Comparative Study of TE Materials for Heat Energy Harvesting With The Help of TEC Module

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ABSTRACT

Thermoelectric materials are gaining more focus in the area of energy harvesting due to their ability to convert heat into electricity efficiently with less maintenance. This topic presents the idea of harvesting ThermoElectric(TE) energy with the help of TE leg configuration using different materials. Along with this the Thermoelectric Cooler (TEC) configuration is also discussed. And practical applications for harvesting of heat energy from heat producing objects like boiling water, Hot Pad and Electric Iron is performed. The topic further discusses on the TE effects, the study of internal structure of TE modules, thermoelectric materials and the use of TEC as TEG.

Keywords:Energy Harvesting, TEC and TEG modules, Thermoelectric Materials, Thermoelectricity.

I. INTRODUCTION

Modern portable devices and equipment's offer an always growing functionality but are dependent on the replaceable and rechargeable batteries for their energy purposes. Energy harvesting is a phenomenon to consume the available energy instead of reducing power consumption to a minimum for extending battery life. Among all the available transducers for energy harvesting, those with the greatest technical development and commercial availability are the Piezoelectric, Photovoltaic and Thermoelectric ones [1].

Piezoelectric transducers produce energy from vibrations and are more frequent. These transducer offers too low power for practical applications but have low efficiency because of the use of rectifiers, very high voltages and very low charge production. Photovoltaic transducers harvests energy from light and offer highest available power densities. These transducers can generate DC power directly. But as soon as light disappears the circuit gets disconnected. There is no way to obtain light for longer times, so the storage device should be physically bulky and expensive. Hence the easiest way to harvest such an energy is with the help of thermoelectric transducers. Because thermal transducers have several advantages like absence of mechanical moving parts, precise temperature control ability, compact size, low maintenance, high reliability, long lifetime, low efficiencies, direct DC conversion, intrinsically safe for hazardous electrical conditions, environment friendly nature due to lack of refrigerant gases and ability to couple directly to the external periphery[1-6].

Typical applications for thermoelectric harvesting systems are in military, aerospace, instrument, industrial or commercial products such as refrigerators, integrated circuit coolers and solar thermoelectric generation. They are also used in the fields of ocean thermals, steam power plants, wireless sensors, industrial motors, mechanical vibrations, light, acoustical noise, radio frequency, biological sources(such as body motion, biomass), etc.

II. THEORY

2.1. Thermoelectric Effects

The Thermoelectricity is the concept used for conversion of a temperature gradient into an voltage gradient and vice versa [7]. And the Thermoelectric Effect is the effect caused in this conversion. It is the combination of three effects: Seebeck effect, Peltier effect, and Thomson effect.

Seebeck Effect

Conversion of temperature difference (ΔT) into electrical potential difference (ΔV) is known as Seebeck Effect. Practically if two electric wires are connected and when temperature difference is imposed between the junctions, a tension raise is observed in the loop. If we put a voltmeter in the loop we get electric potential. Mathematically this effect is given by,

$$\Delta V = S\Delta T \qquad (1)$$

where S is the Seebeck Coefficient.

Peltier Effect

Generated heat flux ($q_{Peltier}$) is directly proportional to the electric current (J) in any electrical circuit. This phenomenon is known as Peltier Effect. Practically if we connect two wires and apply a potential difference in the loop, we get heat flux one positive and one negative running in and out of the junction. Here the polarities get reversed. Mathematically this effect is given by,

$$q_{Peltier} = -PJ \qquad (2)$$

where P is the Peltier Coefficient.

Thomson Effect

Thomson Effect is the combination of both Seebeck and Peltier Effects. In this, heat source ($Q_{Thomson}$) is proportional to both electric current and temperature gradient. Practically, this effect is not only occurring at junctions but also in the wires. Mathematically this effect is given by,

$$Q_{Thomson} = -\mu_{Th} J.\Delta T \qquad (3)$$

where$\mu_{Th} J$ is the Thomson Coefficient.

