Thermoelectric Generator Analysis Through ANSYS and Matlab/Simulink

Md.Sadequr Rahman Bhuiyan
Department of Electrical and Computer Engineering
Georgia Southern University
Statesboro,GA-30460,USA
mb34812@georgiasouthern.edu

Adel El-Shahat
Department of Electrical and Computer Engineering
Georgia Southern University
Statesboro,GA-30460,USA
aahmed@georgiasouthern.edu

Valentin Soloiu
Department of Mechanical Engineering
Georgia Southern University
Statesboro,GA-30460,USA
vsoloiu@georgiasouthern.edu

***Abstract*— The gradual increase in the price of fossil fuel and their adverse impact on the environment, it is high time to think about renewable energy sources. Having a wide range of applications from mW to W power, thermoelectric generators (TEG) are extensively used as self-governing renewable energy sources. To predict the performances of TEG materials, simulation is a suitable option which gives us the notion about the characteristic behavior of that specific material under certain circumstances. In this paper, it has been designed TEG unit by using ANSYS and finally, the mathematical modeling of TEG has been represented by MATLAB/ Simulink to analyze the various parameters i.e. voltage, current and power in terms of changing the temperature gradient.**

Keywords—Renewable Energy, TEG, ANSYS, MATLAB/Simulink, Temperature gradient.

I. Introduction

Thermoelectric generator as a rising environment friendly energy harvesting source mainly from waste heat by means of temperature gradient could be the future prospect to meet up the energy challenges in the upcoming decades. A solid-state device using Seebeck effect phenomenon generating electricity is known as Thermo-Electric Generator (TEG). By mechanism it is a static device having no moving parts and could be used in power plants to utilize the waste heat for generating additional power as well as in automobile as automotive thermoelectric generators to increase the efficiency of used fuel. Thermo-Electric energy conversion system mainly depends on the physical properties of materials and the temperature gradient in between the connection point of two different materials and the open points. However, electrical energy harvesting by using Thermo-Electric Generator concept from different appliances which are emitting heat as waste when these are operating could be one of the most promising approach of alternative green technology.

Thermo-Electric behavior was first observed by Thomas Johann Seebeck in 1821 and he discovered the deflection of compass magnet when a temperature gradient is maintained between the junctions of two different metals. This deflection is the results of induced electrical current through the closed circuit, which is defined by Ampere's law. The driving current in the closed circuit is the potential difference between the cold and hot junctions for creating temperature gradient, which is termed as the "Seebeck effect". This potential (Voltage) difference is directly related with temperature difference, which varies proportionally. The constant of the above proportionality is called Seebeck co-efficient and most often it is said "Thermo-Power". Researchers from different times had worked on that field and it is still a developing sector to work on it.

Thermoelectric technology with the integration of solar thermal technology having the combined name as concentrated thermoelectric generator (CTEG) was developed where it was designed and fabricated the CTEG model and tested some fruitful scientific experiments. To achieve the maximum temperature difference, it was introduced a cooling device attached with cold side. It could be convenient to find out the proper materials to get wide range of temperature difference and if the Nano-thermoelectric material is introduced then the overall efficiency of TEG will be increased significantly [1]. To measure the thermoelectric behavior of different materials a model was designed by using MATLAB/Simulink. Some theoretical equations related to thermal conductivity in materials were derived and based on some equations the model was developed with the Simulink blocks. This model can be extended by introducing myriad ways of cooling process for predicting the output thermoelectric values [2]. For introducing some techniques about the use of waste heat as a renewable energy sources and analyzing the properties of thermoelectric generator materials for optimizing their output, COMSOL Multiphysics software based TEG model was designed and analyzed output characteristics in some extant [3]. However, fluid properties and heat exchange performance of materials can be a good factor to optimize the TEG output. It is also important to increase the efficiency by reducing the resistivity in thermal contact along with finding out better thermoelectric materials [4]. There is a vast area of studying the materials property and to improve the performance of TEG module by choosing proper combination of materials [5].

