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Effect of Thermoelectric Legs on Electrical Performance of Single Leg Teg using Multiphyiscs Simulation

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ABSTRACT

This paper was produced to examine the impact of the number of legs on TEGs while also demonstrating how to model and simulate a single-leg thermoelectric generator (TEG) using the COMSOL Multiphysics software platform. Using thermoelectric materials like $SrTiO_3$ and Ca_2FeMoO_6, a simulation study of the performance of TEG was created. Therefore, by altering the hot side temperature from TH = 300K, 400K, and 500K and varying the load resistance from 0Ω to 20Ω, the influence of various performance metrics, such as output voltage and output power, has been demonstrated and investigated. It has been shown that the thermoelectric legs' material characteristics have a significant impact on how hot or cold the TE module is. Finally, it was discovered that single-leg TEG performs worse than TEG using a single thermocouple. By performing additional studies on the modeling of different numbers of TE legs, the performance of the TEG may therefore be further improved to help society deal with the energy issue.

1. Introduction

Any industrial facility must add, remove, or transport heat from one process stream to another, and doing so has grown to be a big job for the industry as stated by Ramanuja *et al.,* [1]. Budiyanto *et al.,* [2] make approach on cooling significantly improves performance as heat demand rises in electronic applications. Direct conversion of thermoelectric (TE) energy between the two states, heat, and electricity is possible and was stated by Dannowski *et al.,* [3], Kondagul and Malaji [4], Parveen *et al.,* [5] and Prasad and Thiagarajan [6]. It is a solid-state device and it is made up of semiconductors placed between two ceramic surfaces and connected by metal parts which can be seen in Prasad and Thiagarajan [6], Doraghi *et al.,* [7], Jaegle [8] and Tulaev [9]. To create thermoelectric, n-type and p-type semiconductors are thermally coupled in parallel and electrically in series was mentioned by Anitha *et al.,* [10], Asenath-Smith *et al.,* [11] and Spriggs and Wang [12].

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Samsudin *et al.,* [13] said that Malaysia is exploring for alternative fuels to produce energy in order to overcome the difficulties and create a sector for sustainable power generation. Besides, Bakar *et al.,* [14] stated that numerous scientific and engineering applications, such as wire drawing, the production of glass-fiber and paper, and insulation design, among others, contain tremendous promise for a thorough understanding of flow and heat transmission across porous surfaces.

Research has been done by Giwa *et al.,* [15], Jaziri *et al.,* [16], and Wu and Gao [17] stated that to maximize the Seebeck Coefficient, S and electrical conductivity while minimizing the thermal conductivity, which will increase the figure of merit (zT) of TE materials. The main issue with TE, however, is that all three TE parameters (α, κ, and σ) must be taken into account at once to improve TE because these values rely on the charge carrier concentration (n). Consequently, Sanad *et al.,* [18] stated choosing a good TE material and optimising the shape are two additional ways to boost its effectiveness. Numerous experts stated by Behera *et al.,* [19] have looked at effective ways to improve efficiency and produce electricity using thermoelectric generators.

The best material for thermoelectric applications at low to medium temperatures, according to Spriggs and Wang [12] evaluation of the thermoelectric performance of commercially available thermoelectric materials, is bismuth. The efficiency of the Bi_2Te_3 thermoelectric material is 2.57% and 3.75% on the hot side temperature for 100°C and 150°C, respectively, according to Hu *et al.,* [20] whom investigated into the electrical and thermal contact of the material between TEG legs. It is clear from the literature before it that most researchers have used Bi_2Te_3 modules to produce electricity.

The previous literature which is Maduabuchi *et al.,* [21], Singsoog *et al.,* [22] and Xiao *et al.,* [23] makes it clear that Bi_2Te_3 modules have been used for power production in the bulk of experiments. It is also well known that Bismuth Telluride is used extensively in the industry because of its excellent performance throughout a certain temperature range. However, Sugahara *et al.,* [24] found that Bi_2Te_3 is not as heat resistant as other materials. Further study by Ivanov *et al.,* [25] is conducted on the coexistence of magnetic order and ferroelectric polarisation in single-phase perovskites as a consequence.