All of these effects are thermodynamically reversible [2].

III. INTERNAL STRUCTURE OF THERMOELECTRICS

3.1 Thermoelectric Leg

A thermoelectric leg also known as thermoelectric couple and is a basic building block of any thermoelectric module. It is made by sandwiching a thermoelectric material between two copper plates. A thermocouple properly calibrated is a temperature sensor and can convert temperature gradient into potential gradient. When a temperature difference is applied, they will show potential gradient across copper junctions. This effect is observed in the COMSOL Multiphysics environment and is as shown in Fig.1.

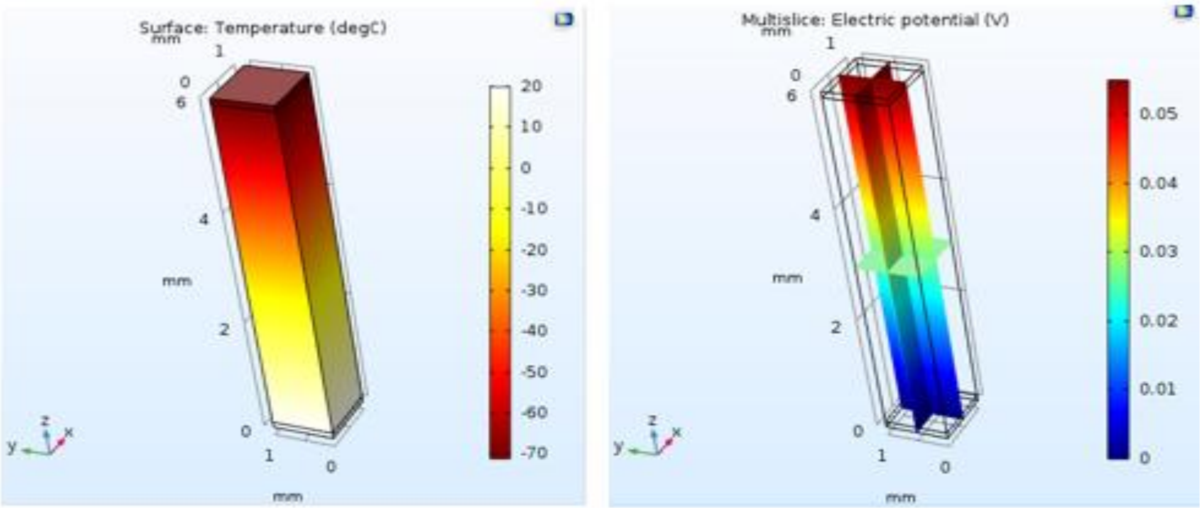

Fig1: TE Leg with temperature variation on left and respective potential variations on right for Bismuth Telluride material

3.2 Thermoelectric Module

Any TE module consists of a lot of thermocouples or TE legs connected electrically in series and thermally in parallel. These couples are the most efficient, and are combining in pairs of 'p type' and 'n type' with the copper contacts as shown in Fig. 2. The electrons flow from hot to cold in the 'n type', while the holes flow from hot to cold in the 'p type'. This allows them to combine electrically in series to increase voltage and power output. And the thermally parallel combination allows them to flow heat from one side to another side. This structure is encircling of ceramic plates for both the TEC and thermoelectric generator(TEG). Both the TEC and TEG structures look very similar and have same dimensions. The Internal Structure of TE module is as shown in Fig. 2.

