Performance Optimization of Thermoelectric Generators using Taguchi Method

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Abstract. The thermoelectric generators (TEGs) are devices that are utilized to convert the heat energy into electrical energy directly and the working principle of this device is based on Seebeck effect. Thermoelectric power production is a smart method for the direct translation of heat energy into an electrical one. This work explores a method to get the optimum process parameters on the performance of various TEGs by finding the conversion efficiency to recover the waste heat and converts it into electricity. For this purpose, an experimental setup was designed and fabricated to determine the performance of TEGs. The TEGs made by Bismuth Telluride (Bi2Te3), Lead Telluride (PbTe), and Aluminium Oxide (Al2O3) were taken for the performance analysis. The process variables are heat input, TEG material and temperature difference. The experiments were conducted by using Taguchi’s L9 orthogonal array to reduce the number of experiments. The results found that the heat input of 90W, TEG material of Bi2Te3 and the temperature difference of 75OC gives the maximum conversion efficiency of 2.45% from thermal to electrical energy. The statistical analysis of variance (ANOVA) showed that the most influential parameter on the performance of TEGs was heat input. The R2 and R2 (adj) values were found to be 93.25% and 86.50%, this shows that the developed model is significant and can predict the optimal solution.

1 Introduction

All the equipments and machines which are used to do work and all other energy transformations produce heat along with the desired output power. This heat is directly allowed to pass in the environment and wasted, so it is called as waste heat. This wasted heat after being passed in the atmosphere causes the rise in the average temperature of the surroundings. This has unpleasant result on the environment [1-3]. In general, the heat energy produced is not fully converted into useful work and some amount of that energy is wasted to the surroundings. Practically there is no potential to transfer all the input energy into work [4, 5]. In this condition, increasing the efficiency of that equipment and machines directly is somewhat difficult. By utilizing the waste heat for other purposes will indirectly shows the increasing of efficiency of that machine. Electricity generation is an alternative and effective method to utilize this waste heat. The direct conversion of heat energy into electricity is done by TEGs [6-8]. The TEGs are working based on the Seebeck effect. This effect is a phenomenon in which the voltage will be generated if there is a temperature gradient between two dissimilar electrical conductors or semiconductors [9, 10]. TEGs comprise of three main elements: Thermoelectric (TE) systems, TE materials and TE modules. Temperature gradient from heat is converting into electric voltage and generates electricity by TE materials. These TE materials should have the properties of higher electrical conductivity ($\sigma_e$) and lower thermal conductivity values ($\kappa_t$).
The lower thermal conductivity value makes sure that if one side of TEG is made as hot then another side remains as cold, which tends to cause a great temperature gradient. The Seebeck coefficient (S) is the measure of the degree of electrons flow with respect to the temperature gradient. The figure of merit zT (S^2σT/k) decides the performance of a given material to generate the TE power [12, 13]. Bi_2Te_3, PbTe, and Al_2O_3 are largely used as TE materials as they have the properties of low thermal conductivity and high electrical conductivity [14]. These TE materials contain unusual elements which make them very costly. The TE module is made up of units of TE materials and is joined electrically in series and thermally in parallel [15]. The negatively and positively charged (n-type and p-type) semiconductor are joined to form a couple. There are several couples in the module. If there is a temperature gradient exists between the two materials then the electricity will flow in the circuit. The TE system produces electric power by absorbing heat from a source like a hot exhaust waste heat using TE modules [16]. Maintaining of high temperature difference in the actual applications is very difficult. Air or water can be utilized to cool the cold side of the TEGs. Heat exchangers are also can be used to supply the heating effect and cooling effect on both sides of the TE modules [17]. Designing of a consistent TEG system which will operate at high temperature is a very difficult task. Balancing of heat transfer through the TE modules and increasing the temperature difference across those modules requires a wide engineering design to attain the maximum efficiency of the system. For attaining this condition, the heat transfer methodologies should be properly designed in TEG field. The minimization of thermal losses at many places because of interfaces between TE materials is also done. Elimination of large drop in pressure between the hot and cold sources is another tough work [18].

