UTILIZATION OF EXHAUST HEAT FROM AUTOMOTIVE USING THERMOPILE

Thesis submitted in partial fulfillment of the requirements for the Degree of Bachelor of Technology

In

ELECTRONICS AND COMMUNICATION ENGINEERING

By

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UNDER THE GUIDANCE OF

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May, 2016

TABLE OF CONTENTS

CHAPTER-5

CHAPTER-6

DECLARATION

I hereby declare that the work reported in the B-Tech thesis entitled **"UTILIZATION OF EXHAUST HEAT FROM AUTOMOTIVE USING THERMOPILE"** submitted at **Jaypee University of Information Technology, Waknaghat, India,** is an authentic record of my work carried out under the supervision of **Prof. Shruti Jain**. I have not submitted this work elsewhere for any other degree or diploma.

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26th May 2016

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY
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Date: 26th May 2016

CERTIFICATE

This is to certify that the work reported in the B-Tech. thesis entitled **“Utilization of Exhaust Heat from Automotive Using Thermopile”**, submitted by **Palak Kaistha, Akshay Kataria and Abhilasha Cahudhary** at **Jaypee University of Information Technology, Waknaghat**, **India,** is a bonafide record of his / her original work carried out under my supervision. This work has not been submitted partially or wholly to any other university or institution for award of this or any other degree program.

Dr. Shruti Jain
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ACKNOWLEDGEMENT

It is our foremost duty to express our deep regards & gratitude to our Project Guide **Dr. Shruti Jain,** under whose guidance & supervision we are able to work on the project ***"Utilization of Exhaust Heat from Automotive Using Thermopile".*** Any amount of gratitude towards our family and friends can never be enough for the constant support they have provided us with, we are totally indebted to them. At last it is him, to whom we owe everything, as without God's blessings this endeavors of ours would never have been a success.

Thanking You.

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LIST OF ABBREVIATIONS & SYMBOLS

Abbreviations and Symbols	**Description**
EMF	Electromotive Force
NIST	National Institute of Standards and Technology
ASMT	American Society for Testing and Materials
AWG	American Wire Gauge
SWG	British Standard Wire Gauge
TEG	Thermoelectric Power Generator
OEM	Original Equipment Manufacturer
DC	Direct Current
AC	Alternating Current
Z	Figure of Merit
T/C	Thermocouple
RTD	Resistors Temperature Detectors

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

With increase in the global warming and the depletion of the renewable sources of energy, the urge to shift towards alternate and green sources of energy has elevated. Extensive research in the field of greener sources of energy has led to the advancement of thermocouple to convert the waste heat into electrical energy there by shifting our concerns from conventional to exceptional ways. Utilizing that amount of heat which generally can't be used in power generation at a huge level, but does play significant role in energy conservation system.

Thermocouples can be used to convert temperature difference into voltage, with several thermocouples when placed together enhances the output of the process. While carrying out this project, we got to know that though the results obtained were highly dependent on the vicinity of the place where the process took place but sufficient amount of potential was generated which could be enhance with the help of booster circuit and could be brought into use for future applications.

Project was carried out first on thermopile with four of them attached in series so that the output was the sum of all individual. High fluctuations were observed due to short circuits as the opening of the exhaust pipe was small. While repeating the same procedure with thermopile having only two thermocouples attached in series, results was up to the mark and sufficient amount of constant voltage was generated. This voltage was further enhanced with the help of booster circuit.

The results obtained were highly dependent upon the climate as well as the vehicle passing by. Therefore, certain preventive measures have to be taken to control the fluctuations so that the circuit voltage and current can be properly boosted.

To widen the scope of the project, we first connected the thermocouple with an operational amplifier which boosts the voltage and we were able to turn on LED. Since, op-amps

require extra external voltage to work, we moved to micro-booster circuit which again amplified the voltage and with sudden change in inductance, boosted the voltage to a greater scale. This circuit had no effect on the current. Third booster circuit with which we worked was DC-DC booster converter using IC-MAX757. It boosted the voltage generated through thermocouple to an optimum level and it even solved our problem of fluctuating output through thermocouples as it gives the constant output voltage.

CHAPTER 1: INTRODUCTION

1.1 What is a Thermocouple?

A thermocouple is a type of temperature sensor, which is made by joining two dissimilar metals at one end. The joined end is referred to as the ***HOT JUNCTION***. The other end of these dissimilar metals is referred to as the ***COLD END*** *or* ***COLD JUNCTION***. The cold junction is actually formed at the last point of thermocouple material.

Thermocouples provide direct energy conversion from thermal to electrical energy due to the temperature gradient. Based on the thermoelectric effect, exhaust heat from automotive can be used for voltage generation. Thermoelectric effect is the direct conversion of differences in the temperature to electric potential and vice versa. The junctions can be referred as heat source (comparatively at high temperature) and heat sink (comparatively at low temperature).

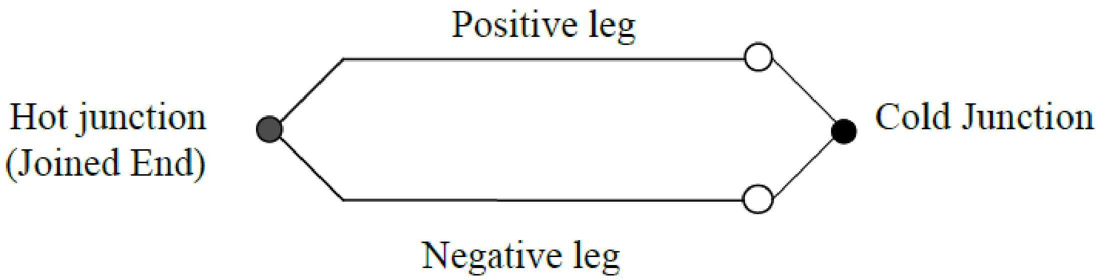


Fig 1.1: Thermocouple Diagram

If there is a difference in temperature between the hot junction and cold junction, a small voltage is created. This voltage is referred to as an **electro-motive force (EMF)** that can be measured and in turn used to indicate temperature. The voltage created by a thermocouple is extremely small and is measured in terms of **millivolts** (one millivolt is equal to one thousandth of a volt). In fact, the human body creates a larger millivolt signal than a thermocouple. To establish a means to measure temperature with thermocouples, a standard scale of millivolt outputs was established. This scale was established using 32 deg. F (0°C) as the standard cold junction temperature (32 deg. F (0°C) = 0 millivolts output).

1.2 What is Thermoelectric effect?

The **thermoelectric effect** is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device creates voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side.

This effect can be used to generate electricity, measure temperature or change the temperature of objects. Because the direction of heating and cooling is determined by the polarity of the applied voltage, thermoelectric devices can be used as temperature controllers.

The term "thermoelectric effect" encompasses three separately identified effects: the **Seebeck effect**, **Peltier effect (**voltage difference or current can produce a heat flow [1]**)**, and **Thomson effect (**any thermoelectric material can be used to either generate power in a temperature gradient or pump heat with an applied current **[2])**. Different amount of emf (E) is being produced due to the thermal gradient at different length across the metal. This effect is known Seebeck Effect.

1.3 Seebeck Effect: The Seebeck effect is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances. Seebeck effect is just another example of emf (E) where all the voltages and currents are measured by the conventional methods only.

$$E = - S \nabla T \qquad \text{………… (1)}$$

Where S is the Seebeck coefficient (also known as thermo power), a property of the local material, and ∇T is the gradient in temperature T. Seebeck coefficient strongly depends upon the composition of the material and varies according to the temperature.

A thermocouple can be described as a combination of two dissimilar conducting wires joined to each other at both ends as shown in Fig.1 [2]. One wire is called positive leg and the other negative leg because of their relative Seebeck coefficient.

The temperature of one of the joined end is held constant or is accurately measured and is used as a reference temperature, can be called as cold junction. The other joined end of the thermocouple is kept at a comparatively different temperature than the cold junction and is known as the measuring end or the hot junction. When these two junctions are kept at different temperatures, an electric current (Seebeck current) starts to flow in a closed loop of two dissimilar conductors continuously. A potential difference is generated (Seebeck voltage) at the reference end (the open end) that is proportional to the temperature difference and the composition or the type of the two conductors (usually alloys).

Thermocouples are used in many industrial, scientific, and OEM applications. They can be found in nearly all industrial markets: Power Generation, Oil/Gas, Pharmaceutical, Biotech, Cement, Paper & Pulp, etc. Thermocouples are also used in everyday appliances like stoves, furnaces, and toasters.

Thermocouples are typically selected because of their low cost, high temperature limits, wide temperature ranges, and durable nature. When heat is applied to one of the two conductors or semiconductors, heated electrons flow toward the cooler one [1]. If the pair is connected through an electrical circuit, direct current (DC) flows through that circuit.

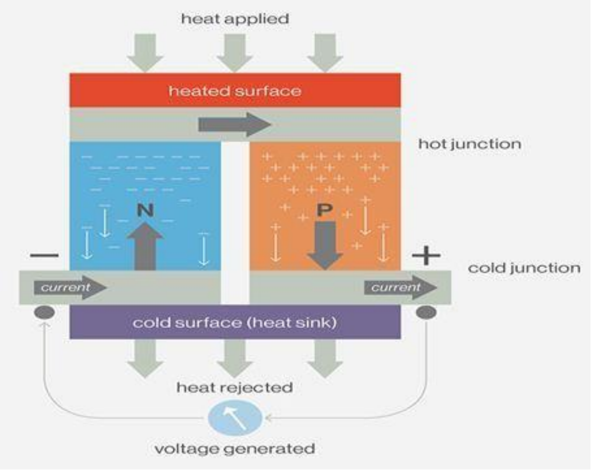


Fig 1.2: Semiconductor Thermocouple Seebeck Effect

The voltages produced by Seebeck effect are small, usually only a few Microvolts per Kelvin of temperature difference at the junction. If the temperature difference is large enough, some Seebeck-effect devices can produce a few millivolts (thousandths of a volt). Numerous such devices can be connected in series to increase the output voltage or in parallel to increase the maximum deliverable current. Large arrays of Seebeck-effect devices can provide useful, small-scale electrical power if a large temperature difference is maintained across the junctions.

The Seebeck effect is responsible for the behaviour of thermocouples, which are used to approximately measure temperature differences or to actuate electronic switches that can turn large systems on and off. This capability is employed in cooling technology. Commonly used thermocouple metal combinations include constantan/copper, constantan/iron, constantan/chromel and constantan/alumel.

Thomas Johann Seebeck discovered the phenomenon in the 1800s [9]. More recently, in 2008, physicists discovered what they are calling the spin Seebeck effect [23]. The spin Seebeck effect is seen when heat is applied to a magnetized metal. As a result, electrons rearrange themselves according to their spin. Unlike ordinary electron movement, this rearrangement does not create heat as a waste product. The spin Seebeck effect could lead to the development of smaller, faster and more energy-efficient microchips as well as spintronics devices.

1.4 How Thermoelectric Effect Works?

Thermoelectric power generation requires three major pieces of technology: thermoelectric materials, thermoelectric modules and systems that interface with the heat source [9].

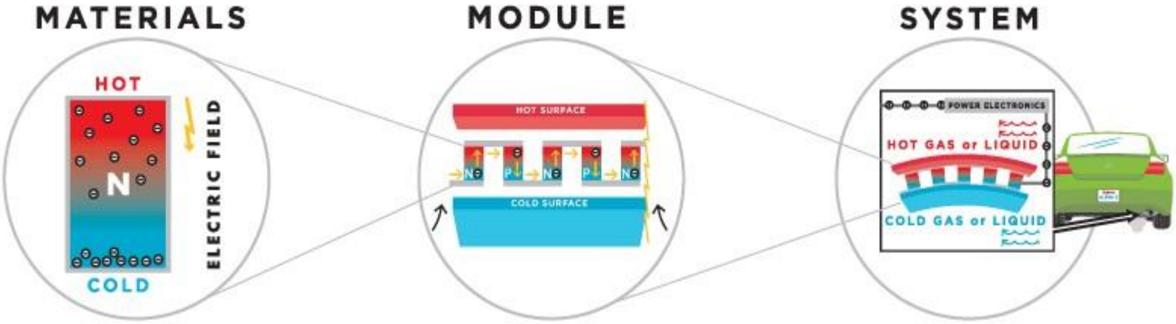


Fig 1.3: Material Module System Diagram

1.4.1 How Thermoelectric Material Work?

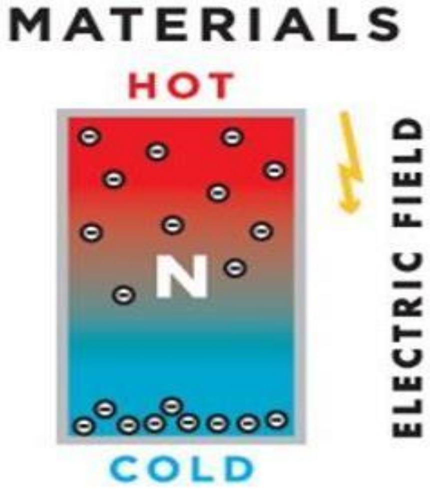


Fig 1.4 Electric Field

Thermoelectric materials generate electricity while in a temperature gradient. In order to be good thermoelectric, materials must have the unique combination of both high electrical conductivity and low thermal conductivity: a rare set of properties for one material to hold. Nanotechnology can now be used to lower the thermal conductivity of semiconductors whose electrical properties are excellent, but manufacturing nanomaterial is not trivial.

Anything—steam, for instance—will flow from hot to cold, in a temperature gradient. In a thermoelectric material, electrons do the same thing. The extent to which electrons flow from hot to cold in an applied temperature gradient is governed by the Seebeck coefficient, also known as the thermo power [9].

In order for a thermoelectric to establish a large voltage while in a temperature gradient, its thermal conductivity must be low. This ensures that when one side is made hot, the other side stays cold. For many decades, the only semiconductors known to have both low thermal conductivity and high power factor were bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon germanium (SiGe): three expensive compounds using rare elements [9].

Today, low thermal conductivity can be achieved by creating nanoscale features such as particles, wires or interfaces in bulk semiconductor materials. These nanoscale features lower the thermal conductivity of the semiconductor and do not affect their strong electrical properties.

The efficiency of thermoelectric materials is governed by their “figure of merit” Z. A large Z is important in creating an efficient thermoelectric generator, but it is not the only important metric.

1.4.2 How Thermoelectric Modules Work?

A thermoelectric module is a circuit containing thermoelectric materials that output usable electricity. There are several types of efficient thermoelectric materials, but not all are capable of operating in a power generation circuit, or “module,” under typical waste heat recovery conditions.

A thermoelectric module for power generation must operate in a very large temperature gradient—and thus be subject to large thermally induced stresses and strains—for long periods of time. They must also be able to withstand a large number of thermal cycles, which cause mechanical fatigue. These two requirements represent some of the toughest thermal and mechanical environments that any electronic device must withstand.

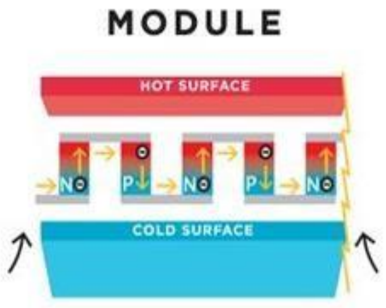


Fig 1.5 Hot and Cold Surface Module

Furthermore, the geometrical design of a thermoelectric module will greatly affect its efficiency [14]. The technology that goes into the design, joining and assembly of a thermoelectric module is copious.

A thermoelectric module requires two thermoelectric materials to function: one, an n-type (negatively charged) semiconductor; the second, a p-type (positively charged) semiconductor. This is so that a continuous circuit can be made whereby current can flow and power can be produced. With only one type of thermoelectric material, a voltage would be induced but current would never flow. These two n-type and p-type semiconductors form a thermoelectric “couple,” but do not form a p-n junction. Both must have high “figure of merit” z and tightly controlled properties.

