Electrical Performance Comparison between Conventional Pi Shaped and Linear Shaped Thermoelectric Generators

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Abstract. The main objective of the present work is to show the superiority in performance of linear thermoelectric generator (TEG) over the conventional Pi shaped thermoelectric generator. Linear thermoelectric generator with various leg lengths as well as different lengths of p-type and n-type semiconductors are modeled. Power and efficiency of the linear thermoelectric generator with various leg lengths and different lengths of p and n legs are compared at the various hot side temperatures numerically using ANSYS 19.1 commercial software. Numerically predicted power of the linear thermoelectric generator is found within 5% error with corresponding theoretical power values. Results presented that, linear thermoelectric generator with a ratio of p leg length to total leg length equal to 0.56 showed higher power output and higher efficiency for all leg lengths as well as all hot side temperatures. Maximum power and maximum efficiency for linear thermoelectric generator with 0.56 length ratio are found 6% higher than maximum power and maximum efficiency of conventional Pi shaped thermoelectric generator with 0.5 length ratio.

1. Introduction

Patil et al. conducted the comparison of segmented and non-segmented thermoelectric generators for symmetrical and assymetrical leg geometry for various geometrical and operating parameters [1]. Haider et al. have shown that, variation in shape parameter has a significant effect on power output and efficiency [2]. Thermoelectric as well as thermomechanical performances of annular thermoelectric generator were investigated numerically by Fan et al. [3]. Segmented thermoelectric generator composed with number of semiconductor materials showed higher performance than conventional thermoelectric generator [4]. The main objective of the present work is to explore the alternative way in order to enhance the performance of the conventional thermoelectric generator. In order to fulfill the objective, linear shaped thermoelectric generator with different lengths of p and n leg were analyzed numerically to compare the power output and efficiency with each other as well as conventional Pi shaped thermoelectric generator.

2. Numerical Analysis Methodology
The physical domain of linear thermoelectric generator considered for the numerical is shown in Figure 1. Similar to conventional Pi shape thermoelectric generator, linear thermoelectric generator also consists of p leg, n leg, top hot plate and bottom two cold plates. However, in case of linear thermoelectric generator, length of p leg \(L_p\) and length of n leg \(L_n\) can be varied which is not possible in case of Pi shaped thermoelectric generator. \(L\) presents the total length which is the sum of length of p leg and length of n leg. Properties of various parts of thermoelectric generator materials which are used in the numerical analysis is shown in Table 1.

![Figure 1 Physical domain](image1)

![Figure 2 Meshing in linear thermoelectric generator](image2)

| Material                        | Thermal conductivity (W/m K) | Electrical resistivity (\(\Omega\) m) | Seebeck coefficient (\(\mu V/K\)) |
|---------------------------------|-----------------------------|-------------------------------------|----------------------------------|
| p leg                           | 2.68-3.62                   | 0.62\(\times10^{-5}\)-0.81\(\times10^{-5}\) | 92-151.4                         |
| n leg                           | 3.04-4.05                   | 0.67\(\times10^{-5}\)-1.17\(\times10^{-5}\) | -226.5 to -162                   |
| Copper (hot and cold plates)    | 385                         | 1.7\(\times10^{8}\)                  | -                                |

Meshing for the considered physical domain of linear thermoelectric generator is presented in the Figure 2. Sweep method with body sizing of 0.0003 m was used as the meshing configuration. Total of 67,516 mesh elements was generated with selected mesh configuration. Power of thermoelectric generator was simulated for five different mesh number and after mesh number of 67,516, power was converged within ±1%. Therefore, mesh number of 67,516 was selected as the final mesh for further detail analysis. Boundary conditions used in the numerical analysis is presented in the Table 2.

![Table 1 Properties of material used in the numerical analysis](image3)

![Table 2 Boundary conditions used in the numerical analysis](image4)

To analyze the electrical performances of the linear thermoelectric generator with length ratio of legs of the thermoelectric module, length ratio of legs was defined as Eq. 1.

\[
\text{Length ratio} = \frac{L_p}{L}
\]  \hspace{1cm} (1)

Where, \(L_p\) is p leg length and \(L\) is total length which is equal to \(L_p + L_n\)

Eqs. (2) to (4) are derived from reference [2]. Optimum voltage is the voltage at which power and efficiency are maximum.

\[
V = \alpha(T_1 - T_2)
\]  \hspace{1cm} (2)
Here, $\alpha$ is Seebeck coefficient. $T_1$ is hot side temperature and $T_2$ is cold side temperature.

Power can be calculated numerically using voltage and corresponding current values. Efficiency of thermoelectric generator is defined as a ratio of power output to the heat absorbed by TEGs.

\[ P = V I \]  
\[ \eta = \frac{P}{\text{Heat absorbed by thermoelectric generator}} \]  

Here, $V$ is high potential voltage and $I$ is current.

3. Analytical Analysis Methodology

To validate the numerically predicted results of the linear thermoelectric generator, the results are compared with theoretical results. Eqs. (5)-(8) are suggested by Jia et al. [5] to calculate the electrical performance parameters of thermoelectric generator.

Maximum power is presented as,

\[ P_{\text{max}} = \frac{\alpha^2 (T_1 - T_2)^2}{4R_i} \]  

Here, $R_i$ is the internal resistance which is calculated as,

\[ R_i = \frac{\rho_p + \rho_n}{L} \]  

Here, $\rho_p$ and $\rho_n$ are electrical resistivity of p and n legs, respectively. $L$ is leg length and $A$ is base area of leg.