Lot of advantages makes the TEGs as a good power producing source. TEGs are devices which have no moving components so that they are free of maintenance. TEGs are pollution free devices because there is no chemical reaction takes place inside them [19]. They are effectively used in space investigation probes due to their low weight and noiseless operations. There is no need of any external power supply for the functioning of TEGs. Because of that they are called as passive devices. Various areas like space investigation, automobiles, remote unmanned locations and cathodic shield etc. are using the TEGs as a power supply [20]. Lower in efficiency and higher surface temperatures are some of the limitations of TEGs. While using TE devices the heating will be increased by high electrical output resistance and it is not suitable for some applications due to the low thermal conductivity. The material which one has less thermal conductivity and more electrical conductivity is best suited for TEGs [21].

Taguchi method is one of the optimization methods to analyze the function of significant process variables to attain a best possible result for an objective function [22, 23]. This technique can be successfully utilized to help in designing trials and get the best possible conditions by using orthogonal array, so that the time and attempt can be minimized [24, 25]. The Taguchi method can give an organized approach for easing the experimental plan. Meanwhile, this method is widely used to find the best possible conditions of a system [26, 27].

In this paper the power at the output and the efficiency of conversion of various TEGs comprised of different materials such as Bismuth Telluride (Bi_2Te_3), Lead Telluride (PbTe) and Aluminium Oxide (Al_2O_3) is experimentally investigated and compared. The details on energy transfer, potential difference, electricity flow and performance are found to give a comparative analysis for various TE materials. The optimum performance of TEGs were found using Taguchi method.

2 Methodology

2.1. Experimental Setup

TEGs are semi-conductor devices that are used to convert the temperature differences and heat energy into a DC power supply. Seeback effect is utilized in TEG semiconductor devices to produce voltage. This produced voltage forces electrical current and generates useful power. TEGs comprised of Bi_2Te_3, PbTe and Al_2O_3 materials were used in this experiment. A voltmeter and an ammeter are used for measuring electric potential difference and the current flow between two points in the
circuit. Dimmer stat is utilized to adjust the output potential/voltage to electrical circuits. Heater is used to provide a heat input to TEG and is controlled by the dimmer stat. Water flow is allowed to TEG to maintain the temperature in the cold side. The Figure 1 and 2 shows the experimental methodology and experimental setup.

2.2 Experimental Procedure

The performance optimization trial was carried out to find the efficiency of conversion of the TEG from thermal energy to electrical energy with process variables. This experiment was done by inserting the TEG between an electrical heating source and water cooling source. Heaters served as heating devices and TEGs with a dimension of 40 mm x 40 mm x 4 mm were used to produce electric power due to the temperature gradient across its junctions. The variation in the heat input value to the electric heater was made and the temperature measurements were noted using thermocouples that were attached to a data measurement system. At this condition, the TEG surface temperature and cooling water temperature were noted down. The output terminal of the TEG is attached to the voltmeter and the ammeter in order to monitor the power produced. If the heater is switched on then simultaneously the cold water is fed to the duct. Then the TEG became hot in one side and cold in another side. This temperature difference produced electricity. The efficiency of energy conversion of the TEG was found by using the following relation.

\[ \eta_{\text{TEG}} = \frac{P_o}{Q_i} \]  

Where, \( P_o \) is the output electrical power produced by the TEG and \( Q_i \) is the rate of heat input to the hot side of the TEG.
The performance optimization experiments were conducted by using the following process variables with 3 levels which are mentioned in Table 1. Taguchi L9 orthogonal array was utilized to find the optimum process variable.

| Factors | Process variables | Symbol | Unit | Level 1 | Level 2 | Level 3 |
|---------|-------------------|--------|------|---------|---------|---------|
| I       | Heat Input        | Q      | W    | 30      | 60      | 90      |
| II      | TEG Material      | M      |      | Bi₂Te₃  | PbTe    | Al₂O₃   |
| III     | Temperature Difference | ΔT | °C  | 25      | 50      | 75      |

3 Results and Discussion

Results were obtained and described for the above mentioned trial conditions with the help of the following figures and tables.