Besides, Sabir *et al.,* [26] stated that perovskite is a potential material for non-volatile storage, microelectromechanical systems (MEMS), catalysts, and magnetoresistance (MR) due to its peculiar ferroelectric and semiconductor features. Asghar and Ying [27] study on metal oxide such as titanium dioxide (TiO_2) is commonly used in nanoparticle known to have better thermal properties than their base fluids, particularly in improving the thermal conductivity of base fluid. Additionally, Sabir *et al.,* [26] with Zheng *et al.,* [28] both agreed that perovskite is also easily accessible, affordable to produce, employs non-toxic materials, and has remarkable thermal and chemical durability at high temperatures. However, Zheng *et al.,* [28] founded that this perovskite's poor electrical conductivity or high heat conductivity present problems for practical use. Therefore, Zheng *et al.,* [28] research in high-entropy ceramics that used this methodology presented a novel idea for developing high-performance thermoelectric oxides with little thermal conductivity. Moreover, Sabir *et al.,* [26] did a series of analysis of the ferromagnetism was done from the structural, electronic, magnetic, optical and thermoelectric properties of $PrYO_3$(Y=Cr, V) and its confirm that the perovskite materials are much suitable for thermoelectric applications. Another research was done by Sugahara *et al.,* [24] using an ambient temperature of 1250K, the perovskite material Ca_2FeMoO_6 was studied which has a strong electrical conductivity but a low thermal conductivity, ZT reaches 0.15 at 1250 K. Next, Ravichandran *et al.,* find that due to the material's high Seebeck coefficient and strong thermal conductivity, which prevent the augmentation of zT, $SrTiO_3$ exhibited a higher ZT, which was 0.2 at 873K [29]. In previous research by Omar *et al.,* [30] three materials, Bi_2Te_3, $SrTiO_3$ and Ca_2FeMoO_6 was simulated in COMSOL Multiphysics to study the thermoelectric materials behaviour in a single-leg thermoelectric. The results show that both Ca_2FeMoO_6 and $SrTiO_3$ generate higher temperature difference and produce higher voltage which are 170mV and 160mV than Bi_2Te_3. Another study by Omar *et al.,* [31] for single thermocouple thermoelectric generator (TEG), a similar simulation was done in same materials, Bi_2Te_3, Ca_2FeMoO_6 and $SrTiO_3$ on the electrical performance of the TEG and the simulation shows that the perovskite, $SrTiO_3$ generate more power and voltage thus show the potential use of perovskite in TEG.

Therefore, there a lot of research that has been done in thermoelectric material beside Bi_2Te_3 as people trying to find alternative resources than Bi_2Te_3. However, it is very difficult to find a good thermoelectric material that have high efficiency. Therefore, the objective of this research was to investigate the thermal and electrical performance of perovskite materials in a single-leg TEG, using thermoelectric materials such as $SrTiO_3$ and Ca_2FeMoO_6. This research also was to study the effect of thermoelectric legs on the performance of the TEG. The geometry module will be created and modeled in COMSOL Multiphysics under the laws of heat transport. Section II goes into further information about the study methodology, while Section III shows the simulation results which was compare to a single thermocouple to see the different from the simulation results. We investigate the temperature distribution, potential distribution, and electrical performance of the two materials as a result of the simulations in the modules.

2. Methodology

2.1 Conceptual Geometry

Using COMSOL Multiphysics software, a single leg TEG was created into a cuboid form leg, as shown in Figure 1. Strontium titanate ($SrTiO_3$) and Ca_2FeMoO_6 (CFMO), two distinct perovskite materials that were previously discussed, are used in this simulation. The leg's dimensions, which were 1 mm x 1 mm x 6 mm, were taken as a reference from Omar *et al.,* [31] work. A copper plate with the dimensions 1 mm x 1 mm x 0.01 mm was used to sandwich the leg.

