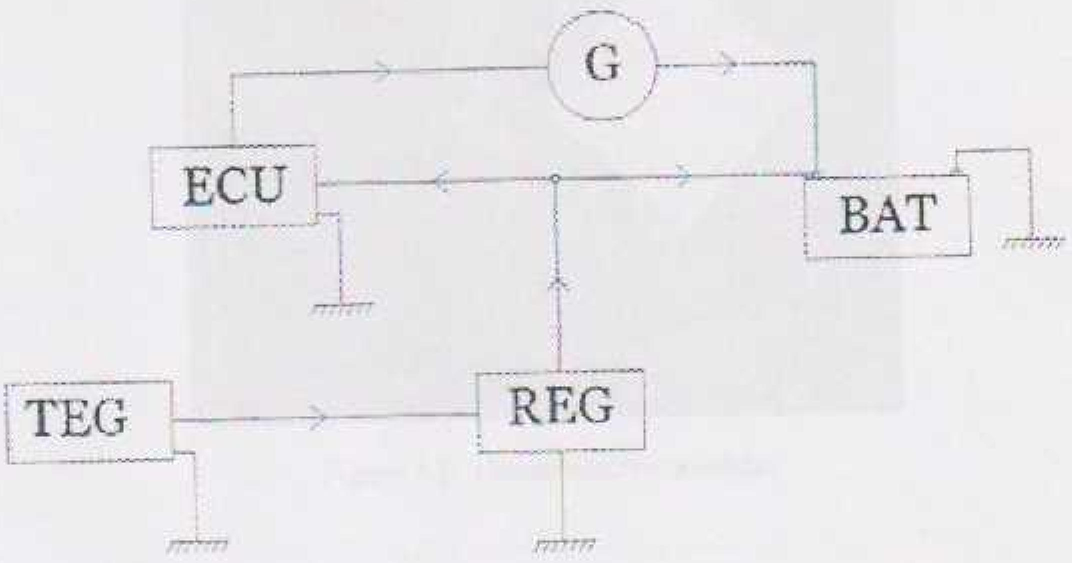

Figure 4.11: TEG's control schematic diagram.

Chapter Five

5. Building the System

To build this system, TEG's with the following proprieties have been used instead of that mentioned in the previous chapter, figure 5.1.

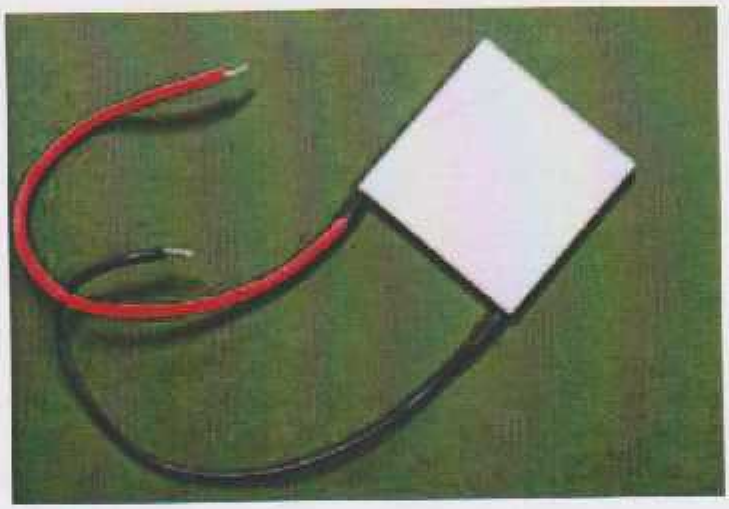

Figure 5.1: Thermoelectric module.

Each piece of this module has a weight of 20 grams, dimensions as shown in figure 5.2 and table 5.1 and output voltage as shown in figure 5.3.

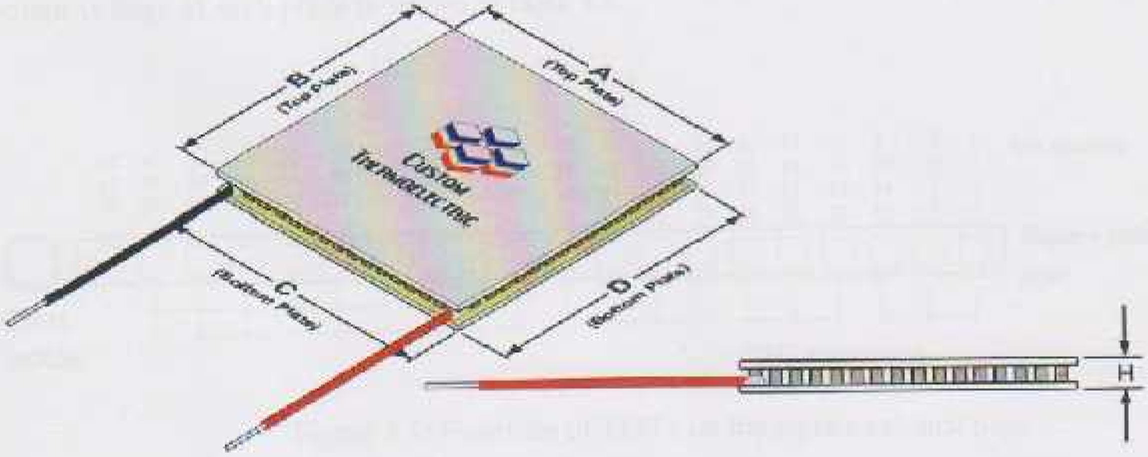

Figure 5.2: Thermoelectric module dimensions.

Table 5.1: Thermoelectric module dimensions.(All dimensions in mm)