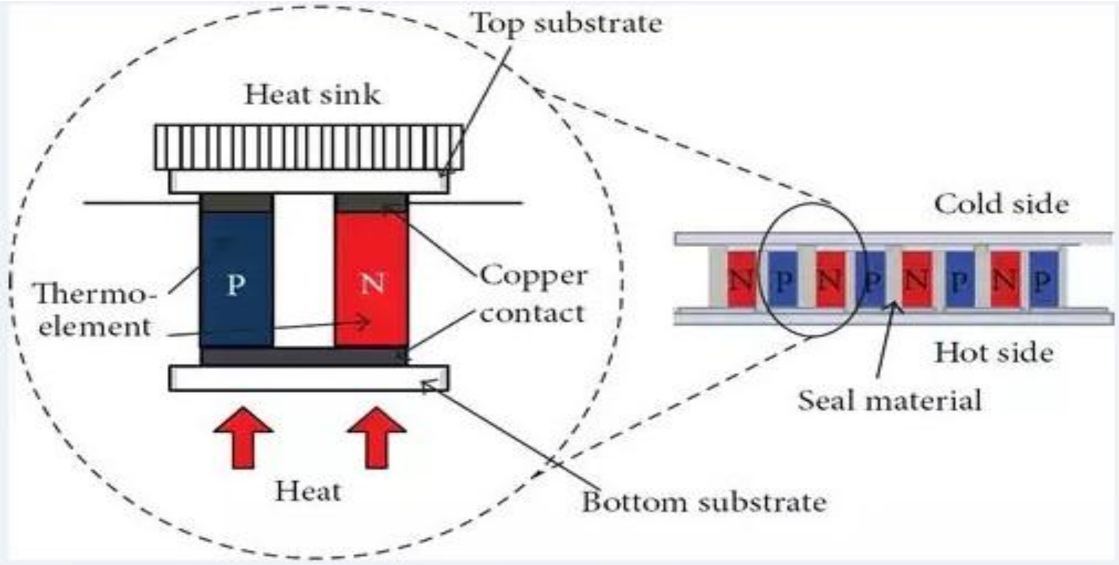

Fig2: Internal Structure of TE Module

TECs are surrounded by a filling material but many TEGs are not. However, there are also some TEGs which are surrounded by a filling material. TEGs are thinner than TECs because of the height of thermoelectric legs. As the size in TEG thermocouples in TEGs is large, a larger heat flow through the device occurs, by increasing the power outputs. The shorter legs are present in TEGs which are optimized for power generation, but with this length, they are more susceptible to the contact effects and in turn reduces the open-circuit voltage. But the size of thermoelectric legs in TECs are larger and so, the contact effects can be neglected. The long thermoelectric legs are used to achieve the maximum figure of merit. Normally, in energy harvesting systems, a combination of TEGs is made by connecting many of them in series to generate a higher power output. In this combination, a uniform contact of all TEGs must be incorporated. Otherwise, there would be an under-heated TEG, which reduces the power output drastically. On the other hand, in TECs, the thickness is not very exact.

IV. THERMOELECTRIC MATERIALS

Recently, the field of thermoelectric materials is rapidly growing with the discovery of high-efficiency materials. Advancements in these fields includes increasing complexity of the unit cell to nano-structured bulk, nano-wire, and thin film materials [9].