The two types of thermoelectric materials must be configured within the module such that they are electrically in series, but thermally in parallel. The module must therefore have internal wiring that accomplishes this, as well as junctions and materials that survive the harsh mechanical conditions it is subject to. A selection of materials that minimize thermal expansion coefficient mismatches—and the technologies to fabricate them and their interfaces—is of utmost importance in a thermoelectric module.

1.4.3 How Thermoelectric Power Generator (TEG) Systems Work?

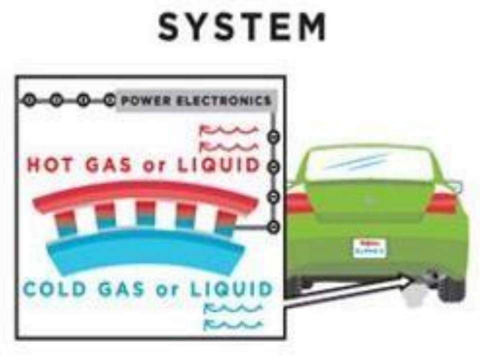


Fig 1.6 How Generator System Works

A thermoelectric power generation system takes in heat from a source such as hot exhaust, and outputs electricity using thermoelectric modules.

A thermoelectric module needs a large temperature gradient to generate electricity: something that is technically challenging to implement in real-world applications. In a power generation system, the heat for the hot side of this temperature gradient must be supplied efficiently from a heat source such as an exhaust flue. The cold side must be cooled by air, water, or another suitable medium. To supply this heating and cooling, technologies known as heat exchangers are used on both the hot and cold sides. A thermoelectric power generation system can be thought of as two heat exchangers, each of which have to move heat to (or from) the hot (or cold) side of the thermoelectric modules.

Maximizing the efficiency (or, conversely, the total power output) of a thermoelectric power generation system requires extensive engineering design. Trade-offs between total heat flow through the thermoelectric modules and maximizing the temperature gradient across them must be balanced. The design of heat exchanger technologies to accomplish this is one of the most important aspects of engineering of a thermoelectric generator.

In operation, the entirety of a thermoelectric power generator actually sits in multiple large temperature gradients. It also contains interfaces between materials at several places that require low thermal losses. The challenges of designing a reliable system that operates at very high temperatures are many. In addition, the system must not cause large pressure drops in the heating and cooling sources, another difficult engineering constraint.

A thermoelectric generator produces AC power only after the original DC power from the thermoelectric modules passes through an inverter. An integrated power electronics system is necessary to deliver AC power to the customer. The result: electricity from otherwise wasted heat.

Chapter 2: Literature review

In this chapter, various research papers are viewed, what was their purpose.

Chapter 3: Thermocouple

In this chapter, types of thermocouples are explained in detail. Various concepts and terminologies are also discussed which are to be kept in mind while working with thermocouples.

Chapter 4: DC-DC Booster Circuit

In this chapter, the basic functioning of the booster circuit is explained and different circuits are discussed which were being used to increase the voltage generated.

Chapter 5: Proposed Work

In this chapter, whole set-up and results are given.

Chapter 6: Conclusion and Future scope

Conclusion and future scope of our project is viewed.

CHAPTER 2: LITERATURE REVIEW

1. The Seebeck Coefficient, electronicscooling.com (November 1, 2006)

Seebeck Coefficients determine the property of the thermocouples. The Seebeck coefficient is related to the fact that electrons are both carriers of electricity and heat . If a temperature gradient exists over a piece of electrically conductive wire, there is a net diffusion of electrons from the hot end toward the cold end, thereby creating an opposing electric field. In (quasi) equilibrium this field causes a voltage over the wire, the so-called Seebeck voltage. The temperature dependency can be significant, for example a 5-10% increase for metals over a temperature rise of 30°C.

Seebeck effect can’t explain the sign of various Seebeck coefficients. The magnitude and sign of the Seebeck coefficient are related to an asymmetry of the electron distribution around the Fermi level. The most efficient way is to use the combination of a positive seebeck coefficient with the negative one.

2. “Thermoelectric Power Generation Using Waste-Heat Energy as an Alternative Green Technology”, Recent Patents on Electrical Engineering 2009, Vol 2 No. 1, by Basel I. Ismail, Wael H. Ahmed

A background on the basic concepts of thermoelectric power generation is presented and recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed.

The maximum power output follows a clear trend and increases with a decrease in thermo-element length for a given module cross-sectional area. Also, thermal conductivity has to be low.

1) Micro-Scale Waste Heat Applications

Micro thermoelectric power generators can be fabricated using integrated circuit technology. Recently, a patent of a micro-scale thermoelectric device for generating power from waste heat to operate an electronic component is presented. The device includes a heat-conducting substrate (composed, e.g., of diamond or another high thermal conductivity material) disposed in thermal contact with a high temperature region. In this patent, a Bi2Te3 alloy-based film thermoelectric material is placed in thermal contact with the heat-conducting substrate in this innovation, the thermal gradient across the device generates electrical power and drives an electrical component

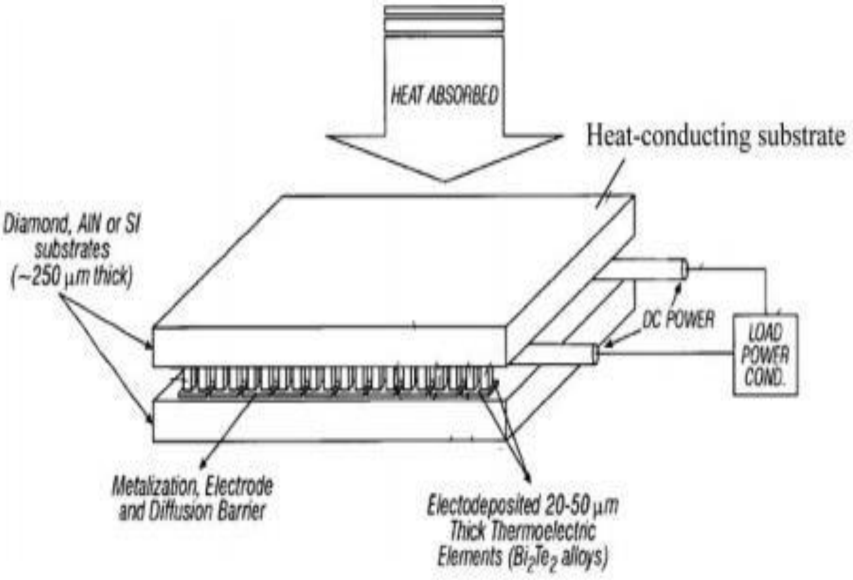


Fig 2.1: A schematic diagram illustrating the concept of this patent

More recently, Glatz et al. presented a novel polymer based wafer level fabrication process for micro thermoelectric power generators for the application on non-planar surfaces.

2) Macro-Scale Waste Heat Applications

Industrial waste heat application: Thermoelectric power generators have also been successfully applied in recovering waste heat from steel manufacturing plants. In this application, large amounts of cooling water are typically discharged at constant temperatures of around 90o C when used for cooling ingots in steel plants. Waste Heat from Incineration of Solid Waste Applications: In the waste heat from incineration applications, the thermoelectric modules are typically placed on walls of the furnace's funnels.

Domestic Waste Heat Applications: Recently, Taguchi invented an exhaust gas based thermoelectric power generator for an automobile application. In this patent, a pump supplies cooling water through each of cooling water circulation paths. The cooling water circulation path includes a cooling water pipe arranged along the exhaust pipe to pass the cooling water. At stacks a plurality of thermoelectric generation elements are attached to the exhaust pipe and the cooling water pipe successively in a direction from the upstream toward downstream of the exhaust gas. The cooling water pipe and the exhaust pipe pass the cooling water and the exhaust gas, respectively, in opposite directions so that the downstream stack has an increased difference in temperature between the exhaust pipe and the cooling water pipe, and the stacks provide power outputs having a reduced difference, and hence an increased total power output.

3. “Thermoelectric Generators as Alternate Energy Source in Heating Systems”, Jelgava, 24.-25.05.2012, by Kakitis Aivars, Ozollapins Martins.

By using thermoelectric generators it is possible to develop independent electric energy source in burning and heating systems – in households and industrial heating. They used two thermoelectric generators TEP1-1264-1.5. One generator is a module consisting of 126 Bi2Te3 p-type and n-type semi-conductor couples.

To get good performance and higher power, no. of modules used has to be increased and the output emf increases linearly with temperature difference.

4. “A Review of Thermoelectric Generator for Waste Heat Recovery from Engine Exhaust”, International Journal of Research in Aeronautical and Mechanical Engineering, Vol.1 Issue.8, December 2013, by Dipak Patil, Dr. R. R. Arakerimath

The electrical power generation of thermoelectric generator is observed to be a strong function of flow rate and inlet exhaust temperature. The temperature difference between the hot and cold junctions of TEG increased as the engine speed or the coolant temperature increase. The output voltage, according to the Seebeck effect, also increased as the temperature difference increase. Therefore, the output power and thermal efficiency can be improved. The parametric evaluation of the longitudinal model indicates that TEG performance improves for configurations that have minimum

TEG height and maximum TEG width. High efficiency heat exchanger is necessary to increase the amount of heat energy extracted from exhaust gas. It is found that exhaust gas parameters and heat exchanger structure have a significant effect on the system power output and the pressure drop. The study also identified the potentials of the technologies when incorporated with other devices to maximize potential energy efficiency of the vehicles.

5. "Criteria For temperature Sensor Selection of T/C and RTD sensor Types" Acromag (online source)

The Basics of Temperature Measurement Using Thermocouple and the Basics of Temperature Measurement Using RTDs and a Comparison of Thermocouple and RTD Temperature Sensors is discussed.

6. "Waste heat energy harvesting using thermo electric generator", IOSR Journal of Engineering (IOSRJEN) A.Jacks delight us peter, Balaji, D.Gowrishankar.

Thermoelectric power generation offers a promising technology in the direct conversion of low-grade thermal energy, such as waste-heat energy, into electrical power. Perhaps the earliest application is the use of waste heat from a kerosene lamp to provide thermoelectric power to power a wireless set. Thermoelectric generators have also been used to provide small amounts electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline powered motor generators. Moreover, cost-per-watt can be reduced by optimizing the device geometry, improving the manufacture quality and simply by operating the device at a larger temperature difference. Thermoelectric Power Generator (TEG) is a solid state device which converts Heat Energy into Electrical Energy. All the exciting conventional power generators convert Thermal Energy into Mechanical Energy then to Electrical Energy. So here no mechanical work (no moving parts). So it produce less noise and no pollution when compare to conventional power generators. TEG is working by Thermo Electric Effect (seebeck) effect. When TEG held between temperature gradients (Hot end, Cold end) it produce some voltage this voltage is called seebeck voltage. TEG has Modules which is semiconductors (p-n). Here electrons acting as a thermoelectric power fluid (working medium). Pair of p-type semiconductor and n-type semiconductor is called as a Module. These semiconductors highly doped by pollutants in order to increase the Electric conductivity. TEG has shield it avoid modules damaging due to high temperature. The efficiency of TEG and voltage generated by TEG is directly proportional to semiconductor material and temperature gradients. So selections of semiconductor based on electric conductivity of the material and try to increase the temperature difference value. This semiconductor is coupled by copper electrode. Increasing no of modules and no of stages and coupling no of TEG increase overall efficiency and voltage output. Exciting efficiency of TEG is 4.2% to 6%. When using stages it increases the efficiency to7%.

7. “AN-20 an Applications Guide for Op Amps – Texas Instrument” - Application Report, SNOA621C–February 1969–Revised May 2013

This application note consists information for all Op-Amps. The circuits discussed in this guide are illustrative of the versatility of the integrated operational amplifier and provide a guide to a number of useful applications. The cautions mentioned in each section has shown the more common pitfalls encountered in amplifier usage. Illustration of the circuit, circuit analysis and the pitfalls while operating with the circuit has been clearly depicted.

8. “Adjustable Voltage Step-Up” by Joohansson, Instructables (online source)

A voltage step-up circuit that works on IC-MAX757. This voltage step-up is a DC/DC adjustable voltage regulator. This circuit will take a low voltage (down to 0.7V) and step it up to adjustable 2.7-5.5V which is basically of the reverse of the usual voltage regulator which is fed by a higher input than output voltage, for example 9V IN to 5V OUT. Since it is a regulator, the output voltage will stay constant regardless input voltage (0.7-5.5V), as long as output voltage is higher than input. This project article includes almost everything. From the description of the circuit to the components required to the circuit analysis. Giving out all the minute details in descriptive format.

9. "Design of Dc-Dc Boost Converter with Thermoelectric Power Source", (IJAREEIE), By Hazli Rafis, Hamidon A.H, M.Y. Azdiana, A.Jaafar, A.A. Latiff, H.H.M. Yusof, W.H.M. Saad

The Seebeck effect-based thermoelectric power source using TEC module has been presented in this paper. One great advantage of the designed concept is that the TEC energy harvester is employed to recover waste heat in industrial process as a renewable energy source and green technology. Experimental results confirm that the designed DC-DC boost converter is able to produce the desired output voltage for powering other electronic circuit. A stage of DC-DC boost converter can be connected to the designed DC-DC boost converter if higher output voltage is required.

Table 2.1: Inference from all the Referred Papers

Journal	Inference
Seebeck Effect	Individual Seebeck co-efficient of various materials is given and why we need the combination of material is discussed.
Thermoelectric Power Generation Using Waste-Heat Energy as an Alternative Green Technology	Recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed.
Thermoelectric Generators as Alternate Energy Source in Heating Systems	Use of thermocouple in domestic appliances is mentioned. They used thermoelectric generators TEP1-1264-1.5
A Review of Thermoelectric Generator for Waste Heat Recovery from Engine	It explains briefly the challenges in enhancing the figure of merit.

Exhaust	
Criteria For temperature Sensor Selection Of T/C and RTD sensor Types	Comparison between the temperature sensors: RTD and T/C is thoroughly discussed.
Waste heat energy harvesting using thermo electric generator	It briefly explains the different components of TEG.
An Applications Guide for Op Amps	Depicted every type of the possible op-amp, its circuit analysis and pitfalls.
Adjustable Voltage Step-Up	Dc-Dc booster circuit describing out all the minute details of circuit. From the requirements to the calculations, everything has been clearly depicted in this article.
Dc-Dc Booster with Thermoelectric Power Source	TEC module has been presented in this paper. Along with the generation of the potential difference with its help, how to boost that potential has also been discussed.

CHAPTER 3: THERMOCOUPLE

3.1 Thermocouple Aging

Aging refers to a positive EMF shift (more output) of nickel thermocouple alloys resulting from a temperature gradient along the thermocouple elements. The temperature that aging occurs is estimated to be around 370° to 540°C (700° to 1000°F). There are a few things that can increase the amount of EMF shift:

- The temperature that is being measured or the previous thermal history of the thermocouple.
- The thermocouple composition.
- Duration of aging temperature.
- Amount of thermocouple exposed to the aging temperatures.

It must be recognized that aging depends on the application for which the thermocouple is being used and the temperature gradient it experiences. The operating temperature of the thermocouple should be checked. If the thermocouple has never been exposed to aging temperatures, it should never have errors due to aging. To reduce the inaccuracy of reading temperatures in the aging range, a pre-aged thermocouple may be used. Pre-aged thermocouples are heat treated and have special compositions to minimize errors caused by aging. However, if these are heated above the aging range then the effect of the pre-aging can be removed. For applications where the temperature is above the aging range, it is important to keep as little length of thermocouple as possible in the aging range. This will help to minimize the aging effects [13].

The effects of the aging process can actually be removed. This is done by heating the entire thermocouple above 870°C (1600°F) for at least 5 minutes. Then the thermocouple should be rapidly cooled to below the aging temperatures. This should restore the wire to its original calibration.