Top plate		Bottom plate		Height
A	B	C	D	H
40	40	40	40	4

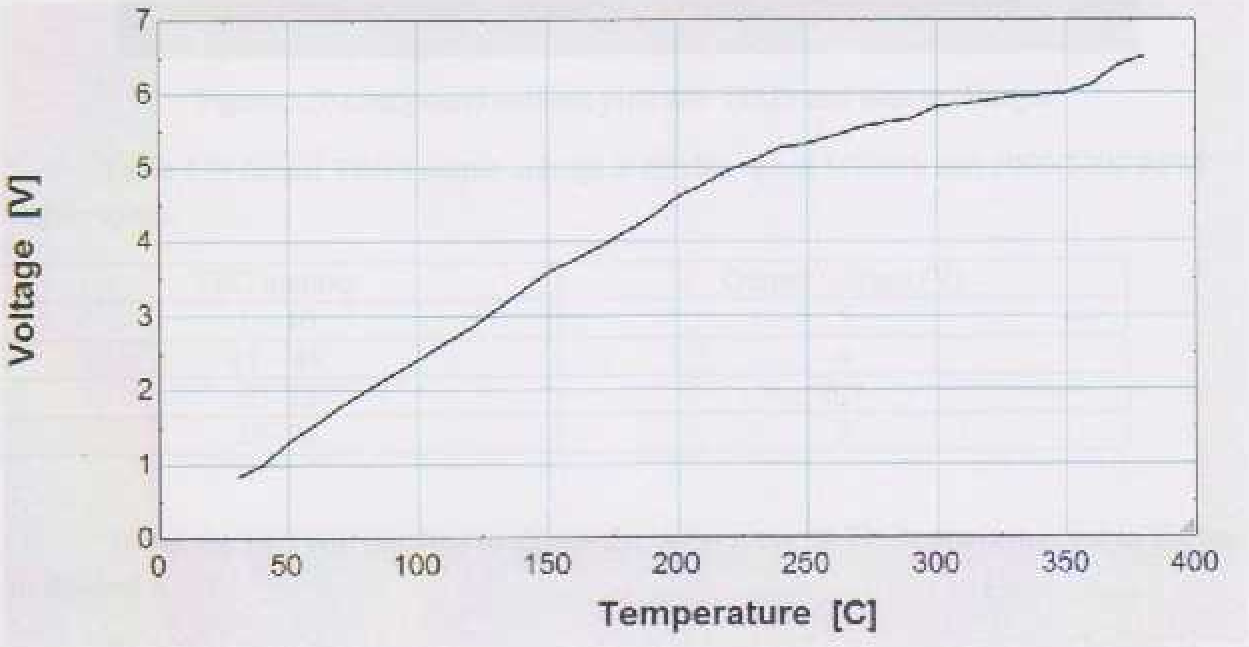

Figure 5.3: TEG output voltage when cold side temperature is 10 °C.

Each TEG can produce 6 volt as shown in figure 5.3 and up to 0.5 ampere.

When 70 pieces of TEG are installed in new exhaust pipe, figure 5.4 and figure 5.5, and driving the vehicle on the road at speed of 50 Km/h and engine speed of 2000 – 3000 RPM, the output voltage of each piece is shown in table 5.2.

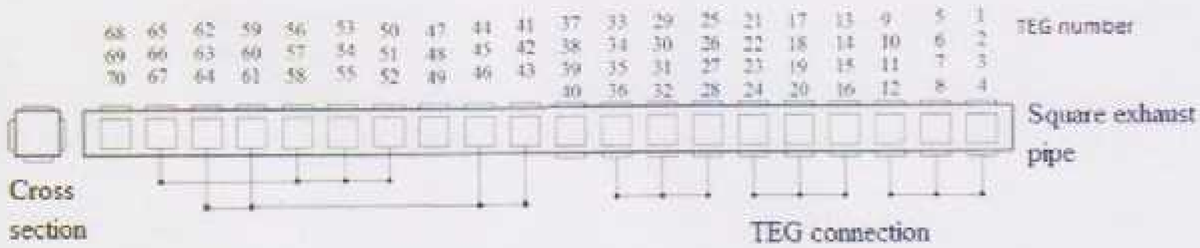

Figure 5.4: Positions of TEG's on the square exhaust pipe.

Figure 5.5: Compound exhaust pipe and TEG's and heat exchanger.

Table 5.2: Actual TEG's output voltage at driving speed 50Km/h and 2000-3000 RPM engine speed.

TEG number	Output voltage (V)
1 – 40	5
41 – 49	4
50 -58	3.7
59 -70	3

To get the 14.2 volt required to charge the battery, the 70 TEG's are connected as shown in figure 5.6.

Each branch in this circuit produces 14 volt at least and 0.5 ampere, so each branch is protected by 0.5 ampere fuse, thus the whole circuit produces 14 volt and 10.5 ampere.

Protection systems and control circuits are as shown in chapter four.