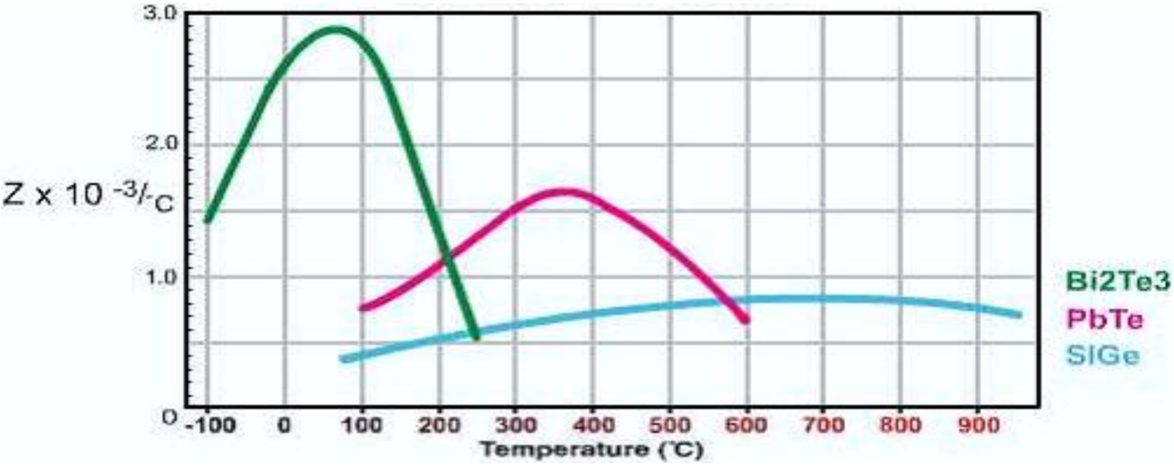

Fig3: Performance of Thermoelectric Materials with Different Temperatures

The mainly used thermoelectric materials are the alloys of the Bismuth-Telluride (Bi-Te), Lead-Telluride (Pb-Te), Silicon Germanium (Si-Ge), and Bismuth-Antimony (Bi-Sb). These materials are suitably doped to provide individual thermoelectric couples having distinct 'N' and 'P' characteristics in TE module configuration. Fig.3 illustrates the relative performance or Figure-of-Merit of various materials over a large range of temperatures [9]. It can be seen from this graph that the performance of Bismuth Telluride peaks within a low temperature range and is best suitable for low temperature applications. Hence commonly it is used to make TE Modules. And as the temperature increases the alloy of Lead Telluride is preferred.

To make any TE module, along with the thermoelectric materials, encircling material and wire material are also important. Basically, Ceramic plates are used for encircling because of their high strength and excellent wear resistance for both TECs and TEGs. For wiring of cathode and anode terminals, insulating materials are used, where Teflon material is used for TEGs and PVC material is used for TECs as they work at higher and lower temperatures respectively [2]. For the operation purpose, the material used at the cooler side must have high thermal conductivity and low coefficient of thermal expansion [8]. Even constituents of the solder can rapidly diffuse into the TE material at high temperatures and degrade performance and, in extreme cases, can cause failure. This process can be controlled by the application of a diffusion barrier onto the TE material [3]. However, some manufacturers of TECs employ no barrier material between the solder and the TE material. This leads to a short term survivability at elevated temperatures. So some qualification testing should also be taken to assure long term operation at the maximum expected operating temperature [1]

In this paper a comparative study of Bismuth Telluride (Bi_2Te_3) and Lead Telluride (Pb-Te) is done. And the practical harvesting is done with the help of TEC made up of Bi_2Te_3 material.

V. MATHEMATICAL FORMULAE

While designing a TE system, the parameters like electrical resistivity(ρ), thermal conductivity (k), and Seebeck coefficient (S) affects the module performance [6].The figure of merit is basic parameter for defining TE material at different temperatures. Hence the figure of merit (ZT) for the temperature (T) at which material is maintained, is mathematically defined as:

$$ZT = \frac{S^2.T}{\rho.k} \qquad (4)$$

Coefficient of performance(Φ_{max}) of thermoelectric module plays very important role in selection of madule. And is given by,

$$\Phi_{max} = \frac{T_h\left(\sqrt{1+ZT} - \frac{T_c}{T_h}\right)}{(T_c - T_h)(\sqrt{1+ZT}+1)} \qquad (5)$$

where(T_c)and (T_h) are temperatures at cold and hot sides respectively.

VI. CONCEPTS USED

6.1.Combination of Seebeck and Peltier Effect

The TE effects are best suited for the harvesting thermoelectricity. Hence we have tried to combine Peltier Effect and Seebeck Effect in this paper because our applications are performed at lower temperature range.

Even when commercial TEGs exists, they are designed for high-temperature gradients which range from tens to hundreds of ^{0}C. TEGs work on Seebeck Effect and TECs work on Peltier Effect. Peltier Effect is reversible to that of Seebeck Effect. All the materials have Seebeck coefficients. But in many materials coefficient is not constant in temperature, and so a special gradient in temperature can result in a gradient of Seebeck coefficient. If a current is driven through this gradient, Peltier coefficient is obtained. Mathematically Seebeck Coefficient and Peltier

Coefficient are related by,

$$P = S.T \qquad (6)$$

Hence both Seebeck effect and Peltier effect appear together, giving TEG to potentially work as TEC and vice versa.

