International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I9P210

Volume 70 Issue 9, 105-110, September 2022

Original Article

Modelling Thermoelectric Generators to Harvest the Low-Temperature Changes in Electronic Devices

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Received: 27 June 2022 Revised: 07 August 2022 Accepted: 17 August 2022 Published: 06 September 2022

Abstract *- As the energy demand grows, people are devising new ways to generate energy. New energy sources will be required to close the energy gap. Distributed energy generation is gaining popularity because of its several benefits, including adaptability, reliability, and adaptability, as well as the fact that it has low transmission losses. The thermoelectric generator is a distributed power source that produces electricity using thermal energy (TEG). The conversion efficiency is measured in terms that are unaffected by module geometry. This means that the thermoelectric generator design is only governed by matching the load resistance to maximise efficiency or power production.*

On the other hand, the thermoelectric module's power output and conversion efficiency are determined by the thermoelement length, contact properties, and operational temperature difference. The optimal length for maximum power production differs from that for maximum conversion efficiency. The ideal length of a thermoelement for power generation appears to be a compromise between the need for maximal power output and conversion efficiency. This paper aims to give the calculations and graphs required to determine the best module configuration.

Keywords *- Thermal Energy, Thermoelectric generator design, Seebeck effect, COMS.*

1. Introduction

The Seebeck effect is utilised to create electricity by changing the voltage in a conductor or semiconductor as the temperature changes. As the hot end of a metal rod is heated, the electrons on the colder end become more energetic and move toward the hot end. Since there are positive and negative charges at either end, there is a potential difference between them. The Seebeck coefficient measures the thermoelectric voltage generated per unit of temperature difference. [1] A thermoelectric generator uses the Seebeck effect to create electricity (TEG). At least one thermoelectric module is coupled to a cooling system in a TEG [2]. A set of thermocouples electrically and thermally connected is known as a module [3]. Thermocouples are made by combining two semiconductors with different Seebeck coefficients.

Temperature change cause hundreds of microvolts in a thermocouple. Basic thermocouple schematic (Fig. 1)

The Seebeck effect provides thermoelectric power by setting the connections at different temperatures.

The conversion efficiency of a thermoelectric material peaks at a particular temperature. As a result, when working in a temperature range, materials often function lower than they should. Materials that are optimised for specific temperature ranges can be divided into TEG to improve their performance. [6-9]

There are three types of thermoelectric materials that are commercially available:

- bismuth telluride -Temperatures of up to 250°C
- lead telluride-Temperatures of up to 600°C
- Silicon germanium alloys-Temperatures of up to 1000°C

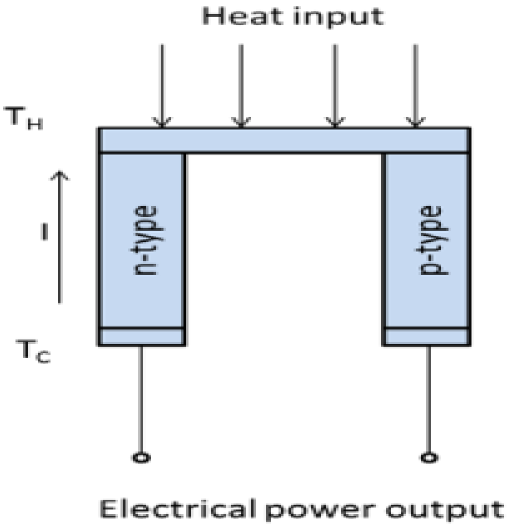


Fig. 1 Simple Thermocouple

Scientists have recently succeeded in synthesising novel materials [10-14].and building low-dimensional materials with improved thermoelectric performance. TEG has the potential to be used in the recovery process. Automotive exhaust gas, incineration plant exhaust, and hot gases and liquids in the industry all contribute to climate change [18]. Uses for TEG are spaceship power production and martian TEG power plants. Overheating in autos has been investigated to conserve precious fossil fuels. O'Shaughnessy et al. presented the findings of employing a TEG to produce power on a modest scale linked to a cooking burner [20]. It was used to power mobile phones, flashlights, and radios in Malawi.