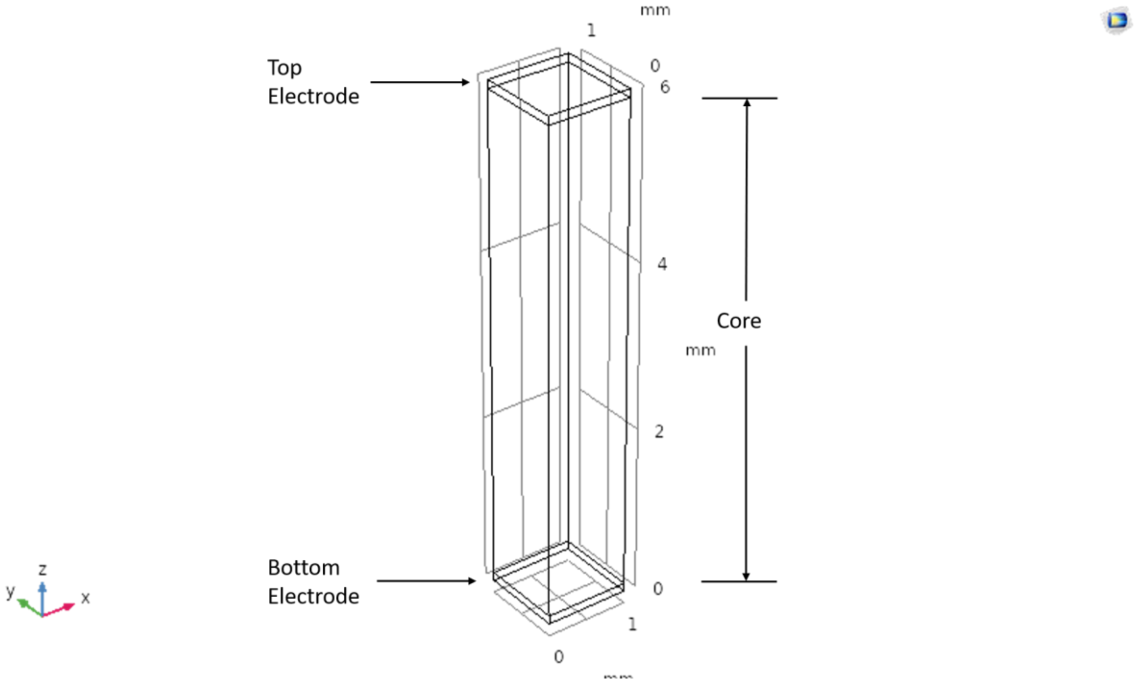


Fig. 1. TE single leg geometry with copper electrode

2.2 Materials

The materials strontium titanate ($SrTiO_3$) and Ca_2FeMoO_6 (CFMO) were selected to be stimulated using COMSOL Multiphysics. In a steady-state setting, the analysis was performed. All materials are accessible in COMSOL Multiphysics and specified in Sugahara *et al.,* [24] and they are all linear-elastic. Table 1 shows the parameter use for each material which are the Seebeck coefficient, electrical conductivity and thermal conductivity for the two materials, $SrTiO_3$ and CFMO and copper electrode.

Table 1
Material parameter of thermoelectric materials

Materials	Seebeck Coefficient (μV.K^{-1})	Electrical Conductivity (S.cm^{-1})	Thermal Conductivity (W.m^{-1}.K^{-1})
Ca_2FeMoO_6	-180	300	3.2
$SrTiO_3$	210	250	12
Cu electrode	65	5.99e^7	400

2.3 Mesh

The mesh arrangement resembles that of the Omar *et al.,* [31]. The module mesh is created using the sweep mesh approach, enabling a finer mesh for the module layer. Furthermore, the meshing procedure is explicitly stated to increase accuracy and reduce calculation time. The greatest element size is 0.473 mm in size, while the smallest element is 0.0344 mm. With a curvature factor of 0.4, the maximum rate of element growth is fixed at 1.4. Figure 2 displays a visual depiction of the mesh.