II. Thermoelectric Energy Conversion and Mathematical Modeling

Mathematical modeling is the prerequisite condition for design and analyzes of any system. To analyze the output parameters of thermoelectric generator it is obvious to find out the relevant formula. The Seebeck coefficient S is defined as:

$$S = \frac{dV}{dT} \quad (1)$$

Where V and T respectively represents the Seebeck voltage and temperature.

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Conversion of energy that occurred in TEG has also three other types.
First one is the conduction of thermal which is represented as:

$$Q_{th} = -K_{th}\Delta T \quad (2)$$

Where the thermal conductivity of the material is K_{th} and the difference temperature between hot side and cold side is ΔT.

Each material has internal resistance which causes the dissipation of heat while operating as TEG and this phenomenon is called joule heating which can be expressed as:

$$Q_j = I^2 R \quad (3)$$

Where R is the material's resistance, and I is the current through the material.

Another energy conversion occurred is known as Peltier cooling/heating effect and described as:

$$Q_{d/a} = SIT_{h/c} \quad (4)$$

However, the heat transfer at the hot and cold side is given by

$$Q_h = K_{th}\Delta T + SIT_h - \frac{1}{2}I^2R \quad (5)$$

$$Q_c = K_{th}\Delta T + SIT_c + \frac{1}{2}I^2R \quad (6)$$

Thus, the net power is given by $P = Q_h - Q_c = [S\Delta T - IR]I$
Moreover, each unit of TEG is formed with p-type and n-type semiconductor whose lengths are L. However, there are some important parameters which are intensively related for the development voltage across the TEG module.
A couple of pellets' electrical Resistance R (Ω) of is given by

$$R = \rho_p \frac{L}{A} + \rho_n \frac{L}{A} \quad (7)$$

Where ρ_p and ρ_n is the electrical resistivity of p type and n type material given in (Ωm) [7]. If there are N couples are combined in TEM then total internal resistance R_m of TEM is calculated as

$$R_m = R.N \quad (8)$$

For a specific material, the Seebeck coefficient (V/K) of any pair is given as

$$\alpha = \alpha_p - \alpha_n \quad (9)$$

Total Seebeck co-efficient of a TEM having N couples is represented as

$$\alpha_m = \alpha.N \quad (10)$$

So, the developed electromotive force (EMF) of the TEM is given by

$$V = \alpha_m(T_h - T_c) \quad (11)$$

The supplied current by the TEM is given by

$$I = \frac{\alpha_m(T_c - T_h)}{R_m + R_L} \quad (12)$$

Where the resistance of the load is considered as R_L.

For maximum power generation it is obvious that the load resistance R_L should be equal the internal resistance of R_m and assuming R_L=R_m=R we can get the expression as [7].

$$I_m = \frac{\alpha_m(T_h - T_c)}{2R} \quad (13)$$

Finally, the maximum power is shown in eq. (14).

$$P_m = \alpha_m(T_h - T_c)I_m - I^2{}_m R \quad (14)$$

By using the above formulas, it could be possible to design a MATLAB/Simulink model of TEM to analyze the performances of various parameters of TEG.

III. Modeling and Simulation of TEG by ANSYS

For performing thermal, thermoelectric and electromagnetic analysis ANSYS workbench software is used. A steady state analysis of TEG has been carried out by using ANSYS Workbench software which allows the geometric modeling of that device and several analyses like temperature distribution and current density throughout the TEG device. Here it is presented the modeling and analysis techniques of thermoelectric generators (TEGs) with ANSYS Workbench Platform.

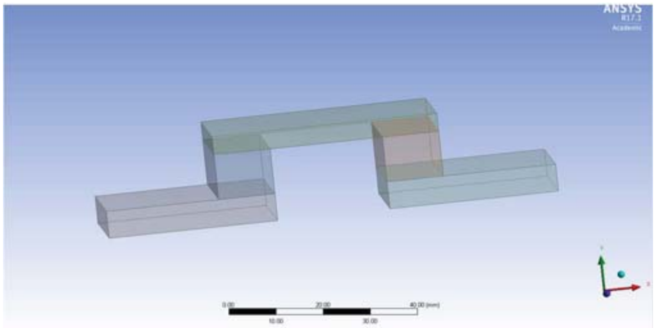

Fig.1. Geometric Model of TEG.