6.2. TECs Working as TEGs

Take a TEG module and apply a temperature difference between the plates. On the hotter temperature side put a heat sink. As soon as the temperature difference is applied, an electric potential is generated across junctions. This DC potential is measured with the help of wires as shown in left side of Fig. 4. If we want to use a TEC instead of TEG in this circuit, we just have to put heat sink on lower temperature side and attach a load between wires. As we apply a temperature difference between plates, an electric potential is observed across load as shown in Fig. 4. Care should be taken for the survivability of the TEC module at both hot and cold junction temperatures. Since TECs are intended for cooling, there is no technical data available for evaluating their behavior as TEGs.

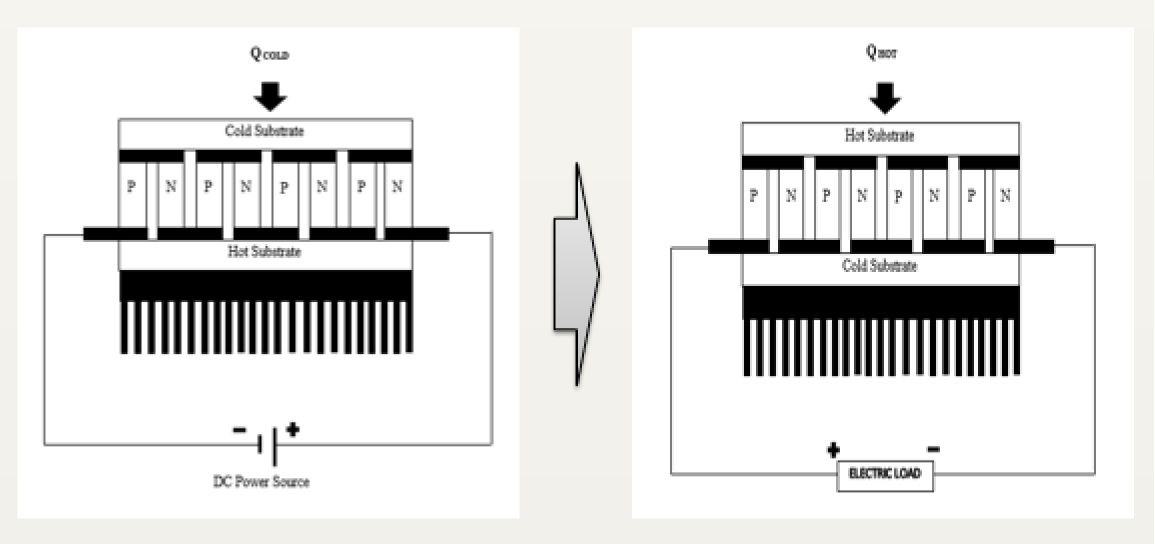

Fig 4: TECs working as TEGs

TECs seem to achieve their highest efficiency on low gradients since the main goal is that they be capable of sink the heat to the atmosphere. Another advantage is that TECs are commercially more widely available than TEGs. So to work at lower temperatures, TEGs can be replaced by TECs. For the power generation in 0 to 100 ^{0}C, TECs can be used instead of TEGs. Hence in this paper, we are dealing with the TEC1-12706 module to harvest energy from different appliances.

VII. RESULTS AND DISCUSSIONS

7.1.TE Leg Outputs

In this paper, two TE legs of similar size of $1mm * 1mm * 6mm$ are made in Comsol Multiphysics software. Two different materials Bismuth Telluride and Lead Telluride are taken for the comparison purpose. The material properties of these materials are formalized in the table I:

Table 1: Material Properties

Property	Bismuth Telluride	Lead Telluride
Thermal Conductivity	1.6 W/m.K	1.46W/m.K
Density	7740Kg/m^3	8160Kg/m^3
Seebeck coefficient	2\ e^{-4}V/K	187 e $^{-6}$ V/K
Electrical Conductivity	1.1\e ^{5}S/m	6.0976e ^{4} S/m
Relative Permitivity	1	1
Heat Capacity at Cold Junction	154.4J/Kg.K	151J/Kg. K

With the help of these standard properties the TE leg is tested by keeping a constant hot side temperature of 20 ^{0}C. By testing so, we got different ranges of temperatures and their respective voltages which are formulated in table II.