3.1 ηₜₑᵍ

Figure 3 indicated the relationship between mean value of SNR to the process variables heat input, TEG material and temperature difference with the method of larger is better because high ηₜₑᵍ essential for energy conversion from thermal to electrical energy. The plot for main effect of means was showed in figure 4. The maximum ηₜₑᵍ would gain at 90W heat input with Bi₂Te₃ material and 75°C of temperature difference. The Table 2 shows the corresponding design in 7th experiment process combinations.

| Experiment No. | Q   | M     | ΔT  | ηₜₑᵍ | SNR  |
|----------------|-----|-------|-----|------|------|
| 1              | 30  | Bi₂Te₃| 25  | 1.98 | 5.93330 |
| 2              | 30  | PbTe  | 50  | 1.95 | 5.80069 |
| 3              | 30  | Al₂O₃ | 75  | 1.90 | 5.57507 |
| 4              | 60  | Bi₂Te₃| 50  | 2.10 | 6.44439 |
| 5              | 60  | PbTe  | 75  | 2.05 | 6.23508 |
| 6              | 60  | Al₂O₃ | 25  | 2.02 | 6.10703 |
| 7              | 90  | Bi₂Te₃| 75  | 2.45 | 7.78332 |
| 8              | 90  | PbTe  | 25  | 2.31 | 7.27224 |
| 9              | 90  | Al₂O₃ | 50  | 2.24 | 7.00496 |
The interaction plot for $\eta_{\text{TEG}}$ with regard to heat input, TEG material and temperature difference was shown in Figure 5. All the relation indicated that the $\eta_{\text{TEG}}$ were directly relative to variables taken. The highest $\eta_{\text{TEG}}$ was produced at higher value of heat input and higher value of temperature difference.

Figure 6 indicated the relation of residual vs percentage in the normal probability plot, fitted value vs residuals in the versus fits, residual vs frequency in the histogram and observation order vs residual in the versus order plot for $\eta_{\text{TEG}}$. It seems that the values in the normal probability plot were almost close to the mean line. In the meanwhile, versus plot also showed that the some points are close to the mean line. In the versus order plot, it showed that the acceptable outcome of 3 values were crossed over the line of zero.

In Table 3 and 4 ranks for the process variables were indicated. The main significant variable was primarily heat input, second material and finally temperature difference for SNR response table.
and table of response for means. Hence the heat input and the temperature difference provided additional contribution in $\eta_{TEG}$ which was indicated in Figure 7. Table 5 shows the response values and the equation of regression and Table 6 shows the ANOVA results.

![Interaction Plot for $\eta_{TEG}$](image1)

**Figure 5.** Interaction plot for $\eta_{TEG}$

![Residual Plots for $\eta_{TEG}$](image2)

**Figure 6.** Residual plots for $\eta_{TEG}$

| Level | Q   | M   | $\Delta T$ |
|-------|-----|-----|------------|
| 1     | 5.694 | 6.693 | 6.324 |
| 2     | 6.192 | 6.130 | 6.149 |
| 3     | 7.107 | 6.170 | 6.519 |
| Delta | 1.413 | 0.563 | 0.371 |
| Rank  | 1    | 2    | 3        |

**Table 3.** $\eta_{TEG}$ – Table of Response for SNR
Table 4. $\eta_{TEG}$ - Table of Response for Means

| Level | Q   | M   | $\Delta T$ |
|-------|-----|-----|------------|
| 1     | 1.927 | 2.170 | 2.073 |
| 2     | 2.040 | 2.030 | 2.033 |
| 3     | 2.270 | 2.037 | 2.130 |
| Delta | 0.343 | 0.140 | 0.097 |
| Rank  | 1     | 2     | 3      |