Fig.1 is the schematic diagram of thermoelectric generator with 5 different parts. The lower two bases are for the cold junction and the top portion is for hot junction. The remaining two other is n-type and p-type semiconductor. The whole structure was formed by copper alloy and the p-type portion having thermal conductivity of 1.46W/m/K, isotropic resistivity 1.46e-5Ωm and Seebeck coefficient 187e-6V/K, on the other hand the n-type portion's selected properties are thermal conductivity 1.46W/m/K, Isotropic Resistivity 1.64e-5 Ωm and Seebeck co-efficient -187e-6V/K.

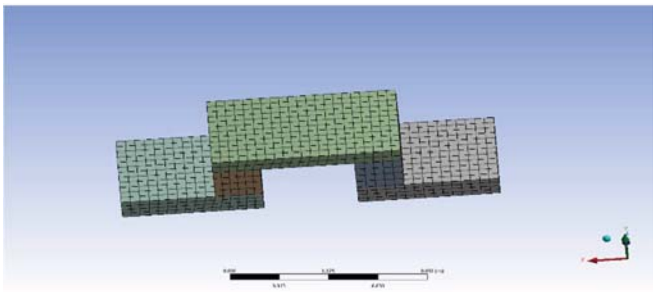

Fig.2. Mesh Analysis of designed TEG.

By using mesh, the whole component is divided into number of pieces to distribute the load uniformly whenever any load is applied and in ANSYS it chooses the suitable mesh automatically so that the simulation of the designed system can be performed efficiently. Here Fig.2 depicts meshing of the designed TEG at ANSYS.

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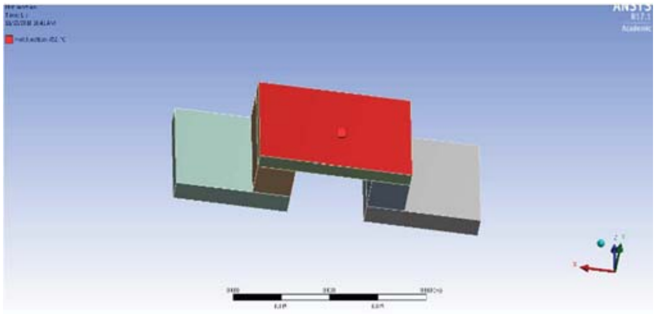

Fig.3. Hot junction of designed TEG.

The indicated portion of the above Fig.3 is for hot junction where the applied temperature is 452^0 C. This temperature can be varied to increase the difference of temperature in between two terminals.

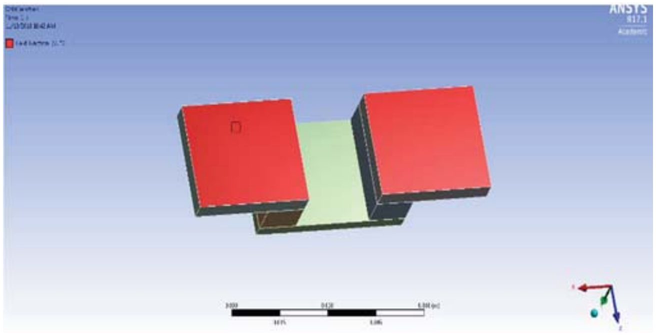

Fig.4. Cold junction of designed TEG.

Fig.4 is for cold junction and its temperature is about 22^0 C so that to create temperature gradient between hot and cold junction. That part of TEG relates to the external circuit for carrying current to the load.