Table 2: TE Leg Output Ranges

	Bismuth Telluride	Lead Telluride
Temperature plots	-70 to 20	-60 to 20
Isothermal counters	-66.55 to 15.45	-53.56 to 16.13
Electric potential	0 to 0.05V	0 to 0.08V

7.2. TEC Module Outputs

In the Comsolmultiphysics, we can even check for applications. So here application outputs are taken for $7mm * 8mm * 2.5mm$ TEC module having pitch of 0.4mm and cross section area of $1mm * 1.1mm$ with conductor thickness of 100 μm and ceramic thickness of 0.3mm as shown in Fig. 5. The basic geometry is taken equal for both the materials(bismuth telluride and lead telluride) which are used for comparison purpose. The simulation is done with temperature of 353 K. As the similar geometry, similar mesh structures are formed.

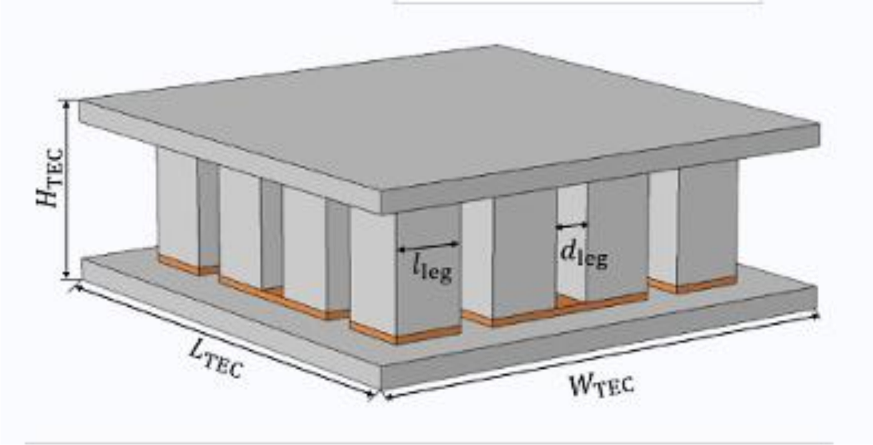

Fig. 5: Internal structure of TE module

As the Q range increases, temperature gradient decreases. So the ΔT v/s Q graph decreases linearly. As the ΔTincreases, current increases exponentially upto its maximum level. If we further increase temperature variations between plates of TEC module,TE couples will get disturbed resulting in damage. So one must have to take precautions while handling temperature variations.

Besides all these similarities, there is main difference occurs between materials for COP v/s $I/Imax$ graph. The graphs for Bismuth Telluride and Lead Telluride are as shown in Fig.6 and Fig.7 respectively. Both the graphs are taken for the temperature differences of 20 ^{0}C, 40 ^{0}Cand 60 ^{0}C.