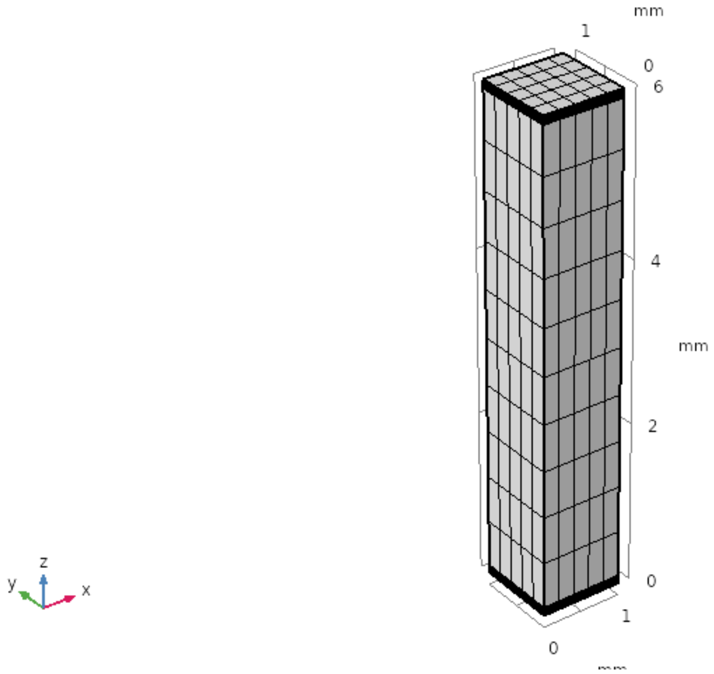


Fig. 2. Mesh design used in the model

3. Results

TEGs with rectangular shape leg geometry have been properly modeled, and their performance thoroughly examined. The simulation was done in a steady-state scenario with the hot and cold ceramic plates in contact with the junctions at temperatures of TH = 300K, 400K, 500 K and TC =

273.15 K, respectively. Temperature distribution, electrical distribution, output voltage, and output power are the primary factors considered for the study. The simulation results were compared to the previous research paper, which is Omar *et al.,* [31], to observe any difference when the number of legs in TE that affect the performance.

3.1 Temperature Distribution

This simulation software includes an interface for electric currents and an interface for heat transfer in solids. Since all surfaces have built-in thermal insulation, convective heat transport was not taken into account in this simulation. The thermoelectric legs materials have a significant influence on the temperature distribution inside the thermoelectric module, as shown in Figure 3 and Figure 4. Overall, the findings were compared, and Figure 4(a) and Figure 4(b) reveal a pattern of resemblance between the temperature distributions of a single leg TE and a single thermocouple. At the top electrode, both generate the same temperature.