Table 5. Response Values and Equation of Regression

| Response | Regression Equation | S  | $R^2$ | $R^2$ (adj) |
|----------|---------------------|----|-------|-------------|
| $\eta_{TEG}$ (%) | 2.0789 - 0.1522 Q_30 - 0.0389 Q_60 + 0.1911 Q_90 + 0.0911 M_Bi2Te3 - 0.0489 M_PbTe - 0.0422 M_Al2O3 - 0.0056 $\Delta T_{25}$ - 0.0456 $\Delta T_{50}$ + 0.0511$\Delta T_{75}$ | 0.0218131 | 93.25% | 86.50% |

Table 6. Analysis of Variance (ANOVA)

| Source        | DF | Adj SS | Adj MS | F-Value | P-Value |
|---------------|----|--------|--------|---------|---------|
| Heat Input    | 2  | 0.183622 | 0.091811 | 24.52  | 0.039   |
| Material      | 2  | 0.037422 | 0.018711 | 5.00   | 0.167   |
| Temp Difference | 2  | 0.014156 | 0.007078 | 1.89   | 0.346   |
| Error         | 2  | 0.007489 | 0.003744 |         |         |
| Total         | 8  | 0.242689 |        |         |         |

Figure 7. Contour plot for $\eta_{TEG}$
4 Conclusions

The experimental investigation on the performance optimization of TEGs using process variables such as heat input, TEG material and temperature difference was done and the conclusions of this work were stated below

1. The main significant parameter for $\eta_{\text{TEG}}$ was heat input and the temperature difference.
2. The maximum value of $\eta_{\text{TEG}}$ was 2.45% for the optimum process variables such as 90W heat input, TEG material of Bi$_2$Te$_3$ and the temperature difference of 75°C.
3. The lowest value of $\eta_{\text{TEG}}$ was 1.90% for the optimum process variables such as 30W heat input, TEG material of Al$_2$O$_3$ and the temperature difference of 75°C.
4. The ANOVA showed that the most influential parameter on the performance of TEGs was heat input. The $R^2$ and $R^2$ (adj) values were found to be 93.25% and 86.50% respectively.

Overall the TEG material of Bi$_2$Te$_3$ indicated the best heat to electric energy conversion efficiency compared to other TEG materials operated under same ranges of temperature. This TEG can be used for efficient electricity generation from waste heat of internal combustion engines, industrial hot chimneys, silencer of on road vehicles and cooking stoves.

Abbreviations

| Symbol | Description                  |
|--------|------------------------------|
| Al$_2$O$_3$ | Silicon Germanium       |
| Bi$_2$Te$_3$ | Bismuth telluride      |
| $k_t$ | Thermal Conductivity      |
| $\eta_{\text{TEG}}$ | TEG-Efficiency          |
| $\sigma_e$ | Electrical Conductivity |
| $\Delta T$ | Temperature Difference |
| ANOVA | Analysis of Variance     |
| DC | Direct current        |
| DF | Degree of freedom      |
| M | TEG Material         |
| $^\circ C$ | Degree Celsius        |
| PbTe | Lead Telluride        |
| $P_o$ | Output electrical power |
| Q | Heat Input            |
| $Q_i$ | Rate of heat input     |
| S | Seebeck Coefficient   |
| SNR | Signal to Noise Ratio  |
| TE | Thermoelectric       |
| TEG | Thermoelectric Generator |
| W | Watt                  |
References

[1] Hewawasam LS, Jayasena AS, AfnanMMM, Ranasinghe RACP and Wijewardane MA 2020 Waste heat recovery from thermo-electric generators (TEGs) Energy Reports 6 474-479.