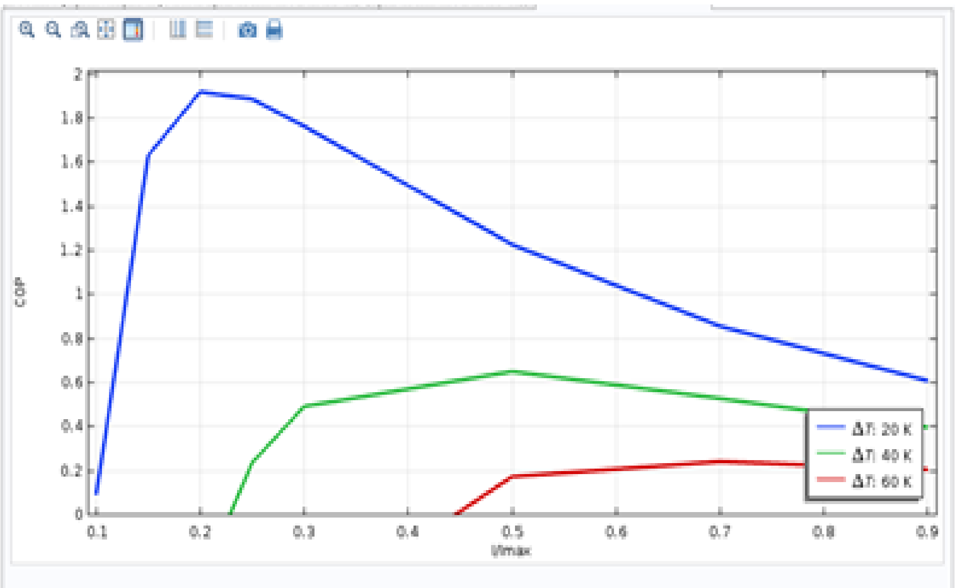

Figure 6: COP for Bismuth Telluride

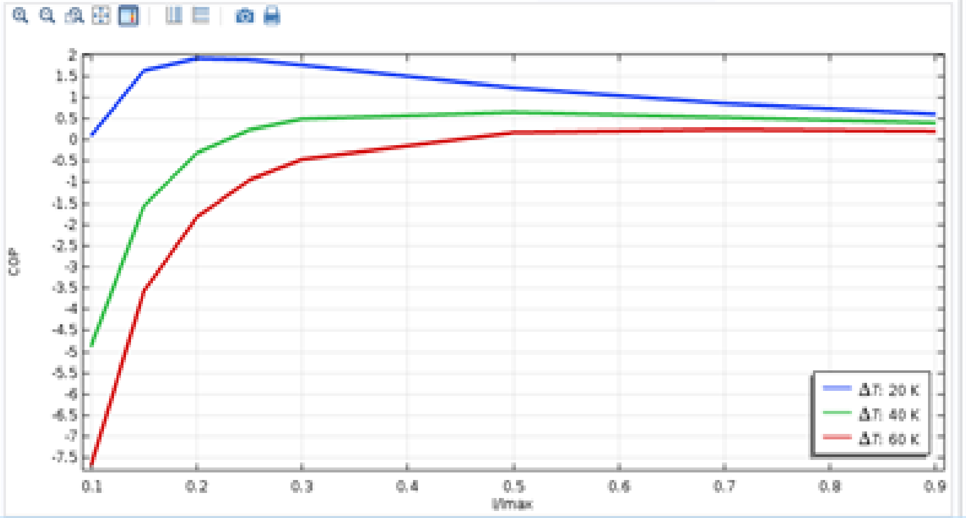

Figure 7: COP for Lead Telluride

7.3. Testing with Practical applications

The TEC module used in this work is manufactured by Hebei I.T. (Shanghai) Co., Ltd. with 127 thermocouples. Based on the datasheet, TEC1-12706 can withstand with maximum voltage around 16.4V and maximum operating temperature of 125 ^{0}C. This module is able to produce higher voltages at higher temperature difference. A patch of material of one square centimeter in area can produce up to 30 μwatts [4]. A thermoelectric device placed on the hot bodies will generate power as long as the ambient air is at a lower temperature than that body.

Figure 8: Testing with Hot Water

The initial testing was done with boiling water. We have placed TEC module on the cup filled with hot water and on other side of TEC module, heat sink was placed, to maintain stable output and prevent TEC from any damage. The setup is as shown in Fig.8. Here aluminum heat sink with fin geometry is chosen to increase the heat gradient. Also, as we are not exceeding the temperature values beyond the limit of TEC, hence no extra cooling circuitry is needed. By measuring the voltage with the help of multimeter a potential difference upto 334 mV is observed.