3.2 Principle Involved In Thermocouple Circuit

Effect of the additional thermocouples and variance in the temperature on our circuit can be minimized by considering the following principles:

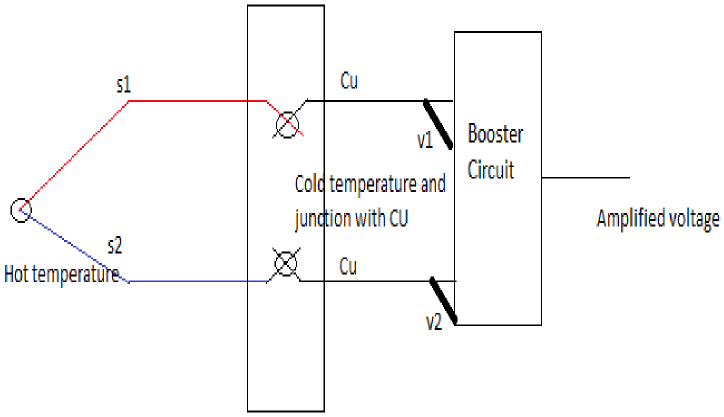


Fig 3.1: Structure of a thermocouple made up of two metals having relative Seebeck coefficient s_1, s_2. Seebeck coefficient of the thermocouple $S=s_1-s_2$. One terminal is welded together at hot temperature and the other are connected with copper (Cu) wire at different temperature (preferably lower). V_1 and V_2 are the terminal voltages. $E = V_1 - V_2$

Law of Homogenous Material:

In Fig. 8, heat or temperature difference alone won't be able to sustain the thermoelectric current in the circuit comprising of single homogenous material only. The output of the circuit will not be altered on the basis of the temperature difference between the input and output, provided all the wires are made are of the same material as that of the thermocouple. No current flows in the circuit made of a single metal by the application of heat alone [10].

Law of Intermediate Materials:

If all the junctions are kept at the same temperature, no matter how many dissimilar materials it comprises of, the algebraic sum of the thermoelectric emf (E) in a circuit is zero. Thus, if a third metal is inserted in either or both wires while making our cold junction connections, there will be no net voltage contribution generated by the new metal in the measurement system as long as the two new junctions are at the same temperature [10].

Law of Intermediate Temperatures:

In Fig.8, two dissimilar homogeneous materials produce thermal emf,(E), V_1 when the junctions are at T_1 and T_2, and produce thermal emf,(E), V_2 when the junctions are at T_2 and T_3, then the emf,(E) generated when the junctions are at T_1 and T_3 will be

$$V_1 = V_3 + V_2, \qquad \text{If } T_1 < T_2 < T_3 \qquad \ldots\ldots\ldots (2)$$

$$V_1 = -(V_2 + V_3), \qquad \text{If } T_1 > T_2 > T_3 \qquad \ldots\ldots\ldots (3)$$

Because as emf (E) produced is directly proportional to the temperature gradient. Therefore, when the sign of the temperature gradient is changed so of the emf (E) produced [10].

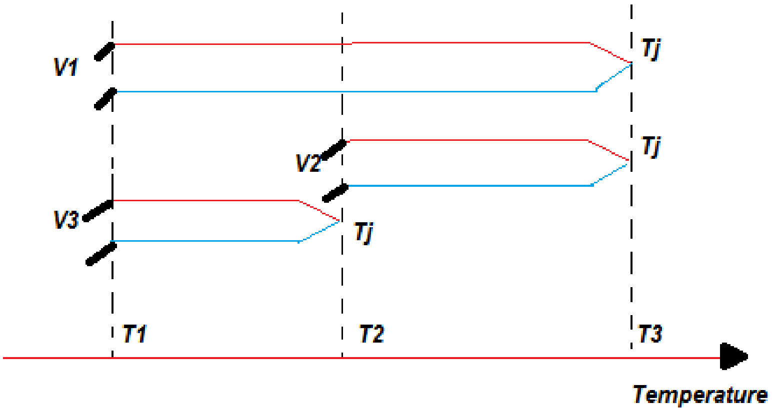


Fig 3.2: Different temperature gradient gives different potential difference

3.3 Types Of Thermocouple

Base metal thermocouples are known as Types E, J, K, T and N and comprise the most commonly used category of Thermocouple. The conductor materials in base metal thermocouples are made of common and inexpensive metals such as Nickel, Copper and Iron.

Type E

The Type E thermocouple has a Chromel (Nickel-10% Chromium) positive leg and a Constantan (Nickel- 45% Copper) negative leg. Type E has a temperature range of -330 to 1600F, has the highest EMF VS Temperature Values of all the commonly used thermocouples, and can be used at sub-zero temperatures. Type E thermocouples can be used in oxidizing or inert atmospheres, and should not be used in sulfurous atmospheres, in a vacuum or in low oxygen environments where selective oxidation will occur [10].

Type E has a stronger signal & higher accuracy than the Type K or Type J at moderate temperature ranges of 1,000F and lower [13].

Temperature Range:

- Thermocouple grad wire, -454 to 1600F (-270 to 870C)

- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 1.7C or +/- 0.5%
- Special Limits of Error: +/- 1.0C or 0.4%

Type J

This thermocouple comprises of iron and constantan connected or welds together in series combination. Iron being positive leg or hot body known for positive Seebeck coefficient and constantan as negative leg or cold body, having negative Seebeck coefficient. Therefore, the difference between the two gives us the Seebeck coefficient as 51μV/°C [1][12]. Can be used in vacuum or air where the atmosphere can be reducing or oxidizing. Avoid the use of this type of alloy in highly oxidizing atmosphere with temperature exceeding 900°C [10]. The positive leg is magnetic while the negative is non-magnetic. Therefore, changes in the characteristics of iron can take place above Curie temperature i.e. ~770°C. So the application temperature range limits to 760°C [13].

Temperature Range:

- Thermocouple grad wire, -346 to 1,400F (-210 to 760)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 2.2C or +/- .75%
- Special Limits of Error: +/- 1.1C or 0.4%

Type K

This thermocouple comprises of chromel and alumel connected or weld together in series combination. Chromel is 90% nickel and 10% chromium makes positive leg or hot body and alumel is 95% nickel, 2% manganese, 2% aluminum and 1% silicon makes the negative or the cold body of the thermocouple. Its Seebeck coefficient is $40\mu V/{}^{\circ}C$ [1][12]. Favourable environment – vacuum and low oxidizing environment. Try to avoid its use in atmosphere containing sulphur. Its application range is limited to only 1260°C [13] and is not recommended to cycle around that temperature because of the chances in the alteration of emf (E) generated due to hysteresis effect [10].

Temperature Range:

- Thermocouple grad wire, -454 to 2,300F (-270 to 1260C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 2.2C or+/- .75%
- Special Limits of Error: +/- 1.1C or 0.4%

Type N

The Type N thermocouple has a Nicrosil (Nickel-14% Chromium- 1.5% Silicon) positive leg and a Nisil (Nickel- 4.5% Silicon- .1% Magnesium) negative leg. Type N is very similar to TYPE K but is less susceptible to selective oxidation effects. Type N should not be used in a vacuum or in reducing atmospheres in an unsheathed condition. The temperature range is 32-2300 deg F [13][10]. Type N shares the same accuracy and temperature limits as the Type K. The type N is slightly more expensive.

Temperature Range:

- Thermocouple grad wire, -454 to 2,300F (-270 to 392C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 2.2C or +/- .75%
- Special Limits of Error: +/- 1.1C or 0.4%

Type T

T type thermocouple is made up with the junction of two alloys namely copper and constantan connected in series. Copper being the hot body or positive leg and constantan makes the negative or the cold body of the thermocouple. Its Seebeck coefficient is 40 $\mu V/^{\circ}C$ [1][12]. One of its best feature is that it can be used in any environment-oxidizing, reducing and inert gases. Very suitable for humid atmosphere as it is corrosion resistive in nature. At low oxygen levels it can produce “green rot”, particularly in the 816 - 1038°C range [10][13]. It is highly stable at sub-zero temperatures.

Temperature Range:

- Thermocouple grad wire, -454 to 700F (-270 to 370C)
- Extension wire, 32 to 392F (0 to 200C)

Accuracy (whichever is greater):

- Standard: +/- 1.0C or +/-.75%
- Special Limits of Error: +/- 0.5C or 0.4%

In this project, we are using only J, K and T types.

3.4 Things to be considered while working with thermocouples

Thermal Shunting and Immersion Error

All thermocouples have some mass, and heating this mass will absorb some energy that will ultimately affect the temperature you are trying to measure. In some applications, the thermocouple wire will act like a heat-sink at the point of measurement and that can result in significant measurement error. The use of thin thermocouple wires helps minimize this effect in many applications. For example, consider a thermocouple immersed in a small vial of liquid to monitor its temperature. Heat energy may travel up the thermocouple wire and dissipate to the atmosphere reducing the temperature of the liquid around the wires. Or, if the thermocouple is not sufficiently inserted into the liquid, the cooler ambient air surrounding the wires may actually conduct along the wire and cool the junction to a different temperature than the liquid itself. The use of thinner wires would cause a steeper thermal gradient along the wire at the junction between the ambient air and the liquid itself. However, thin wires have a higher resistance and this can drive other errors (see below). It may be better to use shorter thin thermocouple wires connected to much thicker thermocouple extension wires in order to alleviate the resistance effect for some applications.

Thermocouple wires are very fine by design, as this helps to prevent the mass of the wire from affecting the sensed temperature at the point of contact (the junction). But this has a disadvantage in that the wires can be very delicate and may break easily. Special care must be taken to reduce the strain imposed on the thermocouple wires.

Lead Resistance

To minimize the effects of thermal shunting, thin thermocouple wire is generally used. The use of thin wire is also at least partially driven by the type of wire which is more expensive, in particular for the platinum-based. But the downside to using thin wire in some systems is that it increases the sensor resistance making it more sensitive to noise. Care should be taken to ensure that the loop resistance of a wired thermocouple be kept low, and a general rule of thumb is to keep it below 350**Ω** to avoid excess error, and below 100**Ω** would be better.

Noise

The thermocouple output voltage is a small signal that is prone to errant noise pickup. Likewise, the fine leads are made from other materials than copper and have a higher resistance, making them more sensitive to noise pickup, in particular AC-coupled noise. Further, the high gain that generally operates on these small signals further amplifies this noise. Other sources of thermal noise result from unstable ambient temperatures at the cold junction. The generally fast response time of the thermocouple exhibits this noise at the output as the cold junction generally tracks the junction temperature much slower than the T/C sensor itself, usually as a result of its larger thermal mass and the sensor used to measure its temperature. Noise can usually be minimized by twisting the wires together to make sure that both leads pick up the same signal (i.e. common mode noise is rejected). Likewise, minimize the length or loop area where the cables part to make a connection to the instrument. Operation in noisy environments or nearby electric motors may benefit from the use of screened extension cable. If noise pickup is suspected, simply switch off suspect equipment and observe if the reading changes.

Connection Problems

Potential measurement error is often a result of poor connections which drive unintended thermoelectric voltage contributions to our measurement voltage. Substitution of any other type will add errant thermocouple junctions to our measurement system. If terminals are used to connect the wires, then you must additionally select connectors made up of the same material type, unless you can ensure that the connections are kept at the same temperature. You also need to observe the proper polarity when making connections. Other connection problems arise when an incompatible material type is used for a given environment, or where extension wire has been mismatched to the sensor or its environment.

CHAPTER 4: DC-DC BOOSTER CIRCUIT

4.1 Introduction

A boost converter (step-up converter) is a DC-to-DC power converter steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

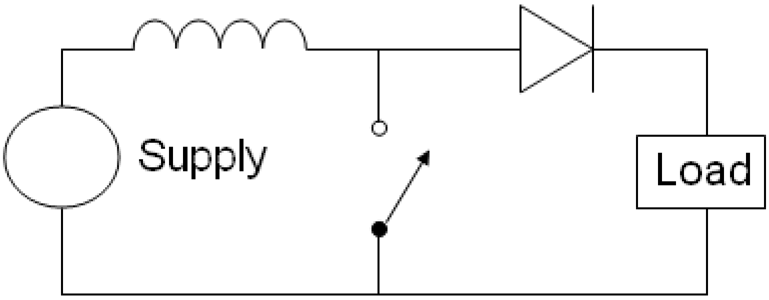


Fig. 4.1: Generic DC-DC booster circuit

Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high voltage applications due to lack of space. Boost converters can increase the voltage and reduce the number of cells [18].

Battery-powered applications that use boost converters are used in hybrid electric vehicles (HEV) and lighting systems. The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cells and boosts the battery voltage from 202 V to 500 V.

Boost converters also power devices at smaller scale applications, such as portable lighting systems. A white LED typically requires 3.3 V to emit light, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the lamp.

Boost converters can also produce higher voltages to operate cold cathode fluorescent tubes (CCFL) in devices such as LCD backlights and some flashlights.

An unregulated boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief' [17][22]. This circuit topology is used with low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a normal load. This energy would remain untapped because many applications do not allow enough current to flow through a load when voltage decreases. This decrease occurs as batteries become depleted, and is a characteristic of the ubiquitous alkaline battery [22]. Since the equation for power is

$$P = \frac{V2}{R} \qquad \text{……… (4)}$$

Where R tends to be stable, power available to the load goes down significantly as voltage decreases.

The boost converter is different to the Buck Converter in that its output voltage is equal to, or greater than its input voltage. However it is important to remember that, as power (P) = voltage (V) x current (I), if the output voltage is increased, the available output current must decrease [18].

4.1.1 Circuit Analysis

Operation:

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field [16]. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Fig. 4.2.

a) When the switch is closed, electrons flow through the inductor in counter-clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
b) When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current

towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

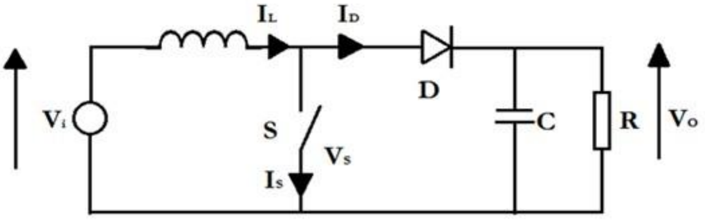


Fig 4.2: Working (Current and Voltage) of the Booster Circuit

The basic principle of a Boost converter consists of 2 distinct states (see figure 4.3): in the On-state, the switch S is closed, resulting in an increase in the inductor current; in the Off-state, the switch is open and the only path offered to inductor current is through the fly-back diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the On-state into the capacitor.

The input current is the same as the inductor current as can be seen in figure 4.3. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter [18].

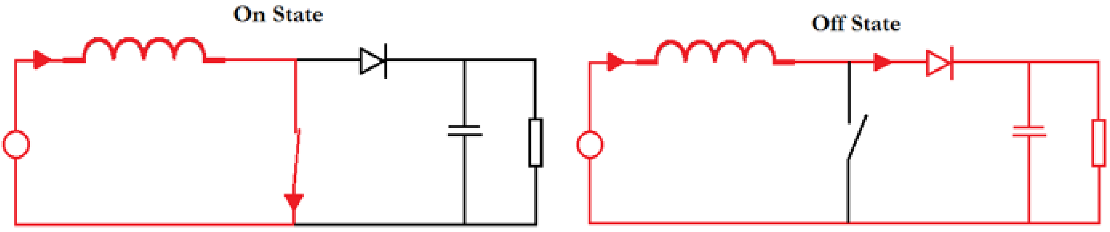


Fig 4.3: On and off state of Booster Circuit

Continuous Mode

When a boost converter operates in continuous mode, the current through the inductor **(I_L)** never falls to zero. Figure 4.4 shows the typical waveforms of currents and voltages in a converter operating in this mode. The output voltage can be calculated as follows, in the case of an ideal converter (i.e. using components with an ideal behaviour) operating in steady conditions.

During the On-state, the switch S is closed, which makes the input voltage **(V_i)** appear across the inductor, which causes a change in current **(I_L)** flowing through the inductor during a time period **(t)** by the formula:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L} \qquad \text{……… (5)}$$

At the end of the On-state, the increase of IL is therefore:

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} V_i\,dt = \frac{DT}{L} V_i \qquad \text{……… (6)}$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is on. Therefore, D ranges between 0 (S is never on) and 1 (S is always on).