Maximum efficiency is calculated as,

\[ \eta_{\text{max}} = \frac{\alpha^2 (T_1 - T_2) R_e}{\alpha^2 T_1 (R_i + R_e) + K_i (R_i + R_e)^2 - 0.5\alpha^2 (T_1 - T_2) R_i} \]  

Where, $R_e$ is external resistance which is calculated as,

\[ R_e = \sqrt{R_i^2 + \frac{\alpha^2 R_i (T_1 + T_2)}{2K_i}} \]  

$K_i$ is internal conductivity of thermoelectric generator.

4. Results

4.1. Validation

Maximum power values were predicted with respect to various hot side temperatures for the linear thermoelectric generator having leg lengths of 1 mm, 2 mm and 3 mm. For each leg length, length ratio is 0.5 means both p-type and n-type legs have equal lengths in each case. Linear thermoelectric generator with same length of p leg and n leg is considered as the Pi shaped thermoelectric generator. Maximum power predicted using thermal electric module of ANSYS 19.1 as well as analytically calculated for each case. Comparison of numerically predicted and corresponding analytical results for the various leg lengths with length ratio of 0.5 is shown in Figure. 3. Error between the numerical and
analytical results were more for the leg length of 1 mm however, it is below 5% over the entire temperature range. Errors between the numerical and analytical results for the leg length of 2 mm is within 2% and for leg length of 3 mm, error is within 2.5%. Numerically predicted results showed acceptable results with corresponding analytical results for the various leg lengths as well as temperatures.

4.2. Effect of Length Ratio

Maximum power of linear thermoelectric generator for the leg length of 1 mm, 2 mm and 3 mm, and various length ratio ranging from 0.1 to 0.9 were predicted at the temperature of 300°C. Maximum power variation for various leg lengths and length ratio at the temperature of 300°C is shown in Figure. 4 (a). In case of conventional Pi-shape thermoelectric generator, maximum power occurred for the equal length of p and n legs. However, in case of linear thermoelectric generator, it is found that, for all the leg lengths, maximum power occurred at the length ratio of 0.56 means length of p leg is higher than the n leg. Compared to maximum power at the length ratio of 0.5 which is similar to Pi shaped thermoelectric generator case, maximum power for the linear thermoelectric generator at the length ratio 0.56 are 2.3%, 4.4% and 5.7% higher for the leg lengths of 1 mm, 2 mm and 3 mm, respectively. Similarly, maximum efficiency of linear thermoelectric generator for various leg lengths and length ratio is predicted at the temperature of 300°C which is presented in Figure. 4 (b). Maximum efficiency for the Pi shaped thermoelectric generator is occurred at the 0.5 length ratio however, it is found at the length ratio of 0.56 for the linear thermoelectric generator. Maximum efficiency for the linear thermoelectric generator is 5.6% higher than the Pi shaped thermoelectric generator for all the leg lengths. From the maximum power and efficiency figures, it can be noticed that, as the leg length increased from 1 mm to 3 mm, maximum power has decreased whereas, maximum efficiency has increased. In present analysis, Pi shaped thermoelectric generator showed higher electrical resistance than linear thermoelectric generator which has resulted in lower power and efficiency of Pi shaped thermoelectric generator.

4.3. Effect of Total Leg Length

Variation of maximum power and maximum efficiency with respect to total leg lengths for various length ratio at temperature of 300°C are presented in Figures. 5 (a) and 5 (b), respectively. Total leg lengths varied from 1 mm to 3 mm with various length ratios of 0.1, 0.5, 0.56 and 0.9. From this result, it is found that, for all the leg lengths, maximum power is higher for length ratio of 0.56 than other length ratio. Here also, it is claimed that, linear thermoelectric generator with length ratio of 0.56 showed 4% higher maximum power than the maximum power of Pi shaped thermoelectric generator with length
ratio of 0.5. Linear thermoelectric generator with length ratio of 0.56 showed 6% higher maximum efficiency than the maximum efficiency of Pi shaped thermoelectric generator with length ratio of 0.5.

**Figure 4** Variation of (a) maximum power and (b) maximum efficiency for various leg lengths and length ratio at the temperature of 300°C

**Figure 5** Variation of (a) maximum power and (b) maximum efficiency with respect to total leg lengths for various length ratio at temperature of 300°C

**Figure 6** Behavior of (a) maximum power and (b) maximum efficiency with respect hot side temperature for various leg lengths and length ratio

### 4.4. Effect of Temperature
Figure 6 (a) and 6 (b) show the maximum power and maximum efficiency behavior with respect to hot side temperature for various leg lengths and length ratio. For all the leg lengths as well as over the entire variation of temperature, length ratio of 0.56 which represents linear thermoelectric generator has maximum power and maximum efficiency values are higher than the corresponding values for the length ratio of 0.5 which represents Pi shaped thermoelectric generator for all the leg lengths.

5. Conclusions
Power and efficiency characteristics of linear thermoelectric generator were compared numerically with conventional Pi shaped thermoelectric generator. In case of Pi shaped thermoelectric generator p-type and n-type have same leg lengths however, leg lengths of p-type and n-type can be varied and it is possible to keep different lengths for both p and n legs. This characteristic of linear thermoelectric generator has resulted into higher power output and higher maximum efficiency. Linear thermoelectric generator was modelled with various leg lengths and length ratio. Effects of various leg lengths, length ratios and hot side temperatures were considered on the power and efficiency of linear thermoelectric generator. It is noticed that, length ratio of 0.56 for all the leg lengths and all the temperatures showed higher maximum power and maximum efficiency which were noticed for the length ratio of 0.5. Therefore, linear thermoelectric generator with different lengths of p and n legs was found better with approximately 6% higher power and efficiency than Pi shaped thermoelectric generator.

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6. References
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