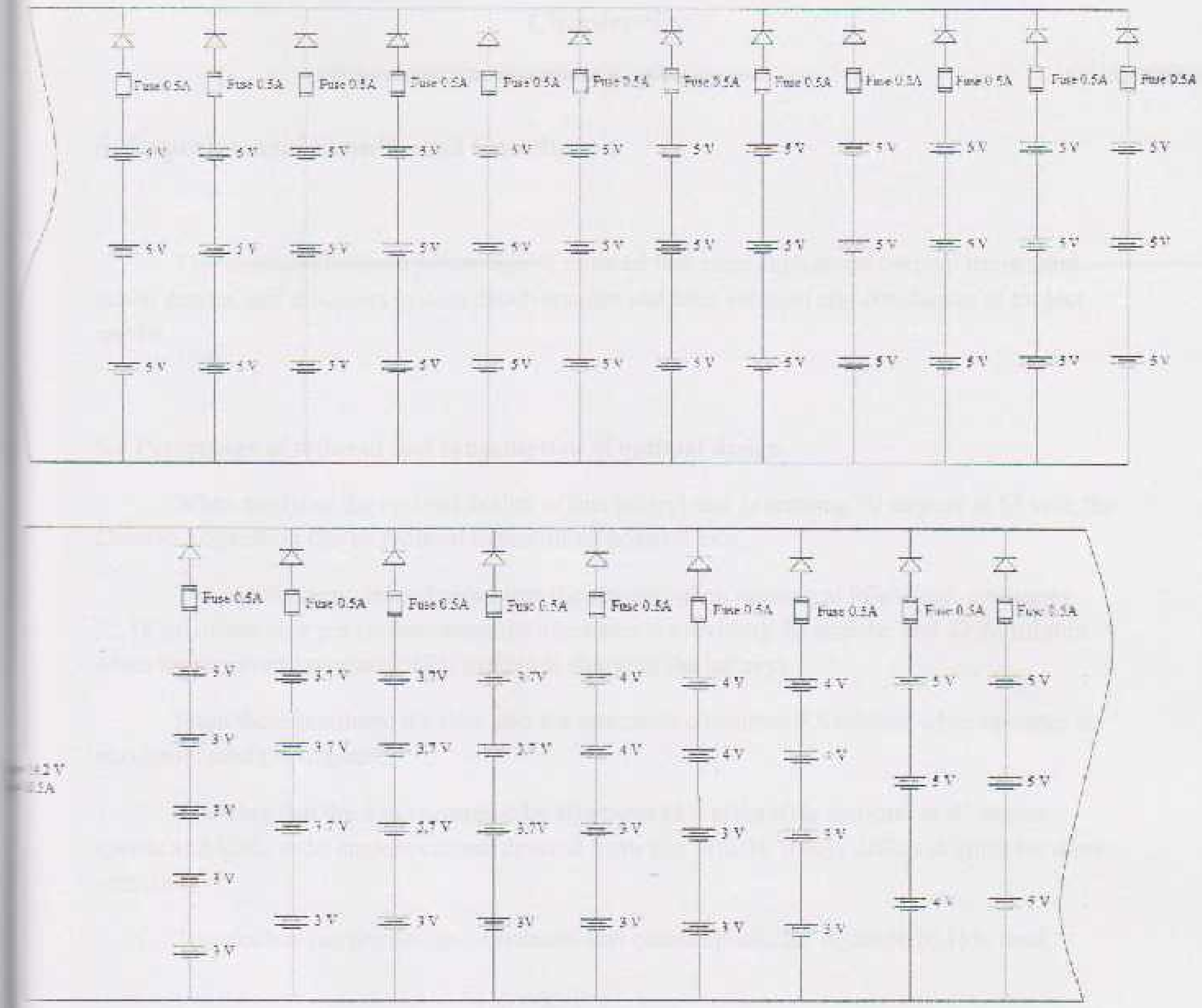

Figure 5.6: TEG's connection circuit.

Chapter Six

6. Experimental Results and Conclusion

This chapter discusses percentage of reduced fuel consumption for optimal design and actual design, and discusses system disadvantages and their solution and conclusion of project results.

6.1 Percentage of reduced fuel consumption of optimal design

When applying the optimal design of this project and generating 50 ampere at 14 volt, the alternator operation can be reduced to minimum possible rate.

The experimental tests showed that the engine, when running at idle speed, consumes 32.18 ml of gasoline per minute when the alternator is providing 50 ampere, and 22.28 ml/min when it's removed (assuming TEG system is charging the battery).

From these numbers, it's clear that the alternator consumes 9.9 ml/min when operates at maximum load (50 ampere).

Knowing that the fuel consumed by alternator (9.9 ml/min) is constant at all engine speeds and loads at 50 ampere current demand from this vehicle, it may differs slightly for other vehicles.

To calculate the percentage of reduced fuel consumption, the equation (6.1) is used

$$\text{Percentage of fuel saving} = \left[\frac{(X_1 - X_2)}{X_1}\right] \times 100\% \qquad (6.1)$$

Where:

X_1: consumed fuel when the alternator is operated at full load.

X_2: consumed fuel when the alternator is removed (assuming the TEG's are charging the battery).

To measure the amount of consumed fuel when the alternator is in operation, the vehicle has been driven for 10 minutes at average speed of 50Km/h, and then driven for the same period at the same speed but when the alternator is removed .The fuel consumptions were 1.13 liter and 1.03 liter respectively.

Substituting these values in equation (6.1) gives that the percentage of reducing fuel consumption is about 10%, as follow:

$$\text{Percentage of fuel saving} = \left[\frac{(1.13-1.03)}{1.13}\right] \times 100\% = 8.85\% \quad (6.2)$$

6.2 Percentage of fuel consumption of actual design

In actual design, the TEG system supplies around 10 ampere, so to calculate the percentage of reduced fuel consumption, equation (6.1) is used.

Such that X1 is the amount of consumed fuel for 10 minutes at 25 ampere supplied by the alternator, and X_2 is the amount of consumed fuel also for 10 minutes at 15 ampere supplied by the alternator and 10ampere supplied by TEG's.

The test shows that X_1 is 1.04 liter and X_2 is 1.02 liter.

$$\text{Percentage of fuel saving} = \left[\frac{(1.04-1.02)}{1.04}\right] \times 100\% = 1.92\% \quad (6.3)$$

6.3 Economic feasibility of the system

As it's previously mentioned, the new system reduces fuel consumption, and this is one of the main objectives of the project, whereas it reduces the alternator load.

To prove the efficiency of TEG system, economic feasibility analysis is done for the car test after and before new system is installed.

6.4 Cash flow of money after and before TEG system is installed

Based on a questionnaire distributed in Hebron city, clarified in appendix C, the average time of engine running is 3 hours per day, which means that the alternator consumes around 1.782 liters per day (9.9 ml ×60 minutes × 3 hours), and 552.4 liters per year (310 days when the holidays are neglected), and the price of a liter of gasoline is 1.96$, it consumes 1085$ per year.

The average of alternator price is 150$, and it costs around 50$ per year for maintenance, with life time of 5 years.

On the other hand, TEG doesn't need any dollar to drive it, doesn't need maintenance, and its life time is 10-15 years, with initial cost of 4640$ as well as the price of the alternator.

Representing these elements on cash flow line after and before installing TEG system for ten years and minimum attractive rate of return (MARR) of 10%, which is taken from table of appendix D, produces Figures 4.1 and 4.2 [8].

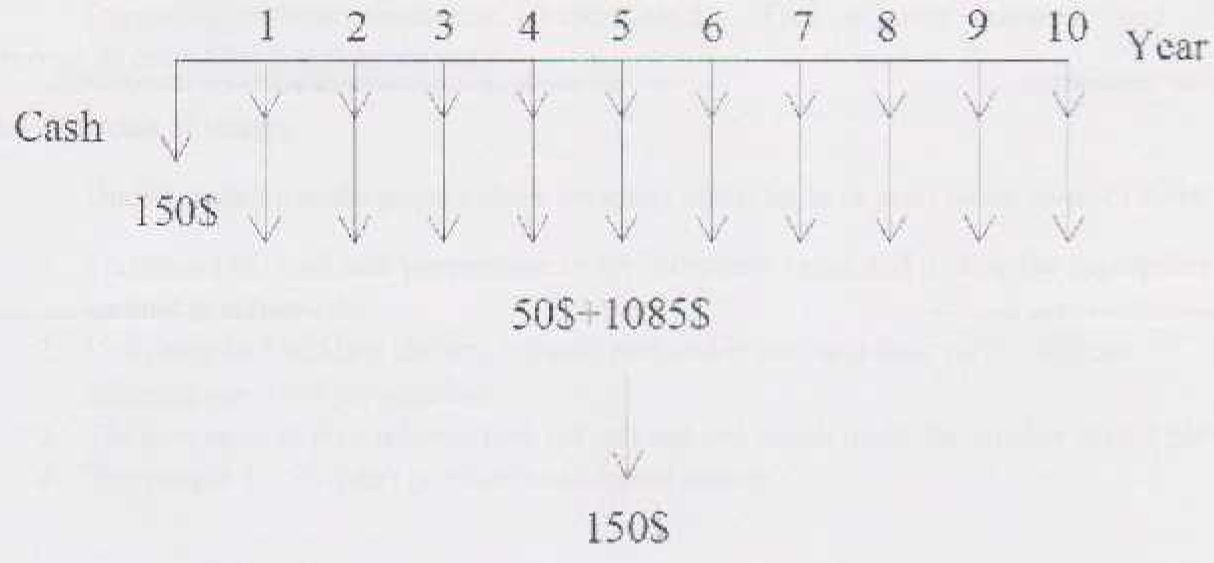

Figure 6.1: Cash flow line before installing the system.