During the Off-state, the switch S is open, so the inductor current flows through the load. If we consider zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of IL is:

$$V_i - V_o = L\frac{dI_L}{dt} \qquad \text{……… (7)}$$

Therefore, the variation of IL during the Off-period is:

$$\Delta I_{L_{Off}} = \int_{DT}^{T} \frac{(V_i - V_o)\,dt}{L} = \frac{(V_i - V_o)(1-D)T}{L} \qquad \text{……… (8)}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2} L I_L^2 \qquad \text{……… (9)}$$

So, the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0 \qquad \text{………(10)}$$

Substituting $\Delta II_{L_{On}}$ and $\Delta II_{L_{Off}}$ by their expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i D T}{L} + \frac{(V_i - V_O)(1-D)T}{L} = 0 \qquad \text{………(11)}$$

This can be written as:

$$\frac{V_O}{V_i} = \frac{1}{1-D} \qquad \text{……… (12)}$$

The above equation shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a step-up converter.

Rearranging the equation reveals the duty cycle to be:

$$D = 1 - \frac{V_i}{V_O} \qquad \text{……… (13)}$$

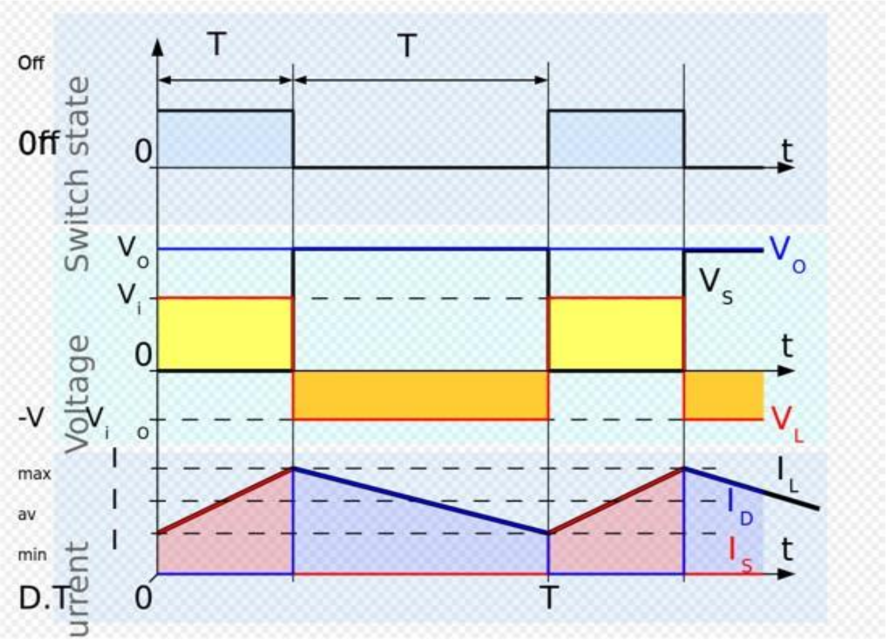


Fig 4.4: Timing Diagram-Continuous Mode

Discontinuous Mode

If the ripple amplitude of the current is too high, the inductor may be completely discharged before the end of a whole commutation cycle. This commonly occurs under light loads. In this case, the current through the inductor falls to zero during part of the period (see waveforms in figure 4.5). Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value I_{LMAX} (at t = DT) is

$$I_{L_{Max}} = \frac{V_i D T}{L} \quad \text{……… (14)}$$

During the off-period, I_L falls to zero after δT:

$$I_{L_{Max}} + \frac{(V_i - V_O)\delta T}{L} = 0 \quad \text{……… (15)}$$

Using the two previous equations, δ is:

$$\delta = \frac{V_i D}{V_O - V_i} \quad \text{……… (16)}$$

The load current Io is equal to the average diode current **(I_D)**. As can be seen on figure 4.5, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_O = I_D = \frac{I_{L_{max}}}{2}\,\delta \quad \text{……… (17)}$$

Replacing I_L max and δ by their respective expressions yields:

$$I_O = \frac{V_i D T}{2L} \cdot \frac{V_i D}{V_O - V_i} = \frac{V_i^2 D^2 T}{2L(V_O - V_i)} \quad \text{……… (18)}$$

Therefore, the output voltage gain can be written as follows:

$$\frac{V_O}{V_i} = 1 + \frac{V_i D^2 T}{2 L I_O} \quad \text{……… (19)}$$

Compared to the expression of the output voltage gain for continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage gain not only depends on the duty cycle **(*D*)**, but also on the inductor value **(*L*)**, the input voltage **(V_i)**, the commutation period **(*T*)** and the output current **(I_o)**.

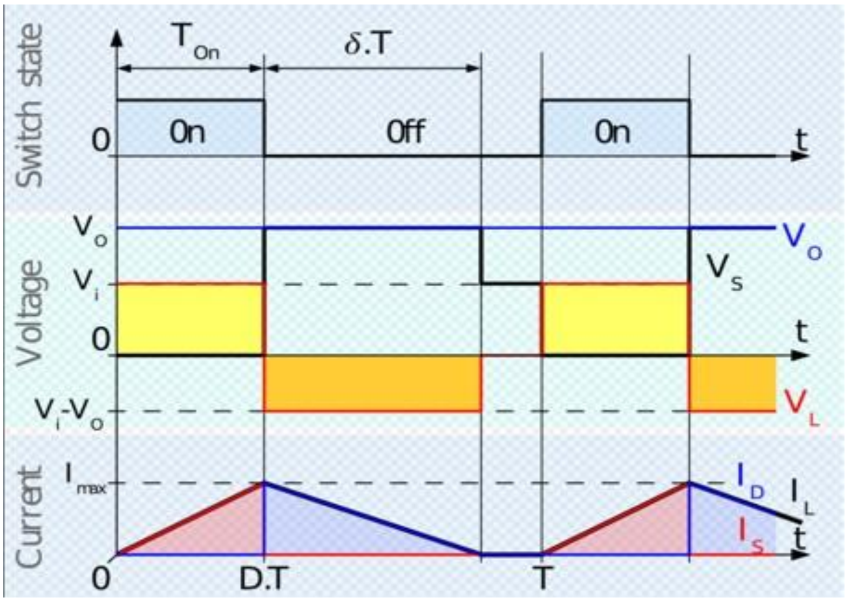


Fig 4.5: Timing Diagram-Discontinuous Mode

In this project, we experimented with three different types of booster circuits namely

- Closed-loop Non-Inverting Circuit
- Micro Voltage Booster Circuit
- DC-DC Max 757 Booster Circuit

4.2 Closed-loop Non-Inverting Circuit

Operational amplifiers can be used in two basic configurations to amplify circuits. One is the inverting amplifier where the output is the inverse or 180° out of phase with the input, and the other is the non-inverting amplifier where the output is in the same sense or in phase with the input.

It is often necessary to know the input impedance of a circuit. The input impedance of this non-inverting amplifier circuit is very high, and may typically be well in excess of 10^7 ohms. For most circuit applications this can be completely ignored. This is a significant difference to the inverting configuration of an operational amplifier circuit which provided only a relatively low impedance dependent upon the value of the input resistor.

Voltage series Feedback Amplifier

The circuit shown in figure is also known as non-inverting amplifier with feedback (or closed-loop non-inverting amplifier) because it uses feedback, and the input signal is applied to the non-inverting input of the amplifier [21]. However the feedback is taken from the output via a resistor to the inverting input of the operational amplifier where another resistor is taken to ground. It is not the value of these two resistors that govern the gain of the operational amplifier circuit but is their ratio [21] i.e.

$$\text{Gain,} \quad A_v = \frac{Vout}{Vin} = 1 + R_f/R \qquad \ldots\ldots\ldots (20)$$

Where R_f is the feedback resistor (in our case, $R_f = 33.33\text{k}\Omega$) and $R = 2.22\text{k}\Omega$ is the external input resistance.

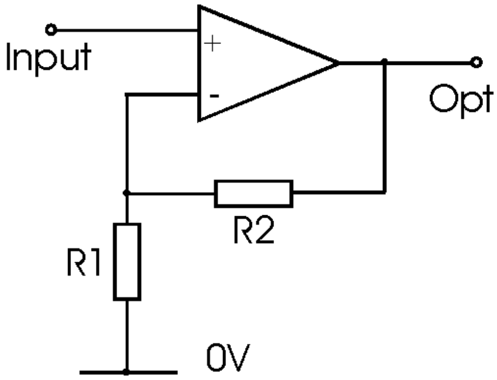


Fig 4.6: Block Diagram of an Op-Amp

The gain of the non-inverting amplifier circuit for the operational amplifier is easy to determine. The calculation hinges around the fact that the voltage at both inputs is the same. This arises from the fact that the gain of the amplifier is exceedingly high. If the output of the circuit remains within the supply rails of the amplifier, then the output voltage divided by the gain means that there is virtually no difference between the two inputs [7].

As the input to the op-amp draws no current this means that the current flowing in the resistors R_f and R is the same. The voltage at the inverting input is formed from a potential divider consisting of R_f and R, and as the voltage at both inputs is the same, the voltage at the inverting input must be the same as that at the non-inverting input. This means that

$$V_{\text{in}} = V_{\text{out}} * \frac{R_f}{R_f + R} \qquad \text{……… (21)}$$

The amplifier output will go into saturation if the input is allowed to float [20].

4.3 Micro Voltage Booster Circuit

A voltage booster circuit that takes very low input values (in the range of mV) and gives a boosted output and can drive low power devices.

The circuit employs a Sziklai Darlington pair. The Sziklai Darlington pair, named after its Hungarian inventor George Sziklai, is a complementary or compound Darlington device that consists of separate NPN and PNP complementary transistors connected together as shown below. This cascaded combination of NPN and PNP transistors has the advantage that the Sziklai pair performs the same basic function of a Darlington pair except that it only requires 0.7 V for it to turn – On and like the standard configuration, the current gain is equal to β^2 for equally matched transistors or is given by the product of the two current gains for unmatched individual transistors [19].

The circuit takes very low input values, which are stepped up to a value that is sufficiently higher than the input.

4.4 DC-DC Booster Circuit Using MAX757

A voltage step-up is a circuit that increases the voltage. It can be AC/AC, AC/DC, DC/AC or DC/DC. This voltage step-up is a DC/DC adjustable voltage regulator. This circuit will take a low voltage (down to 0.7V) and step it [5].Since it is a regulator, the output voltage will stay constant regardless input voltage (0.7-5.5V), as long as output voltage is higher than input [24].

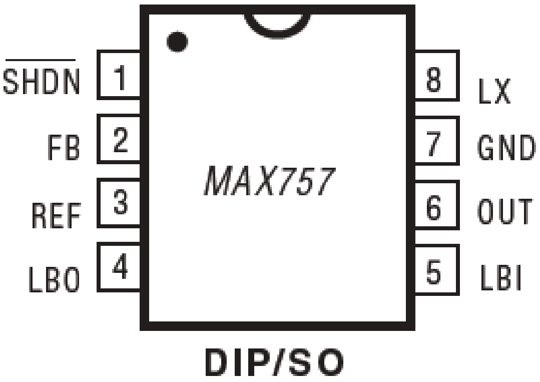


Fig 4.7: Pin-Out of MAX 757 IC [16]

The MAX756/MAX757 are CMOS step-up DC-DC switching regulators for small, low input voltage or battery-powered systems. The MAX756 accepts a positive input voltage down to 0.7V and converts it to a higher pin selectable output voltage of 3.3V or 5V. The MAX757 is an adjustable version that accepts an input voltage down to 0.7V and generates a higher adjustable output voltage [5]. Typical full-load efficiencies for the MAX756/MAX757 are greater than 87%. The MAX756/MAX757 provide three improvements over previous devices. Physical size is reduced—the high switching frequencies (up to 0.5MHz) made possible by MOSFET power transistors allow for tiny (<5mm diameter) surface-mount magnetics. Efficiency is improved to 87% (10% better than with low-voltage regulators fabricated in bipolar technology). Supply current is reduced to 60µA by CMOS construction and a unique constant-off-time pulse-frequency modulation control scheme [17][24].

CHAPTER 5: PROPOSED WORK

With increase in the global warming and the depletion of the renewable sources of energy, the urge to shift towards alternate and green sources of energy has elevated. Extensive research in the field of greener sources of energy has led to the advancement of thermocouple to convert the waste heat into electrical energy there by shifting our concerns from conventional to exceptional ways. Utilizing that amount of heat which generally can't be used in power generation at a huge level, but does play significant role in energy conservation system [11]. Thermocouples were used to convert temperature difference into voltage, with several thermocouples when placed together enhances the output of the process. The voltage so generated by the use of thermocouples was not enough. To overcome this problem, we tried and tested various circuits to boost the voltage to be of any use.

Work was carried out in various steps:

1. Exhaust Pipe
2. Placing of Thermopile in the Exhaust Pipe of Automotive
3. DC-DC Booster Circuit
4. Result and Discussion

5.1 Exhaust Pipe

Exhaust pipe used for the project work is Yamaha Fazer F1 version 1.0 2006-2012 Exhaust System Furore. Referring to the table 1, total length of the thermocouples taken is of 32.5cm of each type. Length of the exhaust pipe that was brought into use is of 22.5cm (up till which the thermopile was inserted in the exhaust). Time taken to heat up so as to provide potential difference of 1mV is 25secs to 1min. Weight of the lightweight exhaust system furore (Fire) silencer is 1.2-2.4 kg.

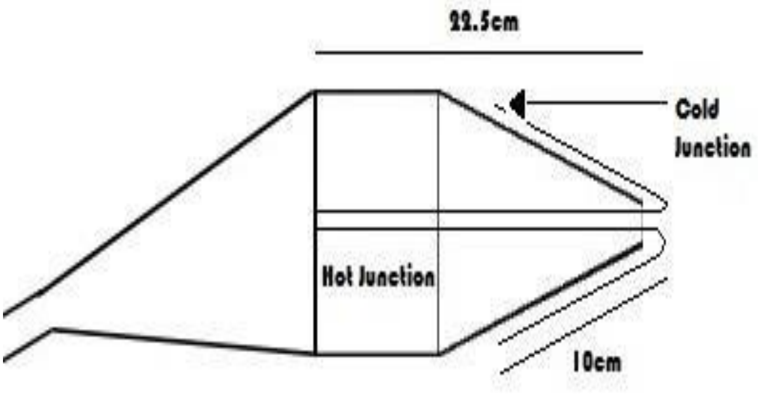


Fig 5.1: Exhaust pipe with the alloys measurement and junction (hot and cold).

Table 5.1: Comparison between the types of Alloys on the basis of Gauze No.

Types	**Diameter (AWG) (cm)**	**Diameter (SWG) (cm)**	**Gauge no.**	**Length Used (cm)**
J	0.1020	0.1220	18	32.500
K	0.1290	0.1630	16	32.500
T	0.0511	0.0559	24	32.500

5.2 Placing of Multiple Thermocouple (Thermopile) In the Exhaust Pipe of Automotive

After welding and combining the thermocouple wires, the thermopile so generated is now placed in such a way so that the efficiency as a whole is maximized. With reference to the Fig.10, all the connections are done in series with one of the temperature zone, here the hot temperature zone is kept inside the exhaust pipe (silencer), with the cold junctions being placed out on the rim of the exhaust pipe so that sufficient amount of temperature difference is generated for the production of electricity [15]. The exhaust pipe of Yamaha (Fazer F1 version 1.0) was selected to carry out the necessary processes. Referring to Fig.5.2, the length of the Type- J, K and T alloys, are so chosen that 22.5cm length of alloys were inside the exhaust pipe and 10 cm length of alloys were placed on the rim. Four thermocouples were being gas welded together so as to get a combined result of the thermopile. Copper wires that were attached to get the readings from the thermopile were kept at the same temperature as that of the temperature of cooler region. There by obeying with the *Law of* Intermediate Materials and thus not affecting the readings much.