The See beck effect is used in TEGs to convert heat to electricity [23]. When temperature disparities exist, creating electromotive force (EMF) through a material is the fundamental principle of a TEG. The n-type elements have a large concentration of negative charge or electrons. At the same time, p-type elements are doped to produce many positive charges or holes. A negative See beck coefficient is produced by atoms with a big number of electrons Elements with a huge number of holes, for example, on the other hand, contribute to a positive See beck coefficient [24]. One or more TE couplings form the basis of a TEG. A thermocouple is the most basic TEG, comprised of a pair of p and n-type TE materials coupled electrically and thermally in series.

$$\eta_{TEC} = \frac{T_H T_C}{T_h} \frac{\sqrt{(1+ZT)}-1}{\sqrt{1+ZT}+T_h-T_C} \qquad (1)$$

The EMF is generated to create an electrical current when an n or p-type element's electron and hole movement causes it to conduct electricity. Current will flow if the two connections have a temperature differential. There is a rise in the temperature gradient as a result. ΔT = Th/Tc, the more electric output power is produced across the TEG unit rises.

EMF production is severely restricted in a pair of n and p-type components. Many of these TE couplings are necessary to produce a high enough voltage. Thermal energy is produced using a thermoelectric generator (TEG) [20]. Consequently, efficiency is the most significant factor in determining the performance of a gadget. It is possible to get the TEG efficiency from [22] for a TEG that operates between a high and low-temperature heat source. The TEG rises as the temperature difference between the connections, T, grows. Progress in TE materials started in the early twentieth century. Altenkirch introduced the ZT value, often known as the coefficient of performance, to show the TE material's efficiency

$$ZT = \frac{S^2 \sigma T}{K} \qquad (2)$$

The Seebeck coefficient(S) is calculated by the temperature differential ratio of the EMF produced. Furthermore, the thermal conductivity in W/mK (which includes the lattice and electronic components) and T is the absolute temperature in K. When temperature variations exist in a material, the Seebeck effect is produced. The Seebeck effect, or S, is the ratio of EMF produced to the temperature differential.

$$s = \frac{S_e \sigma_e + S_h \sigma_h}{\sigma_e + \sigma_h} \qquad (3)$$

where

- S_h-p-type carrier conduction's Seebeck component,
- e-electrical conductivity of the n-type carrier,
- h- p-type carrier electrical conductivity,
- S_e-n-type carrier conduction's Seebeck component

Here, the material property ZT is employed. The material's TE efficiency can be improved by increasing the ZT value. The numerator of Equation (2), S2σ, also known as a "power factor" (PF), must be maximised to obtain it. T will be the temperature(K) at which all properties are measured, and tiny modifications are made to determine Z in the ZT equation. This ideal material would scatter phonons, lowering the lattice contribution to that of glass while allowing electrons to travel freely through the material, just like in a crystal. Atomic lattice vibrations are used to transfer heat in materials. Solids' atoms are held together in a lattice arrangement by chemical bonds. These bonds aren't stiff; instead, they act like springs, joining the atoms via a spring–motion mechanism. If an atom or a row of atoms travels along a crystal, the displacement spreads like a wave and carries energy. The term "phonons" is used to describe these quantized waves.

2. Structure of TEG

A thermocouple is a thermoelectric module's basic unit, consisting of two n- and p-type semiconductors. The fundamental unit is shown schematically in Figure 2. In the diagram, the electric conductors are indicated by the character *. The letters TH and TC stand for junction and base temperatures. Figure 2 shows a common semiconductor pair geometry, with semiconductor dimensions in the millimetre range [11]. A thermoelectric device turns thermal energy into electrical energy using a series of thermocouples. This technology can provide electricity to satellites, space probes, and even autonomous facilities.