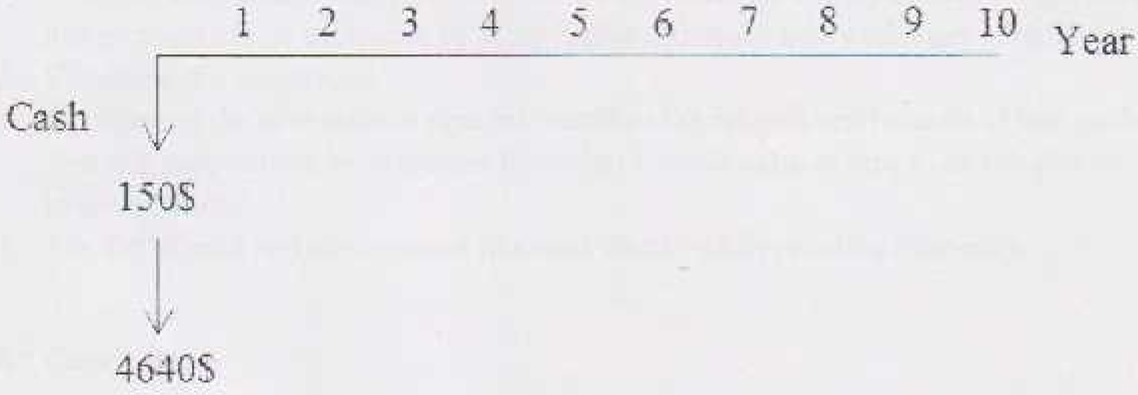

Figure 6.2: Cash flow line after installing the system.

Worth of money calculation after installing the system is done as follow:

Present worth of money = -150 – (1085+50)*(P/A, 10%,10) – 150 * (P/F, 10%, 5)

= -150 – 1135 * 6.145 – 150 * 0.621

= -7217$

Worth of money calculation before installing the system is done as follow:

Present worth of money = -4640 – 150

= -4790$

Depending on these calculations, it's clear that the TEG is more economic and will recover its costs after less than six years.

6.5 Working obstacles

During working in the project, there are many obstacles have been faced, some of them:

1. Maintain TEG cold side temperature in the acceptable range and finding the appropriate method to achieve that.
2. Designing and building the new exhaust pipe and bypass and their valves without affecting gas wave propagation.
3. The new exhaust pipe is lower than the original one which limits the number used TEG's.
4. The bought TEG's didn't provide the excepted current.

6.6 Disadvantages of the system

This project as any other project, has many problems and disadvantages, some of them:

1. Power to weight ratio.

   Additional parts which have been added to vehicle have law power to weight ratio, but this problem can be overcome by using higher efficiency heat exchanger with lighter weight.
2. Unsuitable for rough road

   Whereas the new exhaust pipe is lower than the original one because of heat exchanger. And this problem can be overcome by design a whole exhaust pipe to be suitable for irregular roads.
3. The dirt of road and environment like mud which reduces cooling efficiency.

6.7 Conclusion

4. Percentage of reduced fuel consumption may reach 10%, and differs from vehicle to another and affected by driving mode, but it depends basically on vehicle electrical loads.
5. This technology is expected to be used at most of future vehicles especially as the price of fuel is continuously increasing. And it can be included in vehicle production lines which will not cost huge amount of money.
6. It should be noted that major vehicle manufacturers are making studies, research and tests to apply this system in future vehicles.

6.8 Recommendations

1. This technology is one of alternative energy forms, so it's a good idea to use it in future vehicle.
2. This technology is expected to take a wide range in the future, so it's a good idea to improve this project in upcoming graduation projects in Palestine Polytechnic University.

3. It's possible to apply this technology in other applications which produce waste heat energy like factories and thermal furnaces.
4. This technology needs to be adopted by national scientific associations to see the light.