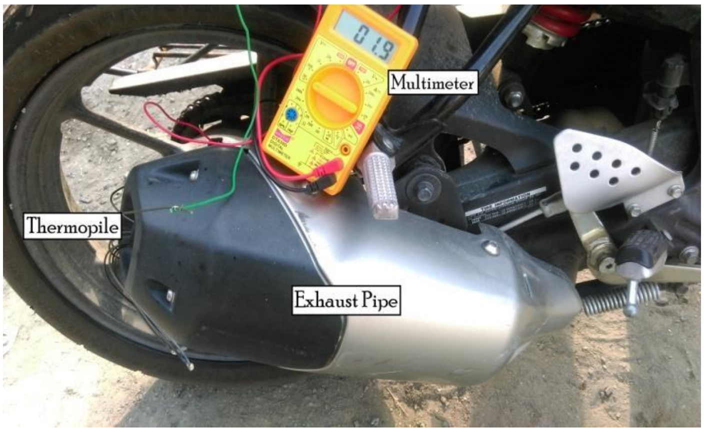


Fig 5.2: Potential drop when K type Thermocouple was inserted in the exhaust.

5.3 DC-DC Booster Circuit

Since, the voltage generated is not enough for any device. Therefore, we need some device to boost our voltage to an optimum level.

5.3.1 Closed-loop Non-Inverting Circuit

In our project, we have used IC 741 as non-inverting amplifier with feedback. In this circuit, we kept the voltages V_{CC} = 12V (pin 7) and V_{EE} = -12V (pin 4) and the feedback resister, R_f = 33.33KΩ resistor R=2.22KΩ and load resister, R_L = 2.22KΩ (from the equation (21))

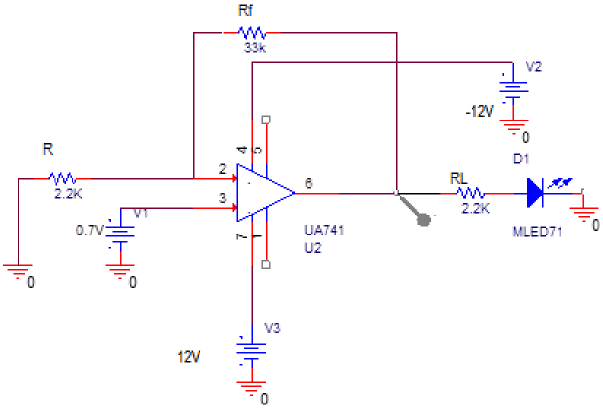


Fig. 5.3 Inverting Closed loop Op-amp-741 with load R_L and a LED

Here, we have also tried to detect the difference between the observed value and the calculated value from equation (21).

i.e.

$$\text{Error} = V_o/I_{o\,\text{(Measured)}} - V_o/I_{o\,\text{(Calculated)}}$$

$$\text{Percentage Error} = \text{Error} / (V_o/I_{o\,\text{(Calculated)}})*100$$

5.3.2 Micro Voltage Booster Circuit

Unlike operational amplifier, micro-booster circuit does not require any extra external voltage supply, although the hardware increases.

The circuit in the fig. 5.4 employs a Sziklai Darlington pair. The compound polarity is determined by the driver, here in fig.5.4 NPN is the driver connected to the PNP through the collector forming a NPN- PNP pair that acts like a single NPN transistor overall. Its advantage over the Darlington pair is that the base turn-on voltage is only about 0.6V or half of the Darlington's 1.2V nominal turn-on voltage.

Components:

NPN transistor (CTBC 547B)

PNP transistor (ST2N3906)

Two capacitors (220 pF, 100pF)

Inductor (3.66 mH)

Resistor (47kΩ)

DC source voltage (<0.8V)

Diode (1N4148)

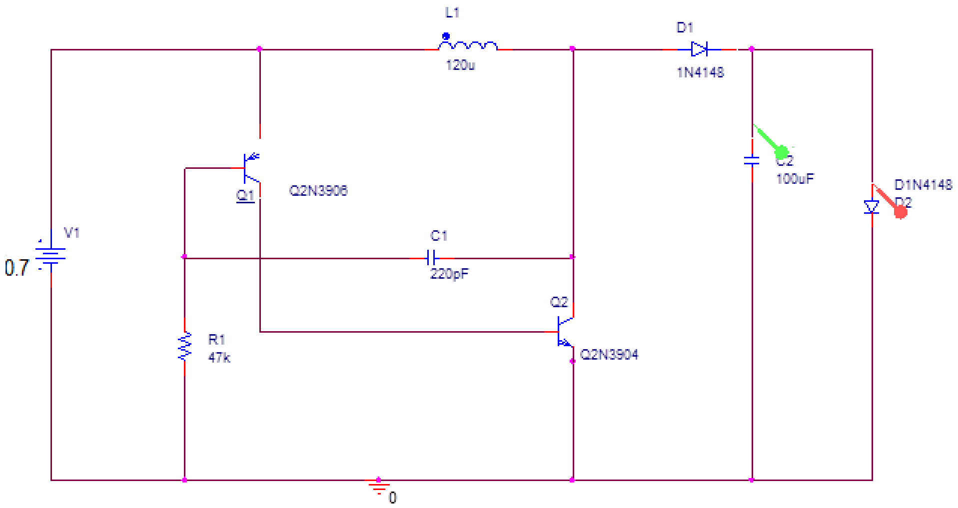


Fig 5.4: Micro-Voltage Booster Circuit

5.3.3 DC-DC Max 757 Booster Circuit

The output voltage of the MAX757 is set by two resistors, R1 and R2, which form a voltage divider between the output and the FB pin. The output voltage is set by the equation:

$$V_{OUT} = (V_{REF})\ [(R_2 + R_1) / R_2] \qquad \ldots\ldots\ldots\ (22)$$

To simplify resistor selection:

$$R_1 = (R_2)\ [(V_{OUT} / V_{REF}) - 1] \qquad \ldots\ldots\ldots\ (23)$$

Where V_{REF} =1.25v, R_3 and R_4, forms a voltage divider between the input voltage and the LBI pin (Low-Battery Input). The threshold voltage is set by R_3 and R_4 using the following equation:

$$R_3 = [(V_{IN} / V_{REF}) - 1]\ (R_4) \qquad \ldots\ldots\ldots\ (24)$$

From these above equations, we calculated resisters values as

$R_1 = 10\text{K}\Omega$ $R_2 = 3.33\text{K}\Omega$ $R_3 = 10\text{K}\Omega$ $R_4 = 4.67\text{K}\Omega$

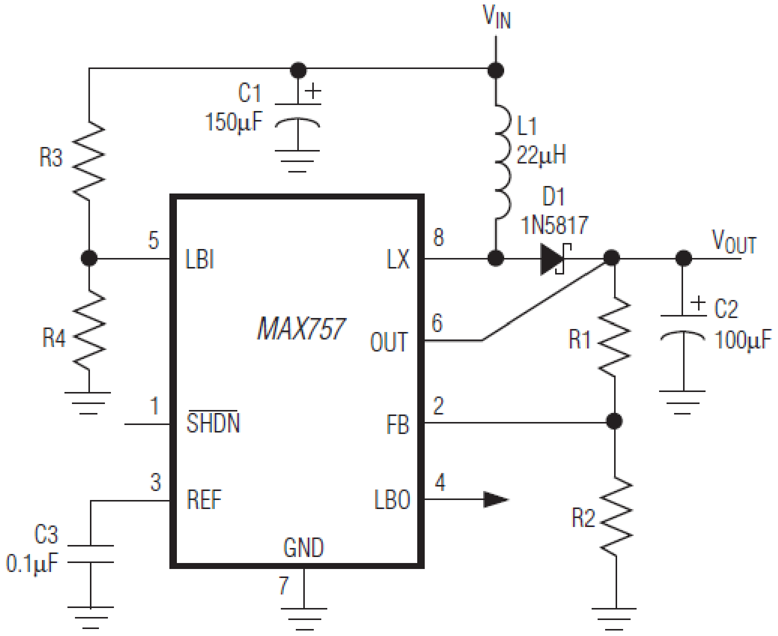


Fig 5.5: DC-DC MAX 757 Booster [24]

5.4 Results and Discussion

The whole process was carried out while riding a Yamaha (Fazer F1 version 1.0) at NH-5, from Waknaghat to Solan (Himachal Pradesh) approximately 15kms apart. Temperature of the cold junction i.e. temperature of surroundings at the time when experiment took place was 11-16°C. The potential difference so obtained by thermopile of J, K and T type was highly fluctuating. The voltage obtained shows its peak value when the bike was at its full throttle and in addition to it if there was a vehicle coming from the opposite lane. Gas emission from the exhaust pipe also plays a crucial role apart from the temperature of the exhaust pipe.

5.4.1 While testing with 4 thermocouples in series

J-type, on an average gave 14-15mV under normal conditions i.e. when the temperature difference between the exhaust pipe and the surroundings were sufficient enough. That happened after 6-7mins of bike ride at normal speed. After every 8-10 sec of bike ride at normal speed, there was 1mV rise in the potential till the temperature of the exhaust pipe becomes constant. After every 5-6sec, 1mV rise in the potential was observed when at good speed, till the temperature of the exhaust becomes constant. The peak value reached up to 18-22mV whenever vehicle passes by us from the opposite side.

K-type gave an average value of 10.5mV on the normal run and on full throttle along with the vehicle passing from opposite side, reached a peak of 20-25mV. There were high chances of error in K-type due to the thickness of the alloy (16 gauge) and its incompetency to fit in the narrow exhaust pipe.

Voltage in most of the cases was constant and fluctuations though appeared but were stabilized when the exhaust pipe reached a specific temperature.

T-type with the least thickness (24 gauge) comparatively produced less significant results. Average voltage that appeared when T-type was being used is 8.5-9mV.

During the project, there were certain sources of error. Few of them have been listed here.

- While placing the thermopiles in the exhaust, there are chances that you may fail to get an output. This is so because the diameter of the exhaust would not be that broad, thus the alloy may touch each other inside the exhaust.
- On measuring, there were fluctuations in the readings. This can be due to the fact that the joints that were inside the exhaust were not firmly fixed. Moreover, the temperature inside the exhaust highly depends on the hot air gushing out.
- At certain time, there was a sudden increase in the peak voltage due to the surroundings conditions. This may damage any circuit that can be implemented further. Thus, proper measurements have to be taken to avoid the hike.
- All the outputs highly depends upon the vicinity, therefore the results may vary accordingly.

Table 5.2: Observation while testing with 4 thermocouples in series

Type	**Output Voltage** (Normal Conditions)	**Inference**
J	14-15 mV	Least fluctuations, high output
K	10.5 mV	High fluctuations due to the short circuiting of alloys inside the exhaust pipe, moderate output
T	8.5-9 mV	High dependency on the vicinity, moderate output

5.4.2 While testing with 3 thermocouples in series

After soldering for 4 thermocouples and recording its values for different conditions we moved to 3 thermocouples because the thermocouples were getting in touch with the surface of the exhaust pipe, thus short circuiting it.

J-type thermocouple as expected gave the highest value amongst all as high as 12mV. It remained stable to 8.2mV but due the change in ambient conditions it shoot up to 12mV whenever vehicle passes by us from the opposite side. All the changes with respect to outside conditions remained same as with the 4-thermocouples in series.

K-type, even after reducing the number of thermocouples, the probability of it touching the exhaust pipe did not decrease to a great value.

T-type thermocouple gave the voltage as low as 6mV with average value being 6.3mV for most of the time.

Table 5.3: Observation while testing with 3 thermocouples in series

Type	**Output Voltage** (Normal Conditions)	**Inference**
J	11-12 mV	Stable, highest output amongst all
K	9.5 mV	High fluctuations due to the short circuiting of alloys inside the exhaust pipe, moderate output
T	6-7 mV	High dependency on the vicinity, moderate output

5.4.3 While testing with 2 thermocouples in series

J-type, on an average gave 0.3-0.4V under normal conditions i.e. when there was sufficient temperature difference to produce the desired output. At a regular speed, output was above expectations under J type. The peak value reached up to 0.63 V whenever vehicle passes by us from the opposite side. 0.02V drop was observed after every 15-30secs when the bike was completely brought to halt and the engine was turned off.

K-type gave an average value between 0.2-0.095V on the normal run and on full throttle along with the vehicle passing from opposite side, reached a peak of 0.25V. There were high chances of error in K-type due to the thickness of the alloy (16 gauge) and its incompetency to fit in the narrow exhaust pipe.

T-type with the least thickness (24 gauge) comparatively produced less significant results. Average voltage that appeared when T-type was used was 0.095V-0.08V. Not much significant results were obtained using T-type alloys.

Table 5.4: Observation while testing with 2 thermocouples in series

Type	**Output Voltage** (Normal Conditions)	**Inference**
J	0.3-.04V	Stable and accurate output with less voltage drop on shutting down engine
K	0.2-0.095V	Stable output with low fluctuations
T	0.095-0.08V	Stable but not significant output with low fluctuations

5.4.4 While testing with a thermocouple

J-type thermocouple on not being connected with any one in series gave a very low value as expected but it reached to a stable and the highest value of 0.1V after a long time. Its value fluctuated with the change in the ambience like when any vehicle passes by or due to high wind (value only increases), though it reached a peak of only 0.1V.

K-type thermocouple was very receptive to fluctuations. Not been able to get any stable value although its value was as low as 0.005V to a high of mere 0.1V.

T-type thermocouple as always gave the least voltage of all. Though it gave us a stable value of 0.007V for maximum time but it ranged from 0.005V-0.01V.

Table 5.5: Observation while testing with a thermocouples

Type	**Output Voltage** (Normal Conditions)	**Inference**
J	0.1-.06V	Reached to the stable value after a long time. Not sufficient to be used, though higher than the rest
K	0.1-0.005V	Rapid fluctuations with the ambient disturbances
T	0.005-0.01V	Stable but minimum value amongst all. Not suitable for further use

Since the voltage (emf) adds up in series and our main focus is to generate as much high electricity as we could. Therefore, we connected the thermocouples in series in such a manner that the hot wire is connected with cold and cold one with hot just like batteries are connected in series with opposite polities so that voltage adds up. Table 5.3 i.e. with three thermocouples in series, we faced similar problem of shortcutting and it gave us low value of voltage as compared to the 4-thermocouples. From table 5.5, we inferred that the voltage generated is not enough, not even enough to boost or to amplify. Therefore, we never moved forward with 3 thermocouples in series and not with single thermocouple.

5.5 Results after Booster Circuit

5.5.1 Closed-loop Non-Inverting Circuit

To boost-up the voltage generated using thermocouples, first we used non-inverting circuit with feedback.