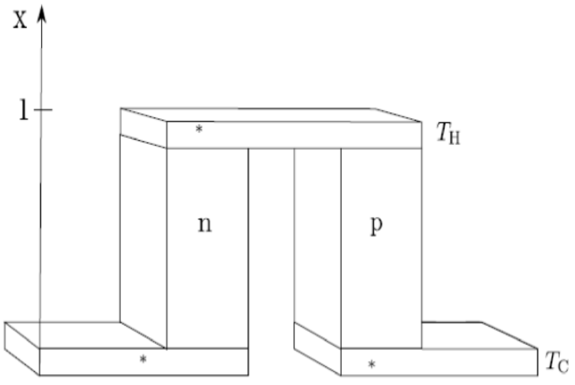


Fig. 2 The basic unit of a thermoelectric device

A formable Seebeck voltage VS exists. Whenever a thermoelectric couple or meander of sequentially linked pairs is positioned between the two particles, Tc and Th are the two distinct temperatures observed. Only the heat conduction and Seebeck effect mechanisms are present in this situation. The thermoelectric system uses the techniques described above when a resistive load RL decreases the electromotive force VS, producing electrical power P [6].

$$p = I^2 R_L = \left(\frac{V_S}{R_{L+}R_I}\right)^2 . R_L = \left(\frac{\alpha(T_h - T_C)}{R_L + R_I}\right)^2 . R_L$$

3. The Finite Element Application (FEA) Model TEG

Many power-generating thermoelectric modules are built using a simplified model that overlooks the module's thermal and electrical contact resistances, which results in an unreliable design. Conversion efficiency may be approximated by utilising a formula independent of the module's geometry. There are two scenarios in which a thermoelectric generator's design might be limited: either by maximising conversion efficiency or increasing power output. On the other hand, a thermoelectric module's power output and conversion efficiency are determined by the length of the thermoelement, the quality of the contact, and the operational temperature difference. To maximise power output, a longer cable is needed. To maximise efficiency, a shorter cable is needed. Temperature and conversion efficiency is generally considered when selecting the ideal length of thermoelement for power production. There are two ways to look at a module's cost: the cost of developing it and operating it. The power-generating module should be modified to lower the cost of produced energy.

3.1. Steps in the design process

The conceptual design determines the system's underlying strategy and broad characteristics. These are the underpinnings of the quantitative design process that follows. The initial or starting design is then defined using the system's setup, the issue statement's supplied quantities and an acceptable collection of design variables. This first set of design variables is based on previous experience with similar designs, current engineering practice, and personal experience. A simplified model for the initial design can be constructed using approximations and idealizations to study the system's behaviour and attributes. Because most thermal systems have complicated governing equations, the system's behaviour in a range of circumstances is typically explored on the computer using a simulation technique. In various situations, an experimental or physical model can be used. This approach requires the articulation of the design challenge as well as conceptual design, which both play important roles at different phases.

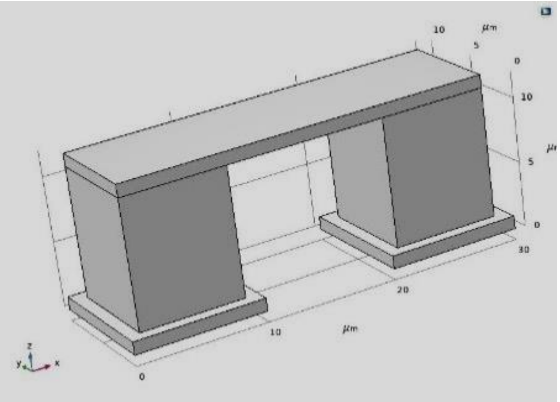


Fig. 3 Teg Design in COMSOL

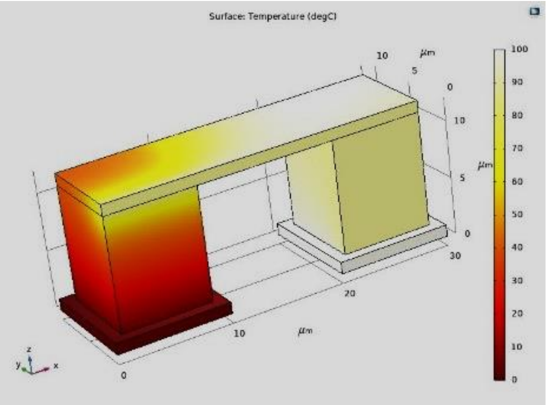


Fig. 4 Surface Temperature (deg C)

Surface Temperature is generated in TEG due to See beck effect induces the movement of charge carriers within p-and n-type semiconductor legs