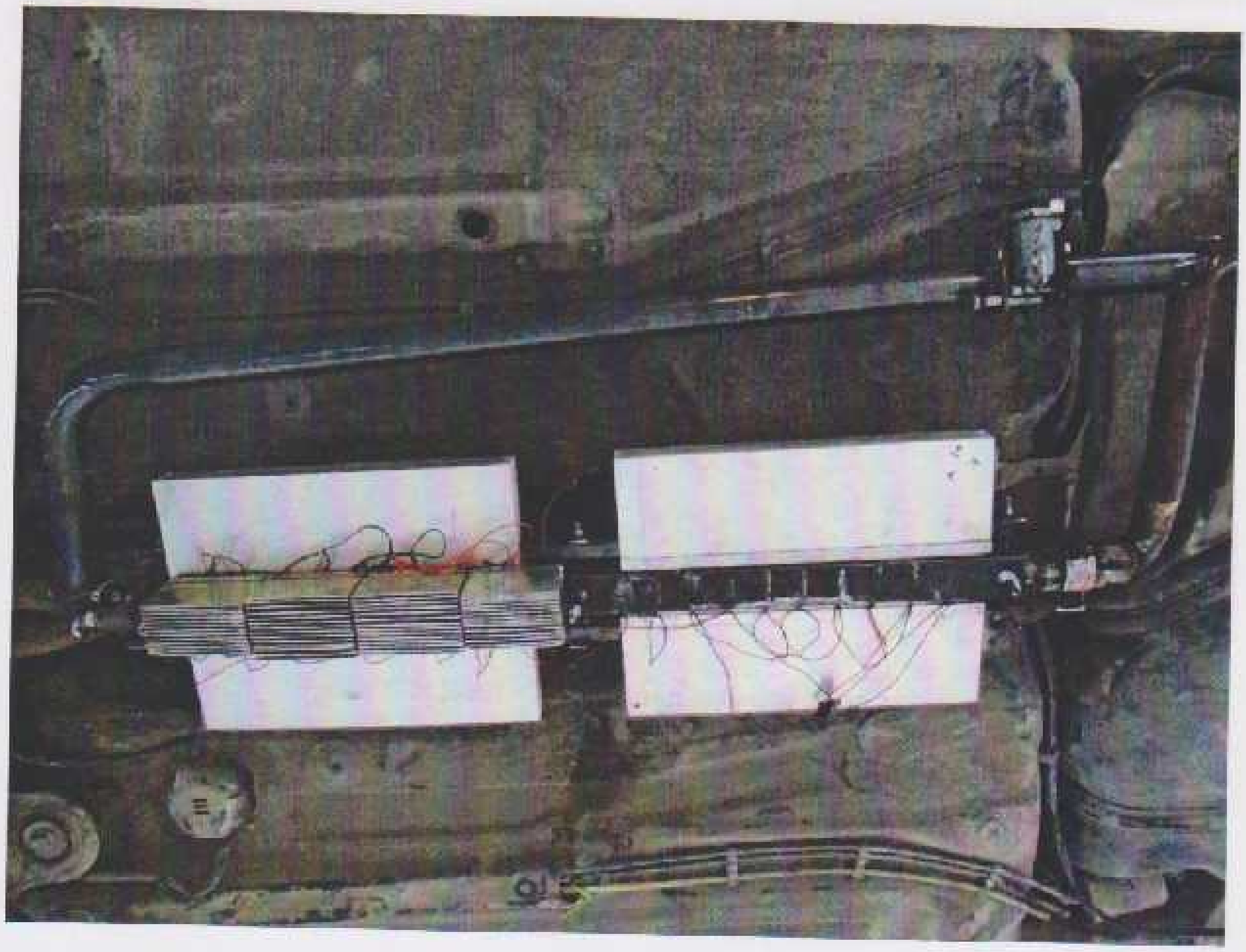

Figure 6.1: Ready TEG system installed at the vehicle.

Figure 6.2: Ready TEG system installed at the vehicle.

References:

[1] Birkholz, U., et al. "Conversion of Waste Exhaust Heat in Automobile using FeSi2 Thermoelements". Proc. 7th International Conference on Thermoelectric Energy Conversion. 1988, Arlington, USA, pp. 124-128.

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AA Car test

R9983
December 1999

VW Bora

Featuring 2.3 V5

SCORECARD

Overtaking / pulling power
●●●●○

Fuel economy
●●●○○

Handling / steering
●●●●○

Comfort / ease of control
●●●●○

Interior space / practicality
●●○○○

Accident / injury avoidance
●●●○○

Costs in service
●●●○○

Depreciation prospects
●●●○○

SO FAR, THE BORA HASN'T BEEN AN overwhelming sales success. It's a saloon version of the more versatile Golf hatchback, and although the back seats tilt and fold forwards in the same exemplary way, rear legroom is inferior on this V5 version; smaller adults still enjoy good posture support, however.

The boot is quite large, as well, although the full-sized spare wheel limits deck height somewhat and there's a prominent load sill.

OK, so there may be limitations imposed by its body style, but this has never prevented BMW's 3-Series from being a runaway success. And we're pleased to say that when it comes to its engine, gearbox and suspension, this Bora V5 is far from boring.

It possesses that still-rare quality of being able to adapt to any traffic condition or driver mood. If you want to amble around the lanes, it will do it all barely above idle speed in third and fourth, without the trace of a tremor or complaint; in spite of a silky-smooth clutch and an ideal gearchange being on hand, you seldom have to use them in this mood.

A change of pace tells a different story, however – rev the engine from 3000 to 6000rpm and the distinctive V5 burbly yowl (reminiscent of an Alfa Romeo) builds up.

All this dynamic delight would be squandered if the car's suspension and steering were not up to par. The Bora doesn't disappoint, however – it's an object lesson in how grippy, responsive cornering agility can be combined with an exemplary ride that feels just right for the part, yet never degenerates to thumpy harshness.

When you're in more tranquil mood, the springing feels suitably composed, as well.

Of course, a car with this potential isn't cheap to insure and it's not particularly frugal on fuel either – an Audi 100 V6 will do almost as well. However, it's a saloon with real merit – when you go out and drive it, it's guaranteed to put a smile on your face.

HOW THE BORA COMPARES	Engine cap/power (cyl/cc/bhp)	Revs at 70mph (rpm)	30-70mph through gears (sec)	30-70mph in 5th/4th gears (sec)	Fuel economy (mpg)	Brakes best stop (m/kgf)†	Maximum legroom - front (cm)	Typical leg/ kneeroom - rear (cm)	Steering turns/ (p) circle (m)	Overall length (cm)
VW BORA 2.3 V5	V5/2324/150	3220	8.5	16.8/14.0	32	24/17	109	93/65	3.4/10.55	438
Audi A6 2.4 V6	V6/2393/165	3100	8.8	21.6/15.2	30½	23/19	109	100/74	2.8/11.15	480
Alfa Romeo 156 2.0 Twin Spark	4/1970/155	3310	7.8	22.6/15.7	31	26/22	106	95/76	2.2/11.4	443
Peugeot 406 2.0 16v	4/1998/135	3210	10.5	27.2/17.6	32½	25½/35	111	99/74	3.2/11.0	456
Ford Mondeo 2.5 V6	V6/2544/170	2955	8.2	21.7/15.0	29	23/33	110	102/76	2.8/11.7	456
						† all with ABS			(p) all power assisted	

PERFORMANCE

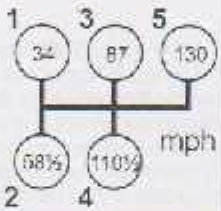
Acceleration time in seconds

mph	30–40	30–50	30–60	30–70
THROUGH THE GEARS	1.7	3.4	5.7	8.5
IN 5TH GEAR	4.8	9.4	13.9	18.8
IN 4TH GEAR	3.6	7.1	10.5	14.0

20 mph	30	40	50	60	70
5TH/4TH SPEED RANGES	9.7/7.4 (20–40)	9.4/7.1 (30–50)	9.1/6.8 (40–60)	9.4/6.9 (50–70)	