In this circuit, we formulated the resistors to be used as

$$R_f = 33.33\ \text{K}\Omega \qquad R = R_L = 2.2\ \text{K}\Omega$$

Table 5.6: Calculated and Observed Voltage and Current across the load R_L and the Percentage Error

V_i(V)	**Observed**		**Calculated**		**Voltage**		**Current**		**LED**
V_i(V)	**V_o(V)**	**I_o(mA)**	**V_o(V)**	**I_o(mA)**	**Error**	**%error**	**Error**	**%error**	**On/Off**
0.028	0.456	0.209	0.4522	0.2055	-.0038	-0.84034	-0.0035	-1.67464	Off
0.1	1.611	0.74	1.615	0.734	0.004	0.247678	-0.006	-0.81081	Off
0.2	3.24	1.492	3.23	1.468	-0.01	-0.3096	-0.024	-1.60858	Off
0.303	4.78	2.212	4.89	2.224	0.11	2.249489	0.012	0.542495	On
0.4	6.38	2.934	6.46	2.936	0.08	1.23839	0.002	0.068166	On
0.5	8.01	3.6	8.075	3.67	0.065	0.804954	0.07	1.944444	On
0.6	9.55	4.3	9.69	4.404	0.14	1.444788	0.104	2.418605	On
0.7	10.96	4.9	11.305	5.13	0.345	3.051747	0.23	4.693878	On
0.8	10.96	4.9	12	5.45	1.04	8.666667	0.55	11.22449	On
0.9	10.96	4.9	12	5.45	1.04	8.666667	0.55	11.22449	On
1	10.96	4.9	12	5.45	1.04	8.666667	0.55	11.22449	On
2	10.96	5	12	5.45	1.04	8.666667	0.45	9	On
3	10.96	5	12	5.45	1.04	8.666667	0.45	9	On

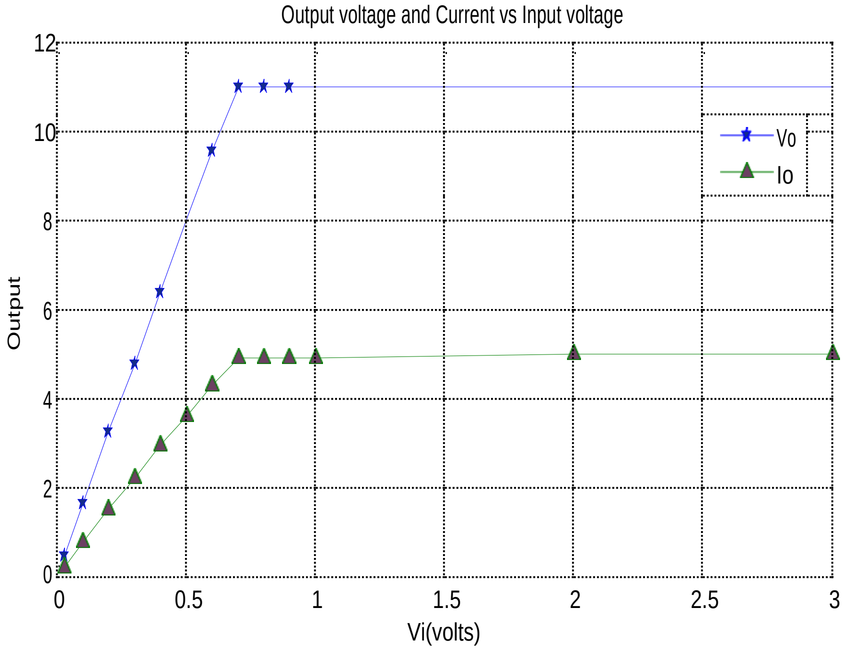


Fig 5.6: Output Current and Voltage VS the Input Voltage

From this table, we observed that the LED starts to glow when the input voltage is mere 0.303V and it kept on glowing after that. Also, the value of the voltage and the current remains constant after input voltage 0.7. This is so because the upper limit in our case is +12 volts.

Its only limitation is that it requires an external voltage (in our case we used 12V) apart from the input voltage.

5.5.2 Micro Voltage Booster Circuit

As mentioned, operational amplifier requires an extra external voltage therefore, we moved to micro booster circuits.

In this circuit, inductor is the boosting device. Therefore, we have kept the input voltage constant to the maximum value obtained from thermocouples i.e. 0.7V and have gradually changed the value of inductance and noted down the output respectively.

Table 5.7: Variation in the Output Voltage and Current with change in Inductance

V_o	I_o(mA)	L(H)
0.485	0	10µ
0.525	0.002	20µ
0.852	0.026	30µ
1.023	0.011	40µ
1.812	0.01	50µ
1.418	0.013	60µ
1.49	0.003	70µ
1.585	0.005	80µ
1.68	0.004	90µ
2.076	0.037	190µ
2.125	0.006	290µ
2.158	0.001	390µ
2.16	0.001	490µ
2.16	0.001	590µ

2.156	0.001	690µ
2.295	0.002	2.59m
2.7	0.019	3.59m
2.9944	0.018	4.59m
3.21	0.012	5.59m
3.46	0.015	6.59m
3.7	0.016	7.59m
3.9	0.013	8.59m
4.1	0.013	9.59m
4.3	0.012	10.59m
5.55	0.048	20.59m
6.84	0.034	30.59m
8.02	0.027	40.59m
8.74	0.024	50.59m
9.1	0.021	60.59m
10	0.022	70.59m
10.35	0.023	80.59m
10.74	0.018	90.59m
11.11	0.018	100.59m
11.4	0.016	110.59m

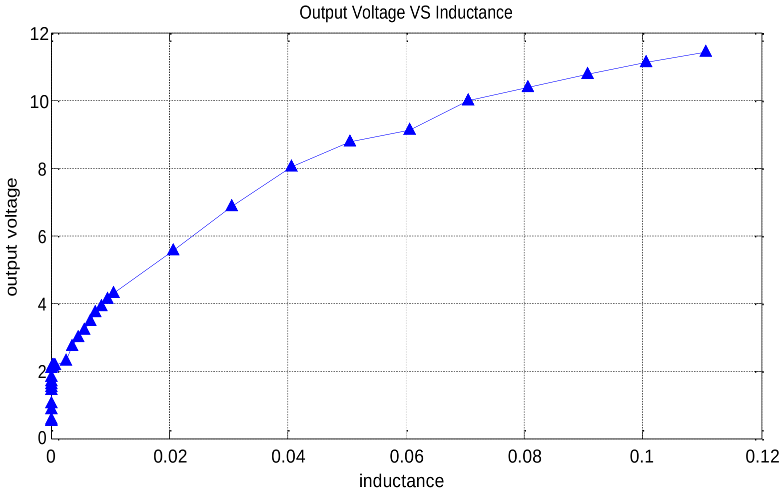


Fig. 5.7: Output Voltage VS Inductance

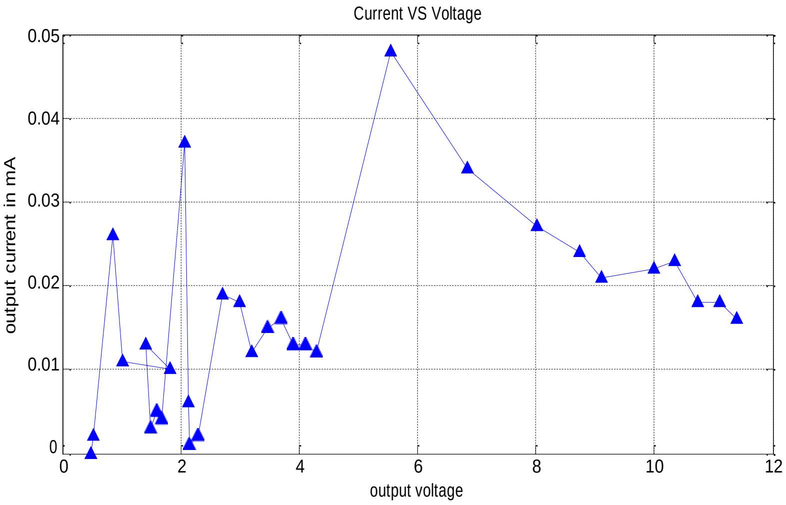


Fig.5.8: Output Current VS Output Voltage

From Table 5.7, we infer that as the voltage increases with increases in inductance but the current decreases. Also, we observed that with the sudden increase in inductance, voltage shoots up to even 14V to 21V. But with this current and voltage combination, we can’t operate any device. Hence, the problem with this circuit is that, though it boosts the voltage but little it does to the current.

5.5.3 DC-DC MAX757 Booster Circuit

In this circuit, first we tested various passive elements to be interconnected with input and output. Following are the passive elements:

L = 22mH $C_{\text{(electrolytic)}} = 100\mu\text{F}$ $C_{\text{(ceramic)}} = 0.1\mu\text{F}$ $R = 2.2\ \text{k}\Omega$

Table 5.8: Output Voltages due to Passive Elements VS the Input Voltage

V_i(V)	Inductor		Capacitor(electrolytic)		Capacitor(ceramic)		Resistor	
	V_o(V)	I_o (mA)	V_o(V)	I_o(mA)	V_o(V)	I_o(mA)	V_o(V)	I_o(mA)
0	0.42	0.191	-0.16	0	0.021	0.01	0.37	0.168
0.1	1.623	0.737	-0.254	0	0.021	0.01	1.257	0.571
0.2	3.39	1.54	-0.242	0	0.02	0.001	1.817	0.826
0.3	4.94	2.245	-0.233	0	0.024	0.01	2.114	0.961
0.4	6.49	2.95	0.4	0.182	0.022	0.01	2.332	1.06

0.5	8.14	3.700	0.334	0.152	0.022	0.01	2.528	1.149
0.6	9.69	4.404	0.392	0.178	0.022	0.01	2.664	1.211
0.7	11.45	5.204	0.447	0.203	0.022	0.01	2.813	1.279
0.8	12.99	5.904	0.458	0.208	0.022	0.01	2.936	1.334
0.9	13.93	6.331	0.318	0.145	0.022	0.01	3.05	1.386
1	13.93	6.331	1.11	0.505	0.029	0.013	3.17	1.441

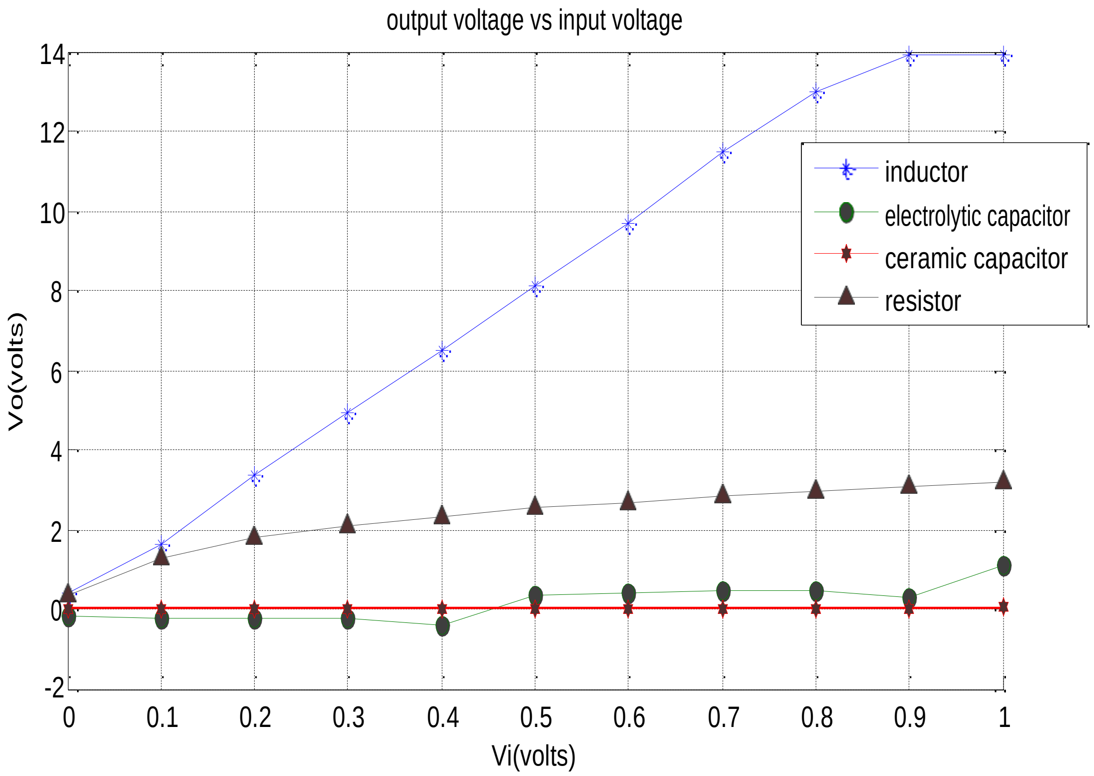


Fig 5.9: Output Voltages due to Passive Elements VS the Input Voltage

From these readings, we infer that amongst all, inductor is the best one to be tapped because like resistor, the output increases with the increase in input voltage but to a greater value.

Therefore, finally we have used an inductor between the output and the input in Max757 to boost the input voltage generated from the exhaust using thermocouple.

Hence, we can say that, to increase the voltage, inductor has to be tapped. Also, the other effect of the tap is to reduce peak switch voltage by:

$$(V_{out}-V_{in}) * N / (N+1) \text{ volts} \qquad \ldots\ldots\ldots (25)$$

Where N=Number of turns. A large value for N will allow high output voltages to be regulated without exceeding maximum switch voltage [6, 22].

Moreover, Max 757 does not require any external voltage.

Table 5.9 Inference of the Circuits

Circuits to Amplify the Voltage being Generated from Thermocouples	**Inference**
Closed-loop Non-Inverting Circuit	An external supply of 12-15V has to be applied. It only amplifies the voltage not the current but is enough to glow a LED.
Micro-voltage booster circuit	No external voltage is necessary. Boosts up the voltage but does little to the current. After a certain value, current decreases.
DC-DC Booster Circuit Using MAX757	No external voltage supply needed. Boost up both current and voltage and gives a constant output voltage though the input fluctuates.

CHAPTER 6: Conclusion and Future work

One of the greatest advantages of thermocouples is their small point of contact that delivers generally fast response times. We have tried to show the utilization of waste heat which could be extracted out from the exhaust of the bike. We have contrasted the working and the output voltages of the three types of alloys used to convert heat energy to electrical energy. The values fluctuate with the change in the ambient conditions. All the three types of thermocouples namely T, J and K gave the satisfactory results though in millivolts but on using booster circuit, we can amplify the output voltages and this voltage can be brought into use in various forms. So, in order to amplify the voltage to an optimum level, we worked with three different circuits (operational amplifier with feedback, micro booster circuit, MAX757), overcoming the limitations of the later in each case. In each and every circuit connected in series was able to light at least an LED. This is one more step towards greener source of energy as it doesn't hinder the normal working of the engine and the waste heat which is usually emitted out in the atmosphere is now of use.

Future Scope:

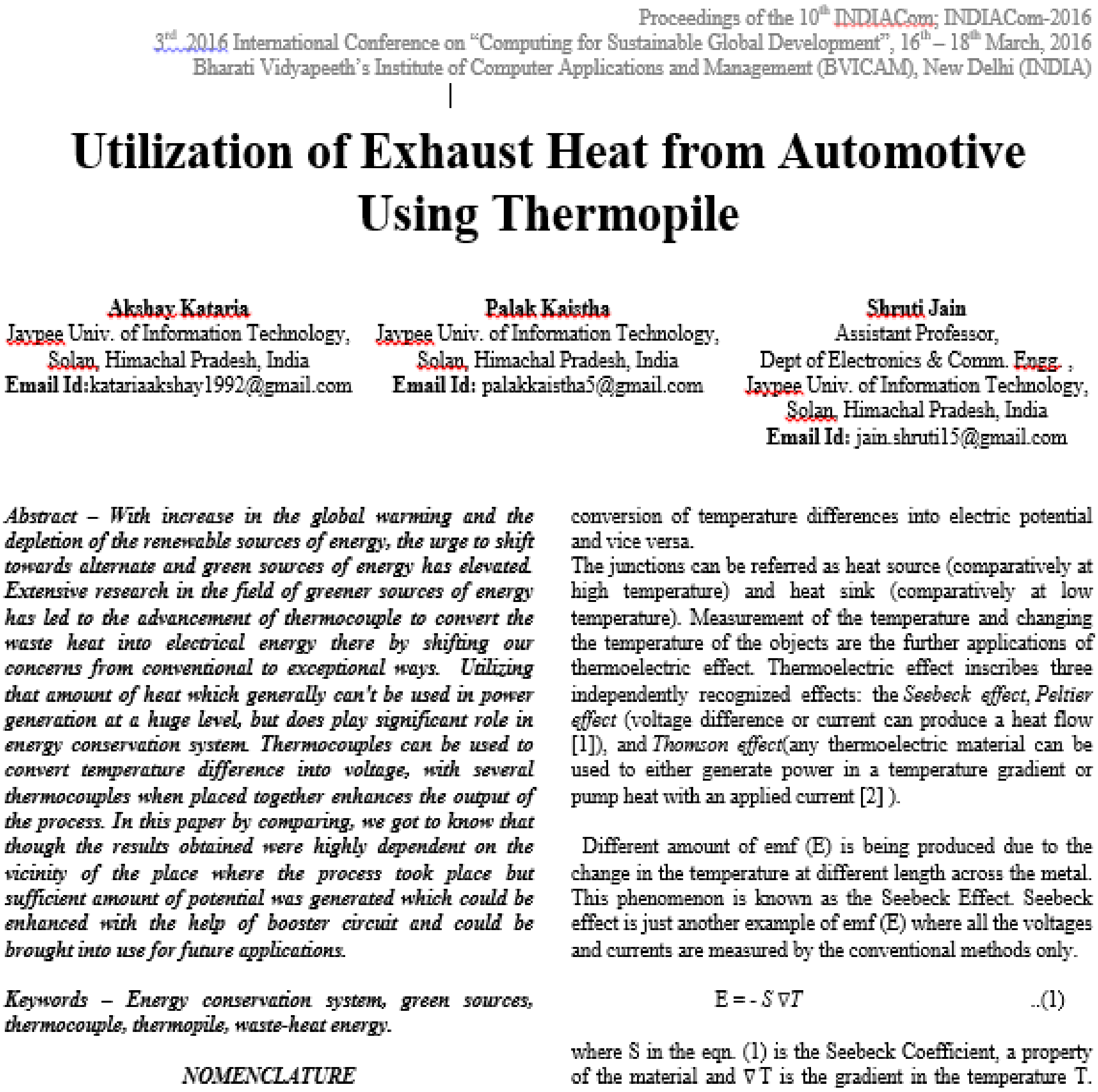
Since, we were able to get the minimum voltage required to run an electronic device. So its practical usage widens up.