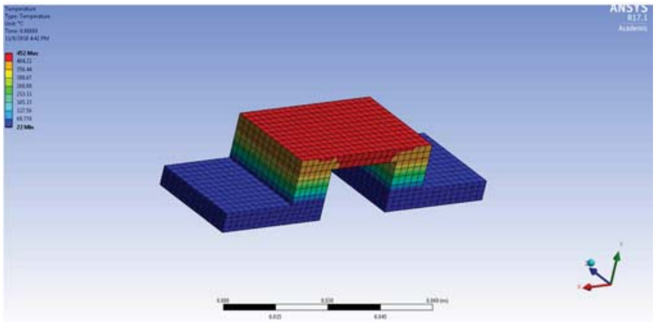

Fig.5. Distribution of temperature of designed TEG.

This figure depicts the temperature distribution of the TEG device and hence the hot junction has higher temperature and the cold junction has lower temperature.

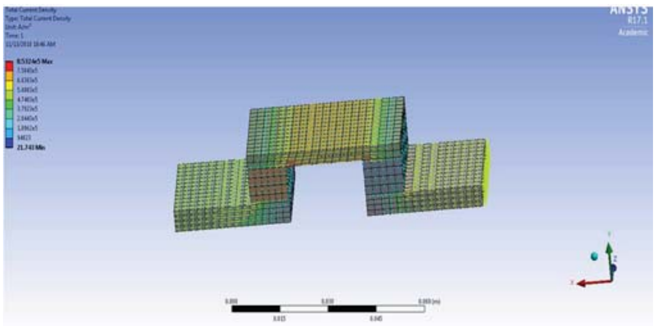

Fig.6. Current density throughout the TEG.

Fig.6 shows the current density throughout the whole TEG device and the minimum current density is 21.743 A/m² whereas the maximum density is 8.5324e+005 A/m². Basically, the electron flows from n-type to the p-type portion. With the changes of temperature gradient between hot and cold junction, the current density has also changed appreciably.

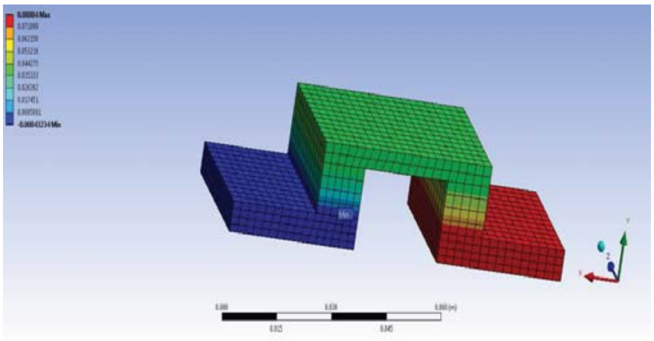

Fig.7. Developed voltage in two leg.

From above Fig.7 minimum voltage -4.3234e-004 V occurs at n-base and the maximum voltage 8.004e-002 V occurs at p-base.

IV. Matlab Model and Simulation of TEG

Due to the proportional correlation between the electrical and thermal conductivity of any material so it would be a daunting task to glean out the proper material with high figure of merit along with cost effective, environment friendly and optimum efficiency. Metal oxides of several materials could be the proper option of thermoelectric materials having good thermal stability, low cost and non-toxins and their power factor can be varied by manipulating crystal structures and compositions. For simulation purpose Be_2Te_3 materials parameters were used as it has high figure of merit, cost effectiveness and availability [6].

TABLE I. TEM PARAMETERS

Sr. No	Parameters	Assumed Value
1	Seebeck coefficient(V/K)	230×10^{-6}
2	Seebeck coefficient(V/K)	195×10^{-6}
3	Electrical Resistivity(ohm-cm)	$\rho_p = 1.75 \times 10^{-3}$
4	Electrical Resistivity(ohm-cm)	$\rho_n = 1.35 \times 10^{-3}$
5	Length of cell(cm)	$L_p = 1cm, L_n = 1cm$
6	Area of cell p type(cm²/couple)	$A_p = 1cm^2/couple$
7	Area of cell p type(cm²/couple)	$A_n = 1cm^2/couple$

The data mentioned on the above table were used to design different segment of TEM in Simulink system. In the Simulink several subsystems were built to model different parts of the TEM and then combined for complete TEM.