Maximum speeds

REVS PER MINUTE	1st	2nd / 3rd	4th	5th
	6150*	6250*	6250*	5975



* for best acceleration

FUEL CONSUMPTION

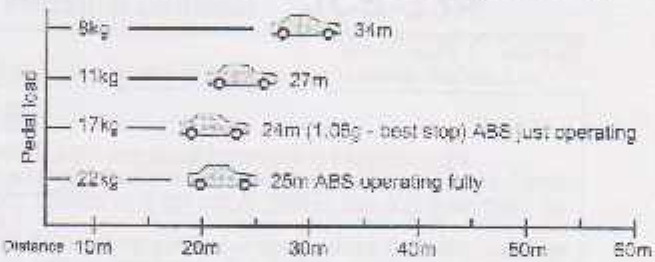
Type of use - with air conditioning off*	mpg
Urban (17mph average/heavy traffic)	22
Suburban (27mph average/6.4 miles from cold start)	27½
Motorway (70mph cruising)	33
Cross-country (brisk driving/20 miles from cold start)	31½
Rural (gentle driving/20 miles from cold start)	36½
Typical mpg overall	**32**

*with air conditioning switched on, consumption will increase by 2–4% in winter and 4–8% in summer

BRAKES

Pedal feel ●●●●○	Behaviour in an emergency ●●●●○	Handbrake ●●●○○

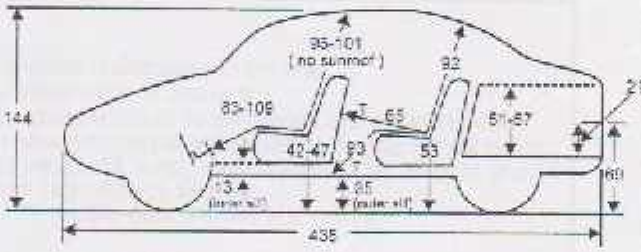
Dry road stopping distance from 50mph (with standard ABS)
(A good-to-average best stop is about 26m at 15-20kg pedal load)



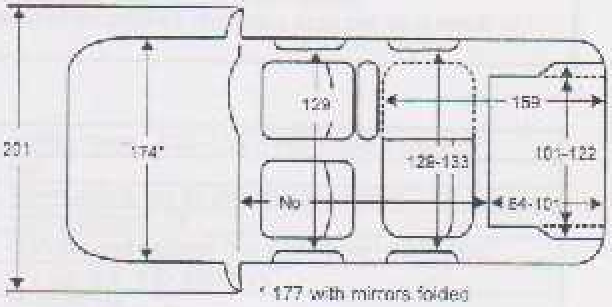
Fade test: pedal load required for a moderate (34m/.75g) stop:
8kg at start of test, 8kg at end of test *(Ideal brakes show no change)*

MEASUREMENTS

Centimetres



T: typical back seat space behind medium-sized front occupants



* 177 with mirrors folded

LIKES AND GRIPES

V5's heavily sculptured seats support well	...	but make it harder to get in and out
Optional 'Sat Now' kit costs £2,500	...	but the radio reception is terrible
Nicely weighted and placed pedals	...	but left footrest too prominent
Air con works sensitively and well	...	but display hard to see low down
Sound security includes independent boot locking	...	but ours played up on test

Appendix B

INSTRUCTION MANUAL

Micro-computer based digital indicating controller **JCS-33A**

No.JCS31E7 2004.07

To prevent accidents arising from the misuse of this controller, please ensure the operator receives this manual.

⚠ SAFETY PRECAUTIONS

- To ensure safe and correct use, thoroughly read and understand this manual before using this instrument.
- This instrument is intended to be used for industrial machinery, machine tools and measuring equipment. Verify correct usage after consulting purpose of use with our agency or main office. (Never use this instrument for medical purposes with which human lives are involved.)
- External protection devices such as protection equipment against excessive temperature rise, etc. must be installed, as malfunction of this product could result in serious damage to the system or injury to personnel. Also proper periodic maintenance is required.
- This instrument must be used under the conditions and environment described in this manual. Shinko Technos Co., Ltd. does not accept liability for any injury, loss of life or damage occurring due to the instrument being used under conditions not otherwise stated in this manual.

Caution with respect to Export Trade Control Ordinance

To avoid this instrument from being used as a component in, or as being utilized in the manufacture of weapons of mass destruction (i.e. military applications, military equipment, etc.), please investigate the end users and the final use of this instrument. In the case of resale, ensure that this instrument is not illegally exported.

⚠ Caution

- This instrument should be used according to the specifications described in the manual. If it is not used according to the specifications, it may malfunction or cause fire.
- Be sure to follow the warnings, cautions and notices. Not doing so could cause serious injury or malfunction.
- Specifications of the JCS-33A and the contents of this instruction manual are subject to change without notice.
- This instrument is designed to be installed in a control panel. If it is not, measures must be taken to ensure that the operator cannot touch power terminals or other high voltage sections.
- Be sure to turn the power supplied to the instrument OFF before cleaning this instrument.
- Use a soft, dry cloth when cleaning the instrument. (Alcohol based substances may cause tarnishing or defacement of the unit.)
- As the display section is vulnerable, do not strike or scratch it with a hard object.
- Any unauthorized transfer or copying of this document, in part or in whole, is prohibited.
- Shinko Technos CO., LTD. is not liable for any damages or secondary damages incurred as a result of using this product, including any indirect damages.

1. Model name

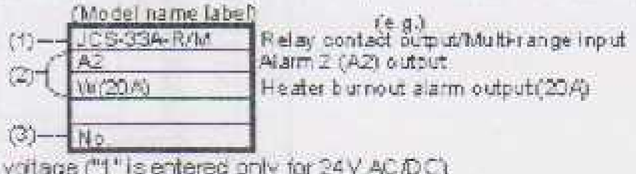
1.1 Model name

J C S – 3 3 □-□/□ □, □□□		Series name: JCS-33A (W48 x H48 x D95mm)	
Control action	3	PID	
A1	A	Alarm action can be selected by keypad. *1	
OUT1 (Control output 1)	R	Relay contact: 1a	
	S	Non-contact voltage (for SSR drive): 12^{+2}_{0}V DC	
	A	DC current: 4 to 20mA DC	
Input	M	Multi-range *2	
Supply voltage	1	24V AC/DC *3	
Option	A2	Alarm 2 (A2) *1	
	W (5A)	Heater burnout alarm	CT rated current: 5A
	W (10A)		CT rated current: 10A
	W (20A)		CT rated current: 20A
	W (50A)		CT rated current: 50A
	DT	OUT2 (Heating/Cooling control output)	Non-contact relay
	C5	Serial communication (RS-485)	
	SM	SV1/SV2 external selection	
	LA	Loop break alarm	
	BK	Color Black	
	TC	Terminal cover	

*1: Alarm actions (9 types and No alarm action) and Energized/Deenergized can be selected by keypad.
*2: Thermocouple, RTD, DC current, and DC voltage can be selected by key operation.
*3: Supply voltage 100 to 240V AC is standard. When ordering 24V AC/DC, enter "1" after the input code.