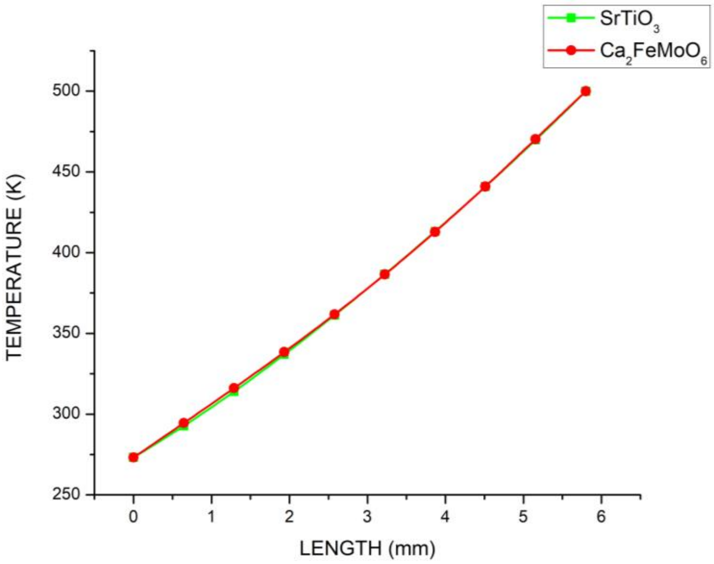
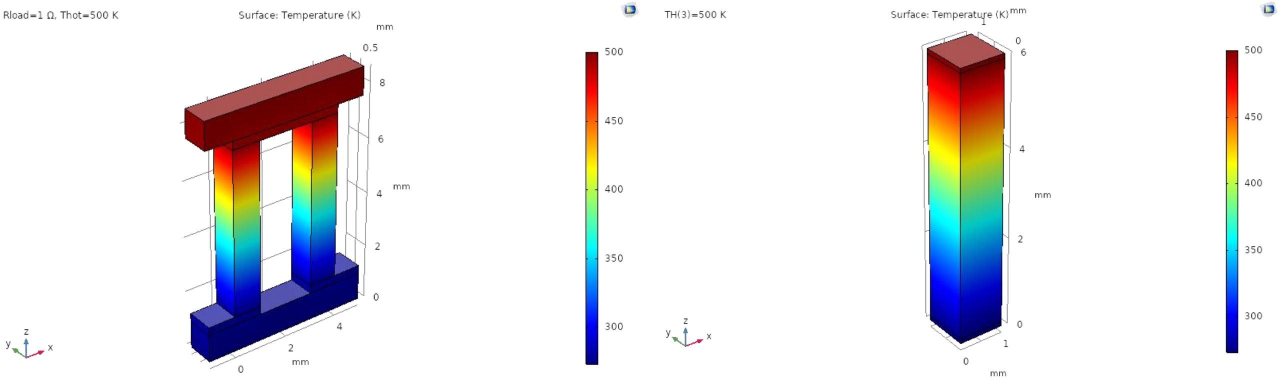


Fig. 3. Temperature across length for $SrTiO_3$ and Ca_2FeMoO_6



(a) (b)

Fig. 4. Temperature Distribution for $SrTiO_3$ for (a) single thermocouple and (b) single leg

3.2 Electrical Distribution

The voltage potential varies from one end of the model to the other due to the thermally linked in parallel and electrically connected in series nature of thermoelectric devices. Following the material qualities, various voltage outputs are produced. Ca_2FeMoO_6 and $SrTiO_3$ both generate voltages of 0.001127V and 0.125V, respectively. Due to the material performance of Ca_2FeMoO_6 having a low ZT value at low temperatures, the results are rather poor in Sugahara *et al.,* [24]. Figure 5 graphed data may be viewed there. Additionally, the single-leg TEG produces less voltage than the thermocouple legs when compared to the findings of earlier studies on electrical distribution. As a result, the number of TEG legs might have an impact on the functionality and output of the TEG. About half of the voltage was lost during this simulation.

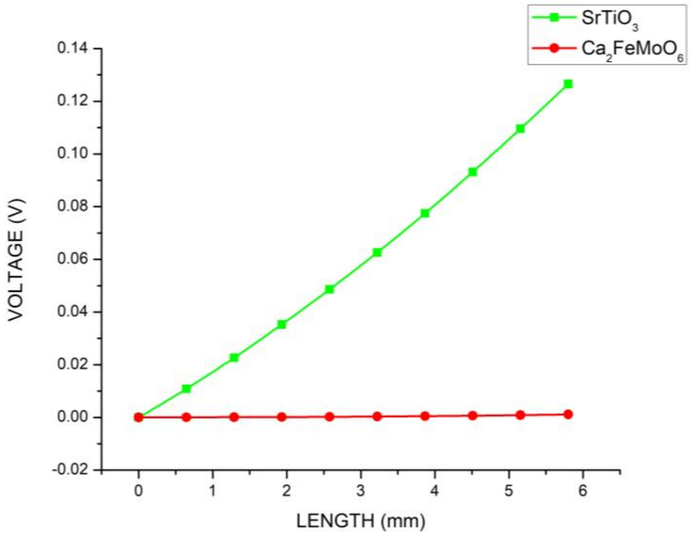


Fig. 5. Voltage across length for $SrTiO_3$ and Ca_2FeMoO_6

3.3 Electrical Performance Analysis

The load resistance has a significant effect on the thermoelectric module's output. Same as the previous simulation, the load resistance was varied from 0Ω to 20Ω and the hot side temperatures were set for T_H = 300K, 400K, and 500K, to observe the effect of temperature difference on the power output of a TEG. For the results, several graphs were drawn between output power with load resistance while maintaining the cold side temperature constant at 273.15K. The simulation data was tabulated in Table 2.