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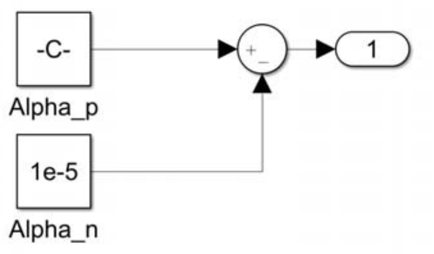

Fig.8. Measuring Seebeck co-efficient (α) for single p-n TEM unit.

This block is used to measure the Seebeck coefficient of a single p-n thermoelectric unit. This block performs the algebraic operation in between the p-type and n-type portion of TEG unit.

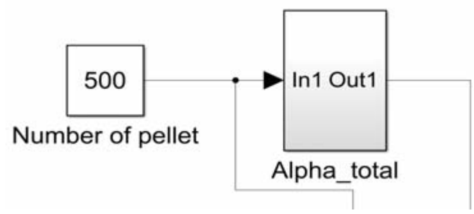

Fig.9. Measuring Total Seebeck co-efficient (α_m).

It measures the total Seebeck coefficient of the whole thermoelectric module. It is seen that 500 pellets are connected all together and their corresponding Seebeck effect is then calculated through this subsystem of the TEM system. It just multiplies the Seebeck coefficient of single unit with the number of pellets.

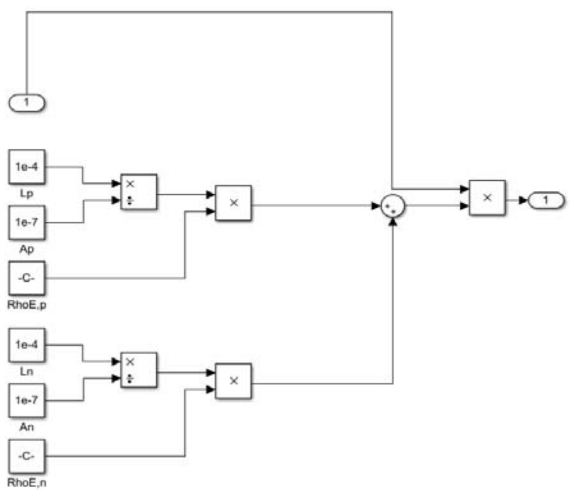

Fig.10. Simulink Block to measure resistance of TEG module

Internal resistance is a big deal in TEG module and that resistance is calculated with the above subsystem in Simulink.

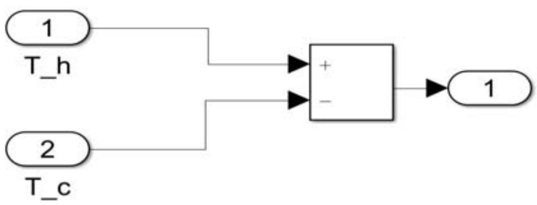

Fig.11. Simulink block to measure temperature gradient.

That block is showing the difference of temperature in between two terminals of TEM.

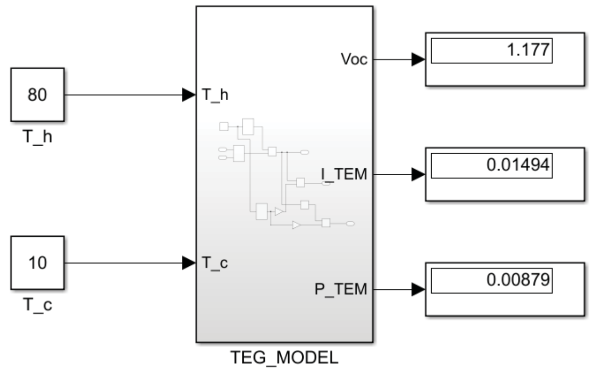

Fig.12. Complete TEG model to measure output parameters.

V. Result and Analysis

With the changes of temperature gradient between the two terminals of TEM, the related voltage, current and developed power has been monitored and then tabulated in a table.