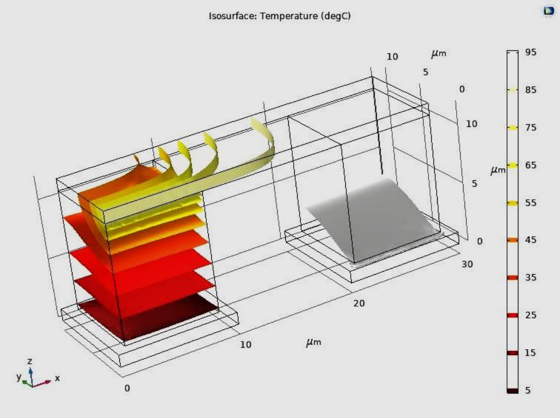


Fig. 5 Isosurface Temperature (degC)

Isosurface Temperature is generated in TEG due to temperature gradient has been induced between the hot and cold sides of TEG,

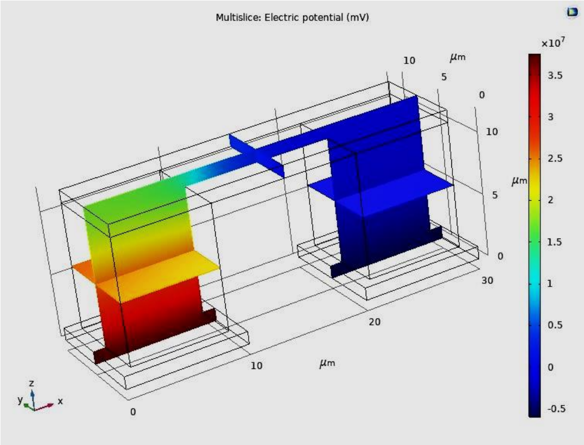


Fig. 6 Multislice: Electric Potential(mV)

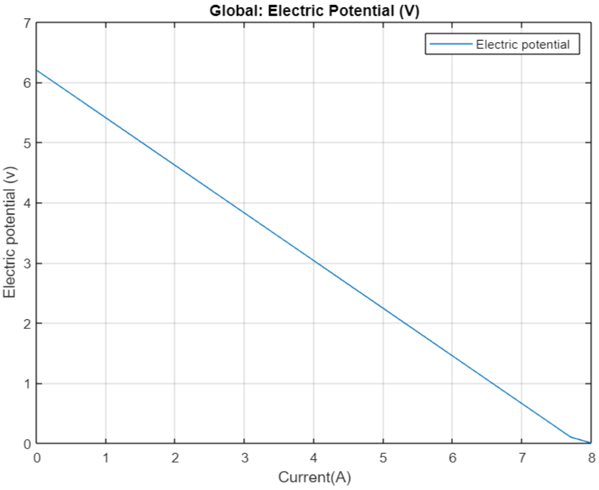
The relationship between metals and the temperature of their contact potentials is important to understanding thermoelectric potential. Temperature affects the contact potential at a particular junction in a thermoelectric circuit.

4. Results and Discussion

The output voltage versus electric current curve is shown in Figure 4. When the circuit is open, the output voltage is maximum; after the load is added, the open circuit voltage declines linearly, which implies that in this equation, maximum voltage minus drop voltage is related to the load.

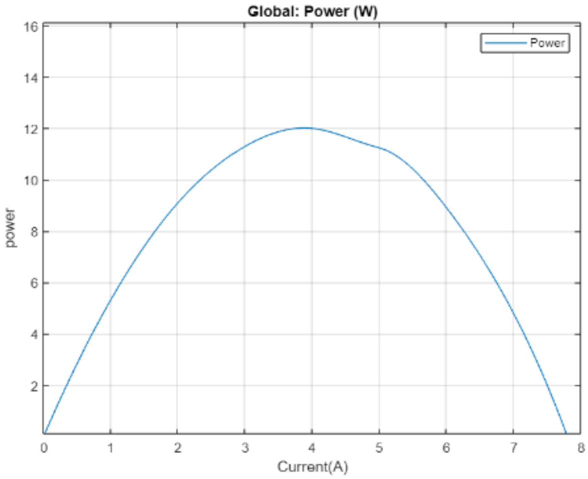
$$V_L = NIR_L = N[\alpha(T_H - T_C) - IR_{TE}]$$

Graph 1 shows the thermoelectric module's output power. The power grows in lockstep with the electrical current until it reaches its peak. As the electrical current grows after the ideal point, the power drops.