Table 2
The Simulation Data Each Hot-Side Temperature (T_H) at Different Load Resistance (R_L)

T_H (K)	R_L (Ω)	Power Output (W)	
		$SrTiO_3$	Ca_2FeMoO_6
300	5	0.000042367	$1.14e^{-9}$
	10	0.000021726	$5.77e^{-10}$
	20	0.000011003	$2.9e^{-9}$
400	5	0.000926	$3.35e^{-8}$
	10	0.000476	$1.69e^{-8}$
	20	0.00024172	$8.52e^{-9}$
500	5	0.003003	$2.49e^{-7}$
	10	0.00155	$1.26e^{-7}$
	20	0.00078761	$6.35e^{-8}$

The power output increases as the temperature on the hot side (T_H) rises. $SrTiO_3$ has a larger power output than the other two minerals, as can be noticed when comparing the three materials. The simulation shows that the power generated rises as the temperature difference rises. This data was compared to the earlier simulation on a single thermocouple like the prior comparison. The findings indicate that the effect of the TEG's number of legs caused the drop to be around 34% larger than that of a single thermocouple. The performance of the TEG can be stated to increase with the number of legs.

The I_{max} and P_{max} of the material can be calculated and plotted in Figure 6(b) and Figure 7(b) for each material with different T_H values.

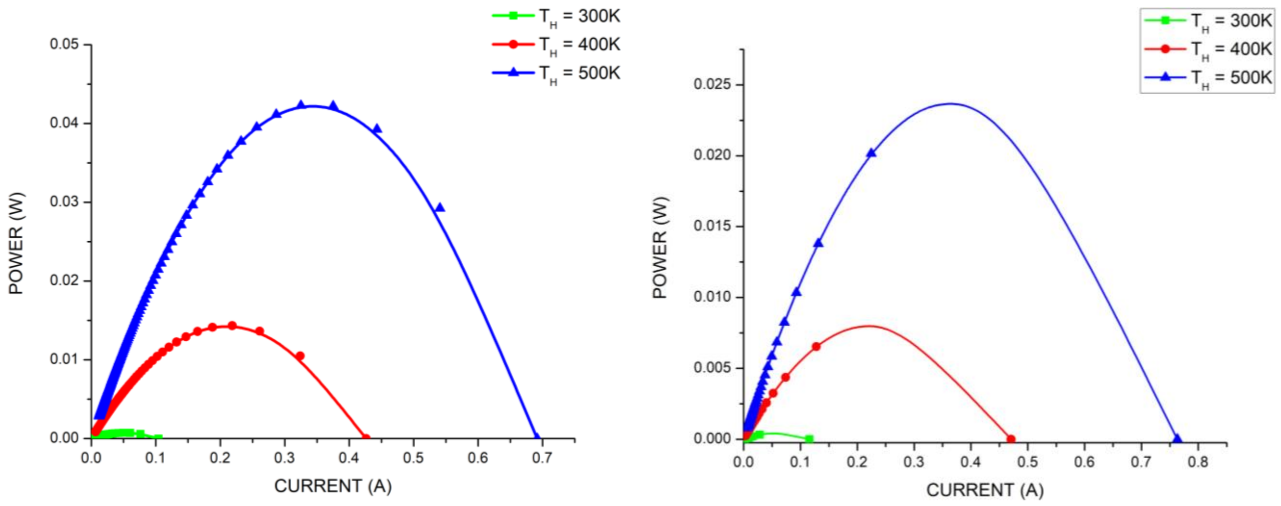
$$I_{max} = \frac{\alpha\,(T_H - T_C)}{2R} \tag{1}$$

$$P_{max} = \frac{(\alpha\,(T_H - T_C))^2}{4R} \tag{2}$$

The presented graphs show that as the current increases, the maximum power output rises in a polynomial trend. Additionally, when comparing P_{max} at various T_H values, P_{max} rises at higher T_H values. The graph below compares the power vs. current of a single thermocouple with a single-leg TEG. It is evident that as the number of legs diminishes, the P_{max} of each material also falls. The reduction is almost as 50%~60% of when comparing between using one thermocouple with one single leg TEG. Table 3 shows the data for both materials.