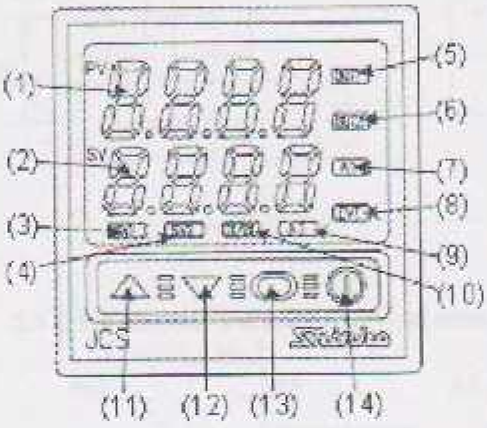
1.2 How to read the model name label

Model name labels are attached to the case and the inner assembly. For Heater burnout alarm output, CT rated current is written in the bracket.



(1): Model name (2): Option, supply voltage ("1" is entered only for 24V AC/DC)
(3): Serial number (Only on inner assembly)

2. Name and functions of the sections



(Fig. 2-1)

(1) **PV display**: Indicates the input value with a red LED.
(2) **SV display**: Indicates the setting value with a green LED.
(3) **SV1 indicator**: A green LED lights up when SV1 is indicated on the SV display.
(4) **SV2 indicator**: A yellowLED lights up when SV2 is indicated on the SV display.
(5) **OUT1 indicator**: When OUT1 or heating output is ON, a green LED lights up. (For A/□ type, it flashes corresponding to the manipulated variable in a 0.25 second cycle)
(6) **OUT2 indicator**: When OUT2 (option DT) is ON, a yellow LED lights up.
(7) **A1 indicator** : When A1 output is ON, a red LED lights up.
(8) **EVT indicator**: When Event output (option: A2, LA or W) is ON, a red LED lights up.
(9) **AT indicator** : When auto-tuning or auto-reset is being performed, a yellowLED flashes.

(10) **TX/RX indicator** : A yellowLED flashes during serial communication output (transmitting)
(11) **Increase key** (△) : Increases the numeric value.
(12) **Decrease key** (▽): Decreases the numeric value.
(13) **Mode key** (◯) : Selects the setting mode or registers the setting value. (By pressing the Mode key, the setting value or selected value can be registered)
(14) **OUT/OFF key** (◯): The control output ON/OFF function or Auto/Manual control function can be switched. (To cancel the control output ON/OFF function, press the OUT/OFF key again for approx. 1 second.)

⚠ Notice

When setting the specifications and functions of this controller, connect terminals 1 and 2 for power source first, then set them referring to Chapter "5. Setup" before performing "3. Mounting to control panel" and "4. Wiring connection".

3. Mounting to control panel

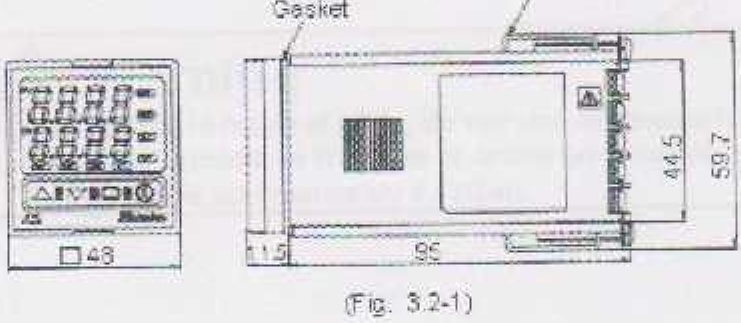
3.1 Site selection

This instrument is intended to be used under the following environmental conditions (IEC61010-1): Overvoltage category Ⅱ, Pollution degree 2

Ensure the mounting location corresponds to the following conditions:

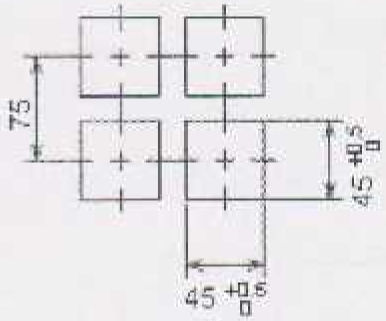
- A minimum of dust, and an absence of corrosive gases
- No flammable, explosive gases
- Few mechanical vibrations or shocks
- No exposure to direct sunlight, an ambient temperature of 0 to 50℃ (32 to 122℉) that does not change rapidly
- An ambient non-condensing humidity of 35 to 85%RH
- No large capacity electromagnetic switches or cables through which large current is flowing
- No water, oil or chemicals or where the vapors of these substances can come into direct contact with the controller

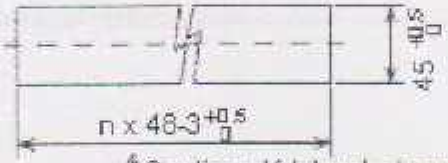
3.2 External dimensions



(Fig. 3.2-1)

3.3 Panel cutout



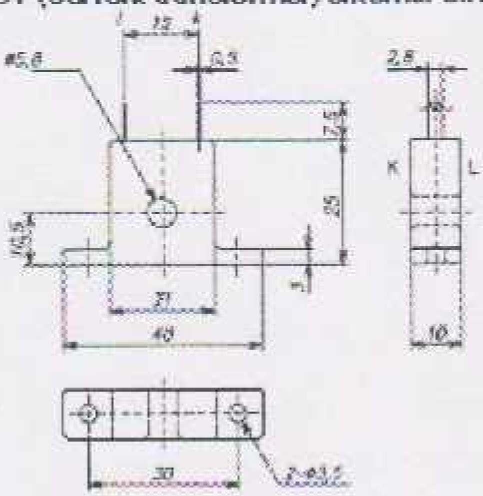


Lateral close mounting
n: Number of units mounted

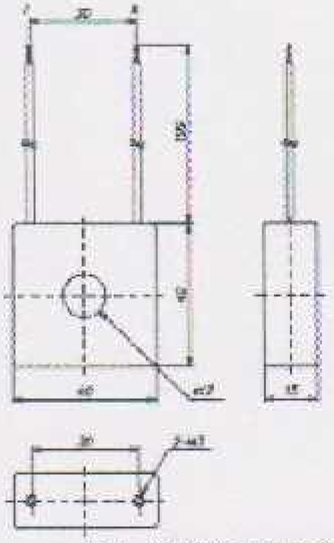
⚠Caution: If lateral close mounting is used for the controller, IP 66 specification will not be fulfilled.