Applications

1. With the minimum of 5 V ,we can connect it with
    1.1. the mobile charger
    1.2. Camera charger
    1.3. Arduino and GPS module(helps in tracking)
2. Thermocouples can not only be used with the exhaust pipe but, we can use this set-up to any domestic appliances like gas stove and chimney etc. to convert that waste heat into electricity.

LIST OF PUBLICATIONS

Akshay Kataria, Palak Kaistha, **Shruti Jain** "Utilization of Exhaust Heat from Automotive Using Thermopile ", March 16th - 18th, 2016, pp 2484-2487, 10th INDIACom: 3rd 2016 International Conference on Computing for Sustainable Global Development, BVICAM, New Delhi.



Proceedings of the 10th INDIACom; INDIACom-2016
3rd 2016 International Conference on "Computing for Sustainable Global Development", 16th – 18th March, 2016
Bharati Vidyapeeth's Institute of Computer Applications and Management (BVICAM), New Delhi (INDIA)

Utilization of Exhaust Heat from Automotive Using Thermopile

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Abstract – With increase in the global warming and the depletion of the renewable sources of energy, the urge to shift towards alternate and green sources of energy has elevated. Extensive research in the field of greener sources of energy has led to the advancement of thermocouple to convert the waste heat into electrical energy there by shifting our concerns from conventional to exceptional ways. Utilizing that amount of heat which generally can't be used in power generation at a huge level, but does play significant role in energy conservation system. Thermocouples can be used to convert temperature difference into voltage, with several thermocouples when placed together enhances the output of the process. In this paper by comparing, we got to know that though the results obtained were highly dependent on the vicinity of the place where the process took place but sufficient amount of potential was generated which could be enhanced with the help of booster circuit and could be brought into use for future applications.

Keywords – Energy conservation system, green sources, thermocouple, thermopile, waste-heat energy.

NOMENCLATURE

conversion of temperature differences into electric potential and vice versa.

The junctions can be referred as heat source (comparatively at high temperature) and heat sink (comparatively at low temperature). Measurement of the temperature and changing the temperature of the objects are the further applications of thermoelectric effect. Thermoelectric effect inscribes three independently recognized effects: the *Seebeck effect*, *Peltier effect* (voltage difference or current can produce a heat flow [1]), and *Thomson effect*(any thermoelectric material can be used to either generate power in a temperature gradient or pump heat with an applied current [2]).

Different amount of emf (E) is being produced due to the change in the temperature at different length across the metal. This phenomenon is known as the Seebeck Effect. Seebeck effect is just another example of emf (E) where all the voltages and currents are measured by the conventional methods only.

$$E = - S \nabla T \qquad ..(1)$$

where S in the eqn. (1) is the Seebeck Coefficient, a property of the material and ∇T is the gradient in the temperature T.

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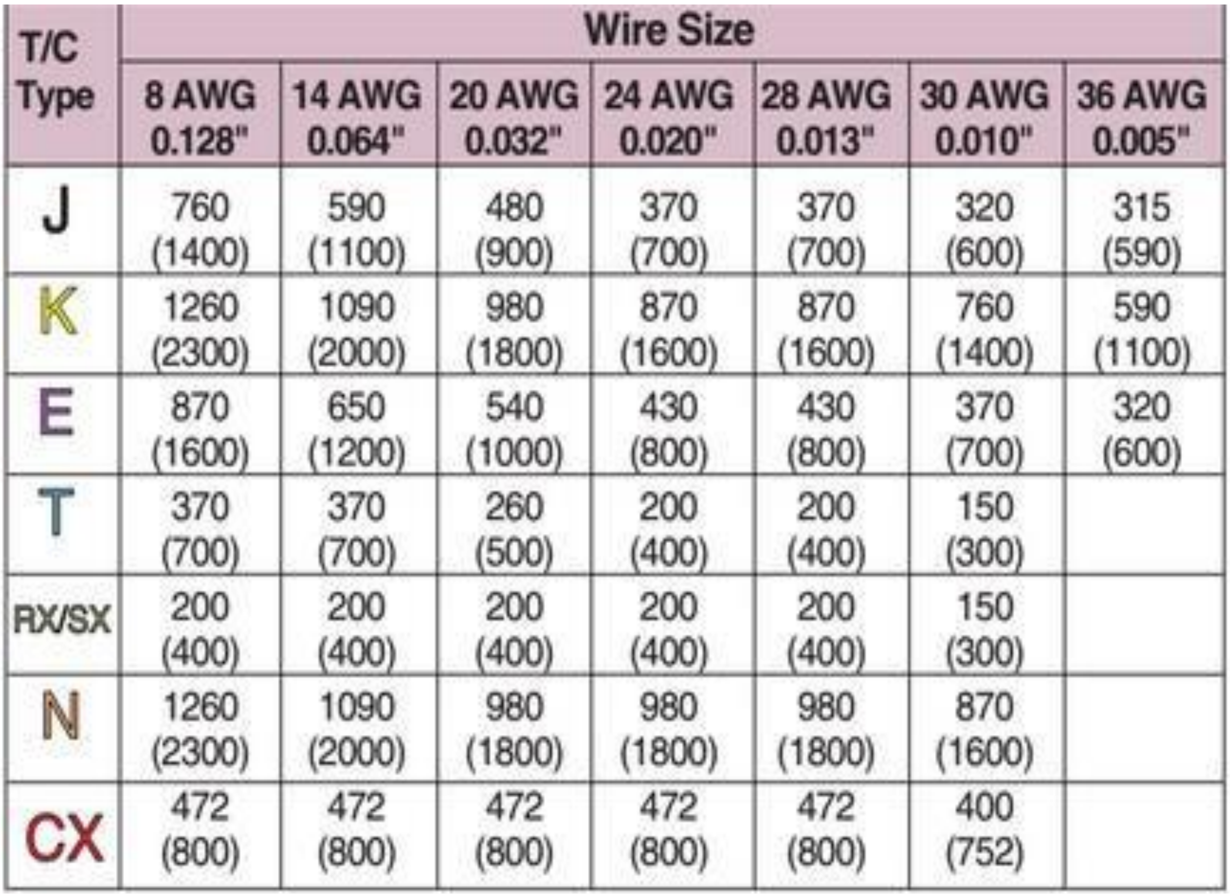
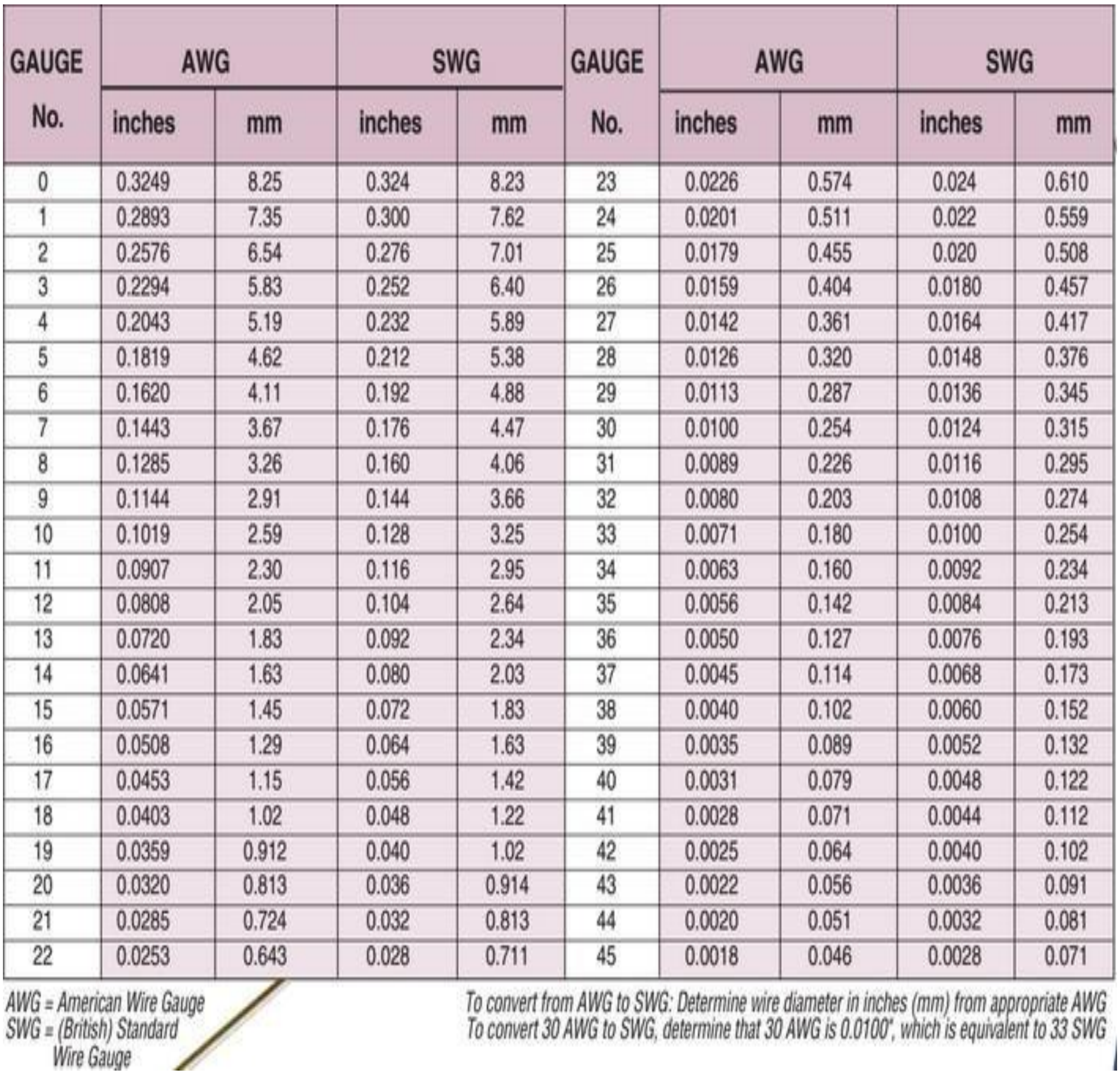
ANNEXURE A-Upper Temperature Limit in °C (°F) of Protected Bare Wire Thermocouples vs. Wire Diameter



T/C Type	Wire Size						
	8 AWG 0.128"	14 AWG 0.064"	20 AWG 0.032"	24 AWG 0.020"	28 AWG 0.013"	30 AWG 0.010"	36 AWG 0.005"
J	760 (1400)	590 (1100)	480 (900)	370 (700)	370 (700)	320 (600)	315 (590)
K	1260 (2300)	1090 (2000)	980 (1800)	870 (1600)	870 (1600)	760 (1400)	590 (1100)
E	870 (1600)	650 (1200)	540 (1000)	430 (800)	430 (800)	370 (700)	320 (600)
T	370 (700)	370 (700)	260 (500)	200 (400)	200 (400)	150 (300)	
RX/SX	200 (400)	200 (400)	200 (400)	200 (400)	200 (400)	150 (300)	
N	1260 (2300)	1090 (2000)	980 (1800)	980 (1800)	980 (1800)	870 (1600)	
CX	472 (800)	472 (800)	472 (800)	472 (800)	472 (800)	400 (752)	

ANNEXURE B-Conductor Size Equivalents

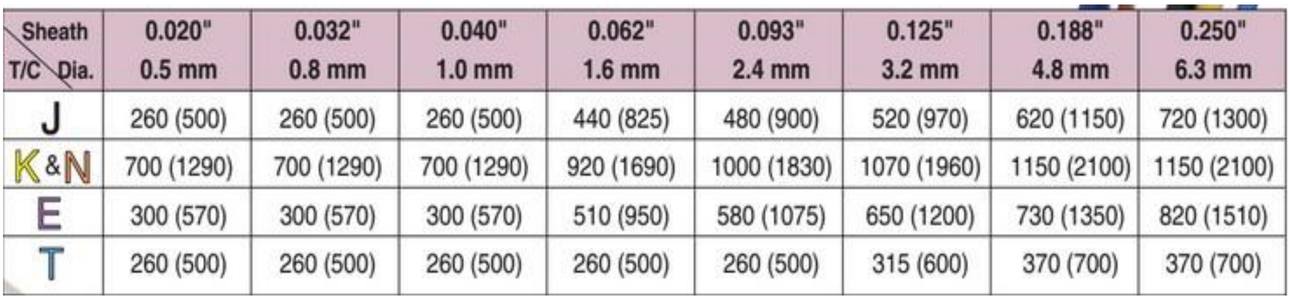


GAUGE No.	AWG inches	AWG mm	SWG inches	SWG mm	GAUGE No.	AWG inches	AWG mm	SWG inches	SWG mm
0	0.3249	8.25	0.324	8.23	23	0.0226	0.574	0.024	0.610
1	0.2893	7.35	0.300	7.62	24	0.0201	0.511	0.022	0.559
2	0.2576	6.54	0.276	7.01	25	0.0179	0.455	0.020	0.508
3	0.2294	5.83	0.252	6.40	26	0.0159	0.404	0.0180	0.457
4	0.2043	5.19	0.232	5.89	27	0.0142	0.361	0.0164	0.417
5	0.1819	4.62	0.212	5.38	28	0.0126	0.320	0.0148	0.376
6	0.1620	4.11	0.192	4.88	29	0.0113	0.287	0.0136	0.345
7	0.1443	3.67	0.176	4.47	30	0.0100	0.254	0.0124	0.315
8	0.1285	3.26	0.160	4.06	31	0.0089	0.226	0.0116	0.295
9	0.1144	2.91	0.144	3.66	32	0.0080	0.203	0.0108	0.274
10	0.1019	2.59	0.128	3.25	33	0.0071	0.180	0.0100	0.254
11	0.0907	2.30	0.116	2.95	34	0.0063	0.160	0.0092	0.234
12	0.0808	2.05	0.104	2.64	35	0.0056	0.142	0.0084	0.213
13	0.0720	1.83	0.092	2.34	36	0.0050	0.127	0.0076	0.193
14	0.0641	1.63	0.080	2.03	37	0.0045	0.114	0.0068	0.173
15	0.0571	1.45	0.072	1.83	38	0.0040	0.102	0.0060	0.152
16	0.0508	1.29	0.064	1.63	39	0.0035	0.089	0.0052	0.132
17	0.0453	1.15	0.056	1.42	40	0.0031	0.079	0.0048	0.122
18	0.0403	1.02	0.048	1.22	41	0.0028	0.071	0.0044	0.112
19	0.0359	0.912	0.040	1.02	42	0.0025	0.064	0.0040	0.102
20	0.0320	0.813	0.036	0.914	43	0.0022	0.056	0.0036	0.091
21	0.0285	0.724	0.032	0.813	44	0.0020	0.051	0.0032	0.081
22	0.0253	0.643	0.028	0.711	45	0.0018	0.046	0.0028	0.071