Then the heat producing devices are tested for the same setup. As these devices produce more temperature than our required range, hence the readings are taken for specific time period.Here the first reading have taken with the heat producing object as Hot Pad. Similar to the above setup one side of TEC is placed with Hot Pad and another side with heat sink. This thermal gradient will produce voltage upto 205mV for a time period of 20seconds. Another reading is taken with Electric Iron. By using same set up the maximum voltage obtained by Electric Iron is 294mV for a time period of 5 seconds.

VIII. CONCLUSION

This paper presents harvesting energy from boiling water, hot pad and electric iron using TECs. The main focus is on converting waste heat into electric potential using thermoelectric module by combining Seebeck and Peltier Effects. The conditions and requirements for working of TECs as TEGs is also explained. Along with this, a study on internal structure and properties of thermoelectric leg and thermoelectric cooler is also done in COMSOL environment. While doing so a comparison with different materials like Bismuth Telluride and Lead Telluride is also done for heat energy harvesting.

IX. FUTURE SCOPE

Heat energy can be easily harvested to achieve a voltage in the range of 20mV to 440mV from daily appliances. This heat leakages can be converted to electricity, with the help of ultra-low voltage step up regulators, in that application only and the generated energy can be used to charge its low potential requirements. And this converted energy can also be used to charge real time applications and batteries for further use.

One can also combine a number of TECs in series or parallel to achieve more potentials. If one wants to decrease the temperature of cooler side the output potential may increase to suppress more heat leakages.

REFERENCES

[1] C. Ugalde, J. Anzurez and I. I. Lazaro, “Thermoelectric Coolers as Alternative Transducers for Solar Energy Harvesting”, 2010 IEEE Electronics,Robotics and Automotive Mechanics Conference, Morelos, 2010, pp. 637- 641.

[2] M. Nesarajah and G. Frey, “Thermoelectric power generation: Peltierelement versus thermoelectric generator”, IECON 2016 - 42nd AnnualConference of the IEEE Industrial Electronics Society, Florence, 2016, pp. 4252-4257.

[3] R. J. Buist and P. G. Lau, “Thermoelectric power generator design and selection from TE cooling module specifications”, Thermoelectrics, 1997.Proceedings ICT ’97. XVI International Conference on, Dresden, 1997, pp. 551-554.

[4] Y. Z. Yap, R. T. Naayagi and W. L. Woo, “Thermoelectric energy harvesting for mobile phone charging application”, 2016 IEEE Region10 Conference (TENCON), Singapore, 2016, pp. 3241-3245.

[5] S. Maneewan and B. Zeghmati, “Comparison power generation by using thermoelectric modules between cooling module and power module for low temperature application”, 2007 26th International Conference onThermoelectrics, Jeju Island, 2007, pp. 290-293.

[6] C. S. Poh et al., “Analysis of characteristics and performance of thermoelectric modules”, 2016 5th International Symposium on Next-GenerationElectronics (ISNE), Hsinchu, 2016, pp. 1-2.

[7] H. U. Zaman, C. E. Shourov, A. AlMahmood and N. E. A. Siddique, “Conversion of wasted heat energy into electrical energy using TEG”, 2017 IEEE 7th Annual Computing and Communication Workshop andConference (CCWC), Las Vegas, NV, 2017, pp. 1-5.

[8] H. Kannan, Reshme T K and P. Parthiban, “Thermoelectric charger”, 2016 Online International Conference on Green Engineering and Technologies (IC-GET), Coimbatore, 2016, pp. 1-4.

[9] Ahmad NazriAbdRazak, N. MohdNor and T. Ibrahim, “Heat Energy Harvesting for Portable Power Supply”, 2011 5th International PowerEngineering and Optimization Conference, Shah Alam, Selangor, 2011, pp. 436-439.

[10] H. C. Rocha Liborio Tenorio, D. A. Vieira and C. P. De Souza, “Measurement of parameters and degradation of thermoelectric modules”, 2017,IEEE Instrumentation Measurement Magazine, vol. 20, no. 2, pp. 13-19, April 2017.