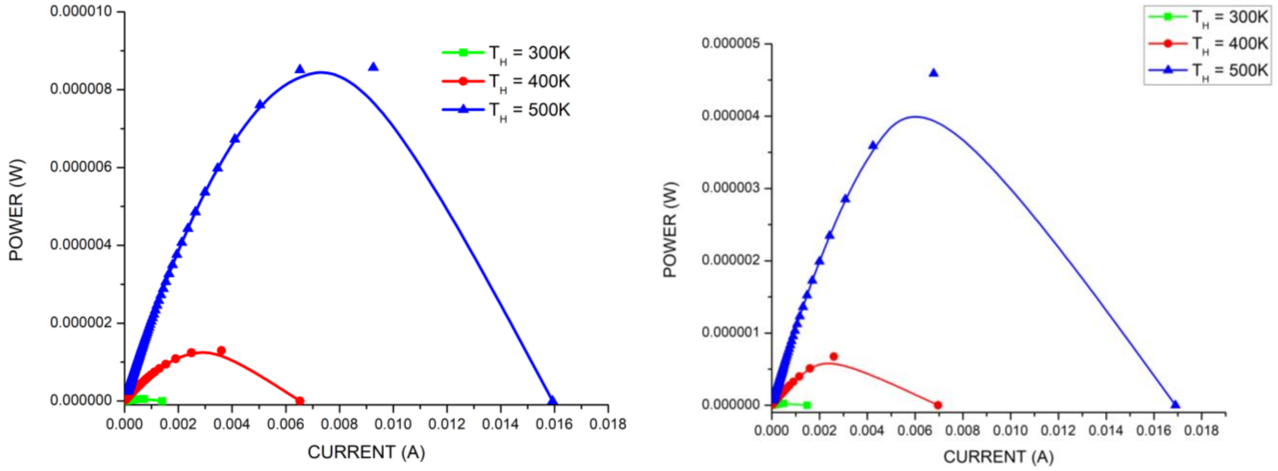
Table 3
Simulation Data of P_{max} between Single Leg TEG with Single Thermocouple TEG

T_H (K)	Pmax (W)			
	$SrTiO_3$		Ca_2FeMoO_6	
	Single Leg	Thermocouple	Single Leg	Thermocouple
300	0.000426	0.000738	2.5359E-08	5.21E-08
400	0.008097	0.014339	6.7404E-07	1.3E-06
500	0.024167	0.0422	4.59E-06	8.6E-06



(a) (b)

Fig. 6. Power Vs Current of different T_H values for $SrTiO_3$ (a) single thermocouple and (b) single leg TEG



(a) (b)

Fig. 7. Power Vs Current of different T_H values for Ca_2FeMoO_6 (a) single thermocouple and (b) single leg TEG

4. Conclusions

It can be inferred from the simulation of the thermoelectric generator (TEG) that the output power, output voltage, and output current of all materials follow a similar graph pattern. The significance of the findings, however, differs amongst the materials. It has been discovered that the thermoelectric leg materials' characteristics significantly affect how hot or cold the TE module is. When temperature differences rise, the TEG produces more voltage and power. The performance of the TEG was shown to be significantly influenced by the number of legs in the TEG when the data from this simulation was compared to previously available simulated data. As can be seen, when just half of the legs were left to execute the simulation, over half of the performance was shortened. This suggest that the number of TE legs does impact on the performance of TE but because the number of leg decreases, to improve the performance, more TE legs can be installed. The performance of the TEG may thus be further enhanced to assist the society with the energy crisis by conducting more research on modification on the TE itself. However, future research can be done in finding the limit of leg number and geometry shape on the performance of the TE because there are a lot of parameters that can affect the TE performance.

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