AWG = American Wire Gauge
SWG = (British) Standard Wire Gauge

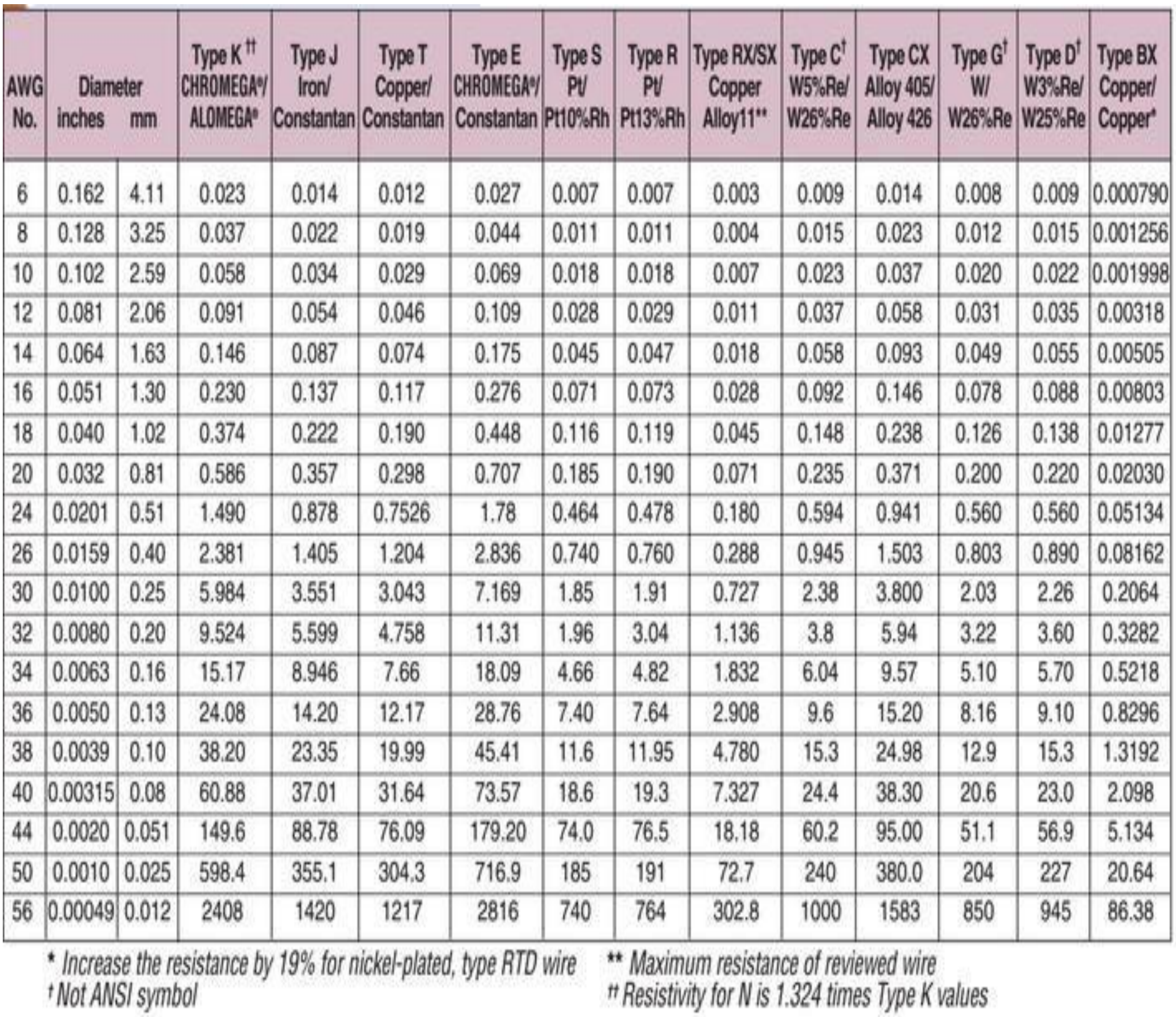
To convert from AWG to SWG: Determine wire diameter in inches (mm) from appropriate AWG
To convert 30 AWG to SWG, determine that 30 AWG is 0.0100", which is equivalent to 33 SWG

ANNEXURE C: Upper temperature in °C (°F) v/s Sheath Diameter



Sheath Dia. / T/C	0.020" 0.5 mm	0.032" 0.8 mm	0.040" 1.0 mm	0.062" 1.6 mm	0.093" 2.4 mm	0.125" 3.2 mm	0.188" 4.8 mm	0.250" 6.3 mm
J	260 (500)	260 (500)	260 (500)	440 (825)	480 (900)	520 (970)	620 (1150)	720 (1300)
K&N	700 (1290)	700 (1290)	700 (1290)	920 (1690)	1000 (1830)	1070 (1960)	1150 (2100)	1150 (2100)
E	300 (570)	300 (570)	300 (570)	510 (950)	580 (1075)	650 (1200)	730 (1350)	820 (1510)
T	260 (500)	260 (500)	260 (500)	260 (500)	260 (500)	315 (600)	370 (700)	370 (700)

ANNEXURE D: Resistance vs. Wire Diameter



AWG No.	Diameter		Type K †† CHROMEGA®/ ALOMEGA®	Type J Iron/ Constantan	Type T Copper/ Constantan	Type E CHROMEGA®/ Constantan	Type S Pt/ Pt10%Rh	Type R Pt/ Pt13%Rh	Type RX/SX Copper Alloy11**	Type C† W5%Re/ W26%Re	Type CX Alloy 405/ Alloy 426	Type G† W/ W26%Re	Type D† W3%Re/ W25%Re	Type BX Copper/ Copper*
	inches	mm												
6	0.162	4.11	0.023	0.014	0.012	0.027	0.007	0.007	0.003	0.009	0.014	0.008	0.009	0.000790
8	0.128	3.25	0.037	0.022	0.019	0.044	0.011	0.011	0.004	0.015	0.023	0.012	0.015	0.001256
10	0.102	2.59	0.058	0.034	0.029	0.069	0.018	0.018	0.007	0.023	0.037	0.020	0.022	0.001998
12	0.081	2.06	0.091	0.054	0.046	0.109	0.028	0.029	0.011	0.037	0.058	0.031	0.035	0.00318
14	0.064	1.63	0.146	0.087	0.074	0.175	0.045	0.047	0.018	0.058	0.093	0.049	0.055	0.00505
16	0.051	1.30	0.230	0.137	0.117	0.276	0.071	0.073	0.028	0.092	0.146	0.078	0.088	0.00803
18	0.040	1.02	0.374	0.222	0.190	0.448	0.116	0.119	0.045	0.148	0.238	0.126	0.138	0.01277
20	0.032	0.81	0.586	0.357	0.298	0.707	0.185	0.190	0.071	0.235	0.371	0.200	0.220	0.02030
24	0.0201	0.51	1.490	0.878	0.7526	1.78	0.464	0.478	0.180	0.594	0.941	0.560	0.560	0.05134
26	0.0159	0.40	2.381	1.405	1.204	2.836	0.740	0.760	0.288	0.945	1.503	0.803	0.890	0.08162
30	0.0100	0.25	5.984	3.551	3.043	7.169	1.85	1.91	0.727	2.38	3.800	2.03	2.26	0.2064
32	0.0080	0.20	9.524	5.599	4.758	11.31	1.96	3.04	1.136	3.8	5.94	3.22	3.60	0.3282
34	0.0063	0.16	15.17	8.946	7.66	18.09	4.66	4.82	1.832	6.04	9.57	5.10	5.70	0.5218
36	0.0050	0.13	24.08	14.20	12.17	28.76	7.40	7.64	2.908	9.6	15.20	8.16	9.10	0.8296
38	0.0039	0.10	38.20	23.35	19.99	45.41	11.6	11.95	4.780	15.3	24.98	12.9	15.3	1.3192
40	0.00315	0.08	60.88	37.01	31.64	73.57	18.6	19.3	7.327	24.4	38.30	20.6	23.0	2.098
44	0.0020	0.051	149.6	88.78	76.09	179.20	74.0	76.5	18.18	60.2	95.00	51.1	56.9	5.134
50	0.0010	0.025	598.4	355.1	304.3	716.9	185	191	72.7	240	380.0	204	227	20.64
56	0.00049	0.012	2408	1420	1217	2816	740	764	302.8	1000	1583	850	945	86.38

** Increase the resistance by 19% for nickel-plated, type RTD wire*

† Not ANSI symbol

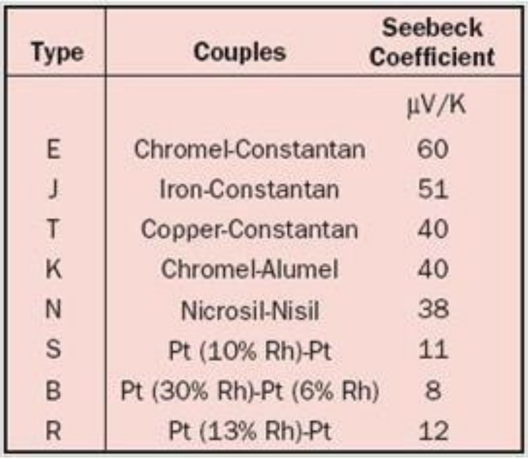
*** Maximum resistance of reviewed wire*

†† Resistivity for N is 1.324 times Type K values

ANNEXURE E: Seebeck Coefficients for Some Metals and Alloys, Compared to Platinum

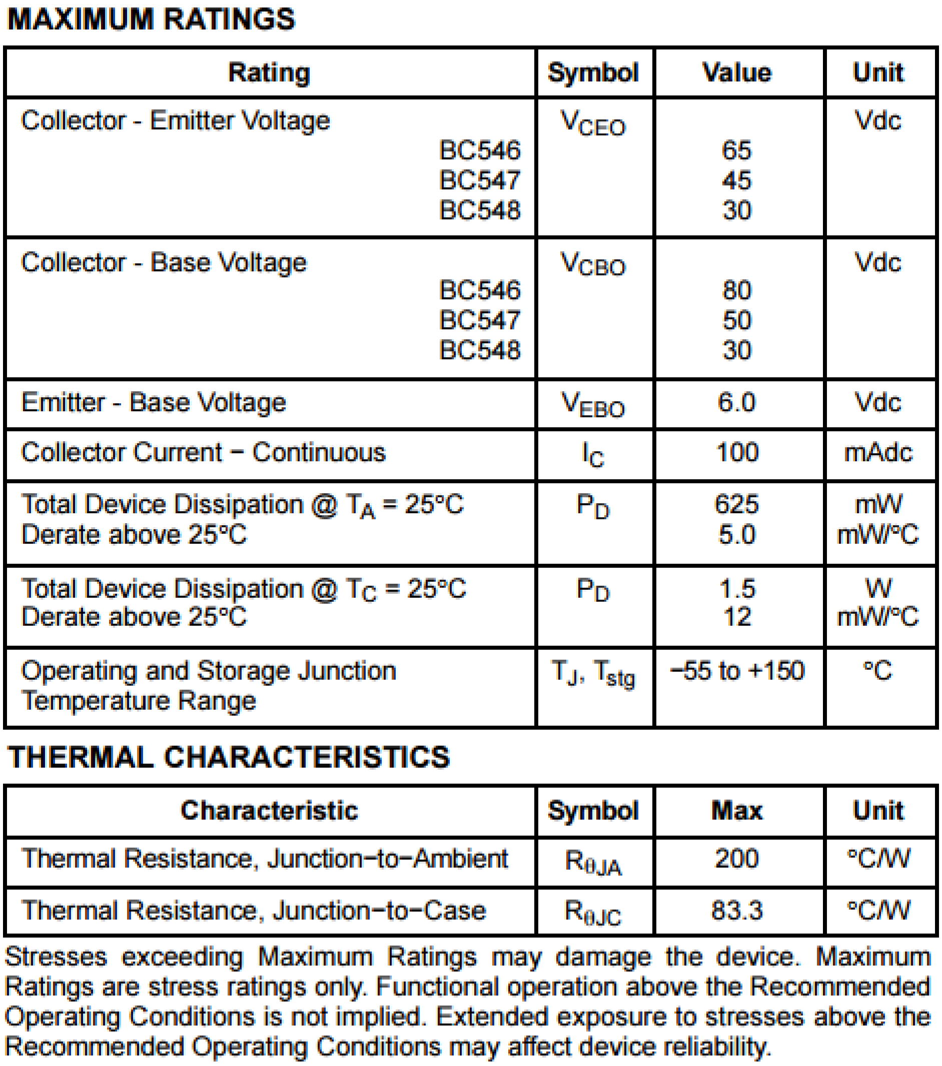
Metals	Seebeck Coefficient
	µV/K
Antimony	47
Nichrome	25
Molybdenum	10
Cadmium	7.5
Tungsten	7.5
Gold	6.5
Silver	6.5
Copper	6.5
Rhodium	6.0
Tantalum	4.5
Lead	4.0
Aluminum	3.5
Carbon	3.0
Mercury	0.6
Platinum	0
Sodium	-2.0
Potassium	-9.0
Nickel	-15
Constantan	-35
Bismuth	-72

ANNEXURE F: Seebeck Coefficients for Standard Thermocouples



Type	Couples	Seebeck Coefficient
		µV/K
E	Chromel-Constantan	60
J	Iron-Constantan	51
T	Copper-Constantan	40
K	Chromel-Alumel	40
N	Nicrosil-Nisil	38
S	Pt (10% Rh)-Pt	11
B	Pt (30% Rh)-Pt (6% Rh)	8
R	Pt (13% Rh)-Pt	12

.**ANNEXURE G:** Maximum ratings and thermal characteristics of NPN- BC546B, BC547A, B, C, BC548B, C



MAXIMUM RATINGS

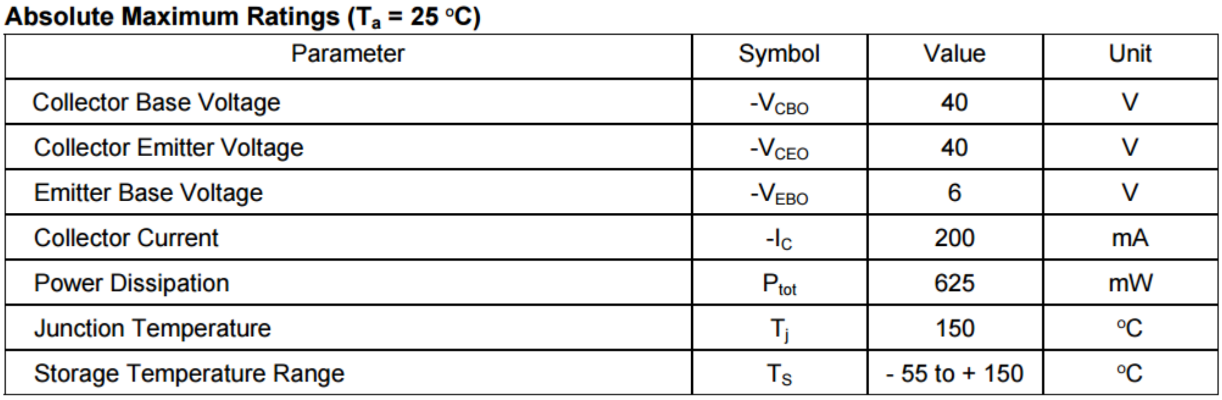
Rating	Symbol	Value	Unit
Collector - Emitter Voltage BC546 BC547 BC548	V_{CEO}	 65 45 30	Vdc
Collector - Base Voltage BC546 BC547 BC548	V_{CBO}	 80 50 30	Vdc
Emitter - Base Voltage	V_{EBO}	6.0	Vdc
Collector Current − Continuous	I_C	100	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0	mW mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12	W mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−55 to +150	°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	200	°C/W
Thermal Resistance, Junction−to−Case	$R_{\theta JC}$	83.3	°C/W

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

ANNEXURE H: Absolute maximum rating of PNP- ST 2N3905 / 2N3906



Absolute Maximum Ratings (T_a = 25 °C)

Parameter	Symbol	Value	Unit
Collector Base Voltage	$-V_{CBO}$	40	V
Collector Emitter Voltage	$-V_{CEO}$	40	V
Emitter Base Voltage	$-V_{EBO}$	6	V
Collector Current	$-I_C$	200	mA
Power Dissipation	P_{tot}	625	mW
Junction Temperature	T_j	150	°C
Storage Temperature Range	T_S	- 55 to + 150	°C