Graph 1. Current Vs Electrical Potential

This maximum of 11 W is attained with the best material. Nevertheless, the variation is very less and is connected to contact resistance in accuracy. This projected power output of 11 W, similar to the power observed without a heat sink, indicates that the proposed cooling system is entirely working.



Graph 2. Current Vs Power

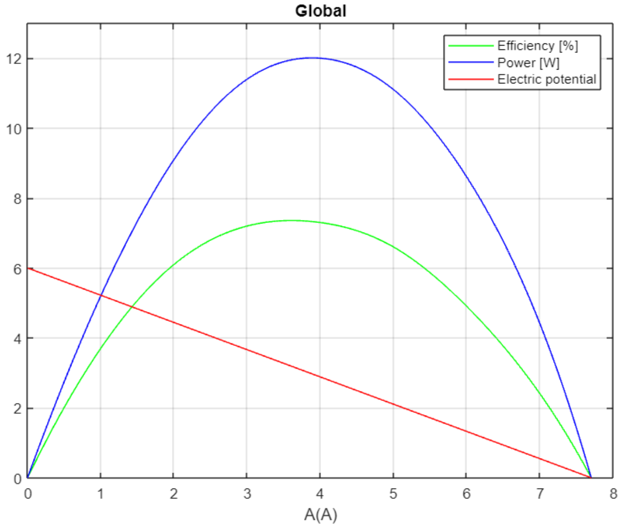
Table 1 illustrates the output results of power and voltage at various hot temperatures, illustrating the maximum output power and open circuit voltage climb as the temperature difference grows. These are the results of a simulated optimum module.

Table 1. Output results of power and voltage

Temperature	Power(W)	Open Circuit Voltage(V)
T_Hot1=200	1.8	1.3
T_Hot_2=400	4.5	30.7
T_Hot3=600	10	6.73

Graph 3. illustrates that power and efficiency are at their highest levels at the same moment; data shows that when the current rises, power and efficiency rise and fall in lockstep. The electrical potential voltage does not change in direction as the current increases, meaning it continues to decline.

The voltage in the open circuit When the load draws no current, the voltage is the voltage, and when the TEG's terminals are shorted together, the current I_{SC} is measured. The highest level of power has been reached.



Graph 3. Power and Efficiency Vs Electric Potential

The temperature at which the TEG works determines its absolute value. Less current flows through the TEG when operated to the left of the maximum power point. The TEG's effective thermal conductivity decreases (which depends on current flow due to the parasitic Peltier effect). The thermal energy carried by the TEG in this scenario is lower than at full power, resulting in a decreased thermal load on the entire system. This is often beneficial because it increases the system's thermal efficiency. The thermal conductivity increases as the TEG is turned on to the right of the maximum power point. The thermal system is turned on energy transported by the TEG exceeds that flowing at its most powerful setting. When the system is operated in the right-hand zone, the system's thermal efficiency degrades.

5. Conclusion

3D TEG modules have been developed at COMSOL geometries. The Seebeck coefficients, electrical resistivities, and thermal conductivities of several TE materials are all temperature dependent and taken straight from recent papers. For T = 200,400 K and 600 K, it was discovered that the TEG modules combining today's best p-type TE materials with the strongest n-type TE materials could achieve efficiencies of up to 15.0% and 22.9%, respectively. By showing that the highest-performing n-type and p-type materials at elevated temperatures may be combined with conventional high-ZT low temperature materials, such as p- and n-types, the researchers have shown that the theoretical efficiency upper limits have been reached. TEG devices may be created without interfering with each other when the intermediate segments are used as a bridge between the components. Due to the general weakness of the n-type TE materials, TEG module efficiency may be properly predicted using the hypothesised connection, as shown by these outcomes. It is possible to segment TE materials successfully by changing the s value gradually from one TEG leg end to another, even while the s values on both the cold and hot sides diverge by more than a factor of two. Additionally, the effects of heat radiation and contact resistances have been examined. Thermal radiation has a negligible influence on TEG performance, but contact resistances, especially electrical ones, might have a devastating effect on TEG efficiency and output power.

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