(Fig. 3.3-1)

3.4 CT (Current transformer) external dimension



CTL-6S (for 5A, 10A, 20A)

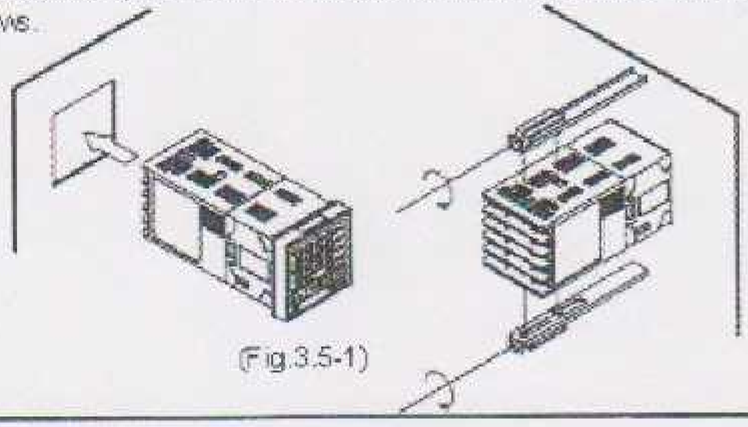


CTL-12-S36-10L1 (for 50A)

(Fig. 3.4-1)

3.5 Mounting

Mount the controller vertically to ensure it adheres to the Dust-proof/Drip-proof specification (IP66).
Mountable panel thickness: Within 1 to 15mm
Insert the controller from the front side of the panel.
Attach the mounting brackets by the holes at the top and bottom of the case and secure the controller in place with the screws.



(Fig.3.5-1)

⚠ Warning

As the case is made of resin, do not use excessive force while screwing in the mounting bracket, or the case or screw type mounting bracket could be damaged.
The torque is approximately 0.12N·m.

Appendix C

استبيان يبين كمية استهلاك الوقود بشكل يومي

استهلاك الوقود في المركبة

السادة سائقو المركبات المحترمون:

يقوم مجموعة من طلبة دائرة الهندسة الميكانيكية- جامعة بوليتكنك فلسطين بعمل استبيان حول تحديد كمية الاستهلاك اليومي من الوقود في المركبة ,وهو شيء مهم لكل شخص يملك أو يقود مركبة. سوف يتم عمل تحليل للنتائج والوصول الى قيم واقعية حول معدل استهلاك الوقود وذلك من خلال مشروع تخرجهم والذي يهدف الى تقليل استهلاك الوقود للمركبة باستخدام طاقة كهربائية بديلة عن الدينامو في المركبة.

لذلك نرجو تعبئة النموذج بجدية ومصداقية

1- هل تقود مركبة :

☐ نعم ☐ لا

2- معدل زمن القيادة في اليوم الواحد (ساعة)

____

3- استخدام المركبة :

☐ خصوصي ☐ عمومي ☐ شاحنات

4- ماركة المركبة (الشركة المصنعة) :-

____

5-نوع وقود المحرك

☐ ديزل ☐ بنزين ☐ غاز

6- سنة الصنع:________

7-حجم المحرك (cc)

1200 ☐ 1400☐ 1600☐ 1900 ☐ 2000 ☐

غير ذلك ________________

8- معدل الاستهلاك اليومي (شيكل):-

____

9- معدل القيادة في اليوم (كيلومتر) :-

____

10- هل تقوم بصيانة دورية :-

☐ نعم ☐ لا

Appendix D

Compound Interest Table for 10% MARR

	Single Payment		Uniform Payment Series				Arithmetic Gradient		
n	Compound Amount Factor Find *F* Given *P* *F/P*	Present Worth Factor Find *P* Given *F* *P/F*	Sinking Fund Factor Find *A* Given *F* *A/F*	Capital Recovery Factor Find *A* Given *P* *A/P*	Compound Amount Factor Find *F* Given *A* *F/A*	Present Worth Factor Find *P* Given *A* *P/A*	Gradient Uniform Series Find *A* Given *G* *A/G*	Gradient Present Worth Find *P* Given *G* *P/G*	n
1	1.100	.9091	1.0000	1.1000	1.000	0.909	0	0	1
2	1.210	.8264	.4762	.5762	2.100	1.736	0.476	0.826	2
3	1.331	.7513	.3021	.4021	3.310	2.487	0.937	2.329	3
4	1.464	.6830	.2155	.3155	4.641	3.170	1.381	4.378	4
5	1.611	.6209	.1638	.2638	6.105	3.791	1.810	6.862	5
6	1.772	.5645	.1296	.2296	7.716	4.355	2.224	9.684	6
7	1.949	.5132	.1054	.2054	9.487	4.868	2.622	12.763	7
8	2.144	.4665	.0874	.1874	11.436	5.335	3.004	16.029	8
9	2.358	.4241	.0736	.1736	13.579	5.759	3.372	19.421	9
10	2.594	.3855	.0627	.1627	15.937	6.145	3.725	22.891	10
11	2.853	.3505	.0540	.1540	18.531	6.495	4.064	26.396	11
12	3.138	.3186	.0468	.1468	21.384	6.814	4.388	29.901	12
13	3.452	.2897	.0408	.1408	24.523	7.103	4.699	33.377	13
14	3.797	.2633	.0357	.1357	27.975	7.367	4.996	36.801	14
15	4.177	.2394	.0315	.1315	31.772	7.606	5.279	40.152	15
16	4.595	.2176	.0278	.1278	35.950	7.824	5.549	43.416	16
17	5.054	.1978	.0247	.1247	40.545	8.022	5.807	46.582	17
18	5.560	.1799	.0219	.1219	45.599	8.201	6.053	49.640	18
19	6.116	.1635	.0195	.1195	51.159	8.365	6.286	52.583	19
20	6.728	.1486	.0175	.1175	57.275	8.514	6.508	55.407	20
21	7.400	.1351	.0156	.1156	64.003	8.649	6.719	58.110	21
22	8.140	.1228	.0140	.1140	71.403	8.772	6.919	60.689	22
23	8.954	.1117	.0126	.1126	79.543	8.883	7.108	63.146	23
24	9.850	.1015	.0113	.1113	88.497	8.985	7.288	65.481	24
25	10.835	.0923	.0102	.1102	98.347	9.077	7.458	67.696	25