TABLE II. SIMULATION OUTPUT RESULTS

T_c	T_h	ΔT	Voltage(V)	Current(A)	Power(W)
25	80	55	0.2774	0.01174	0.001628
	85	60	0.3026	0.01281	0.001937
	90	65	0.3278	0.01387	0.002274
	95	70	0.353	0.01494	0.002637
	100	75	0.3782	0.01601	0.003027
	105	80	0.4035	0.01707	0.003444
	110	85	0.4287	0.01814	0.003888

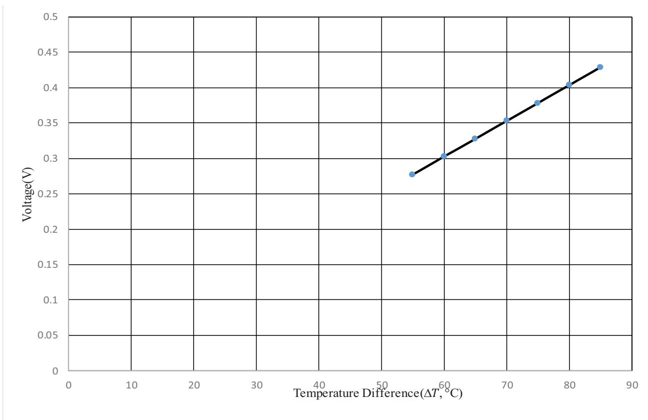

Fig.13. Temperature Gradient vs Voltage curve.

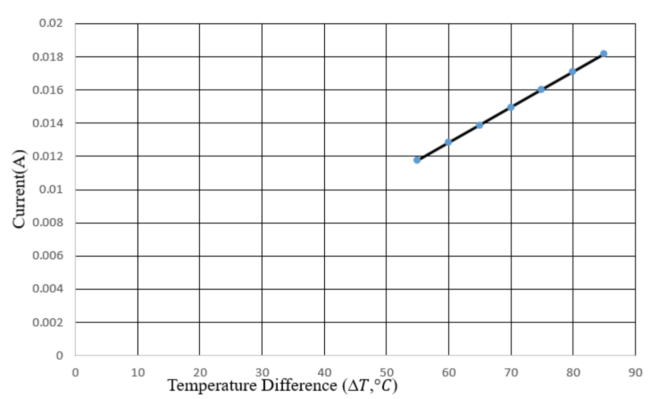

Fig.14. Temperature Gradient vs Current curve.

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Both the Fig.13 and Fig.14 shows the proportional relationship voltage and current with the changes of temperature gradient. Higher the temperature gradient causing higher the current and voltage as output from the module.

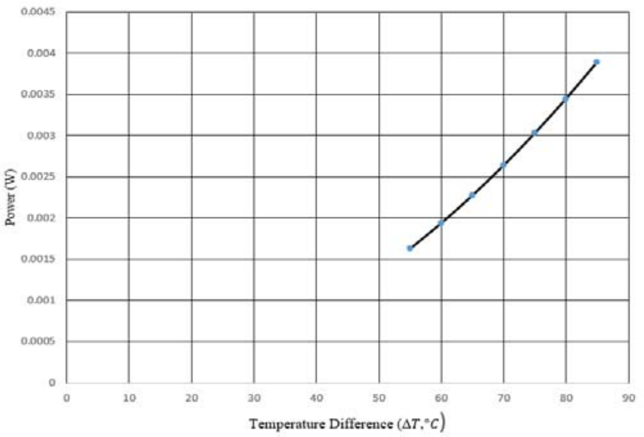

Fig.15. Temperature Gradient vs Power curve.

Fig.15 is showing the output power as a function of temperature's difference. It has incremental relation with the difference of temperature. This power can be significantly increased with increasing the number of pellets on the module.

VI. Conclusion

In this study based on some basic mathematical expression of thermoelectrical materials a TEG model has been developed and analyzed both in ANSYS and MATLAB/Simulink. As a means of generating renewable energy from waste heat TEG is the most convenient way without any emission of carbon. Though the power output and efficiency both are very low, but this sector could be most prominent for energy harvesting by increasing its efficiency with choosing the proper combination of TEG materials.

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