[2] Li W, Paul MC, Siviter J, Montecucco A, Knox AR, Sweet T, Min G, Baig H, Mallick TK, Han G and Gregory DH 2016 Thermal performance of two heat exchangers for thermoelectric generators Case studies in thermal engineering 8 64-175.

[3] Elghool A, Basrawi F, Ibrahim H, Ibrahim TK, Ishak M, Yusof TM and Bagaber SA 2020 Enhancing the performance of a thermo-electric generator through multi-objective optimisation of heat pipes-heat sink under natural convection Energy Conversion and Management 209 112626.

[4] Burma MC, Riaz M, Saidur R and Long BD 2015 Estimation of thermoelectric power generation by recovering waste heat from Biomass fired thermal oil heater Energy Conversion and Management 98 303-313.

[5] Dhass AD, Krishna R and Sreenivasan M 2020 Numerical analysis of a variety of thermoelectric generator materials Materials Today: Proceedings.

[6] Li G, Zhu D, Zheng Y and Guo W 2020 Mesoscale combustor-powered thermoelectric generator with enhanced heat collection Energy Conversion and Management 205 112403.

[7] Addanki S and Nedumaran D 2019 Simulation and fabrication of thermoelectric generators for hand held electronic gadgets Materials Science and Engineering: B 251 114453.

[8] Arsie I, Cricchio A, Marano V, Pianese C, De Cesare M and Nesci W 2014 Modeling analysis of waste heat recovery via thermo electric generators for fuel economy improvement and CO2 reduction in small diesel engines SAE International Journal of Passenger Cars-Electronic and Electrical Systems 7 246-255.

[9] Bensaid S, Brignone M, Ziggioi A and Specchia S 2012 High efficiency Thermo-Electric power generator International journal of hydrogen energy 37 21385-1398.

[10] Chen WH, Huang SR and Lin YL 2015 Performance analysis and optimum operation of a thermoelectric generator by Taguchi method Applied Energy 158 44-54.

[11] Date A, Date A, Dixon C, Singh R and Akbarzadeh A 2015 Theoretical and experimental estimation of limiting input heat flux for thermoelectric power generators with passive cooling Solar Energy 111 201-217.

[12] Ahmed S, Mousa MG and Hegazi AA 2018 Performance analysis of a passively cooled thermoelectric generator Energy Conversion and Management 173 399-411.

[13] Elghool A, Basrawi F, Ibrahim TK, Habib K, Ibrahim H and Idris DMND 2017 A review on heat sink for thermo-electric power generation: Classifications and parameters affecting performance Energy conversion and management 134 260-277.

[14] Jia X and Guo Q 2020 Design study of Bismuth-Telluride-based thermoelectric generators based on thermoelectric and mechanical performance Energy 190 116226.

[15] Lundgaard C and Sigmund O 2019 Design of segmented off-diagonal thermoelectric generators using topology optimization Applied Energy 236 950-960.

[16] Lv S, He W, Jiang Q, Hu Z, Liu X, Chen H and Liu M 2018 Study of different heat exchange technologies influence on the performance of thermoelectric generators Energy Conversion and Management 156 167-177.

[17] Kim CN 2018 Development of a numerical method for the performance analysis of thermoelectric generators with thermal and electric contact resistance Applied thermal engineering 130 408-417.

[18] Shaareef MH, Sajid A, Majeed AA and Adnan MAB Efficiency Calculation of a Thermoelectric Generator International Journal of Science and Research 5 1520-1522.

[19] Wu Y, Zuo L, Chen J and Klein JA 2016 A model to analyze the device level performance of thermoelectric generator Energy 115 591-603.

[20] Ragupathi P, Barik D, Vignesh G and Aravind S 2020 Electricity Generation from Exhaust Waste Heat of Internal Combustion Engine Using Al2O3 Thermoelectric Generators Journal of Applied Science and Engineering 23 55-60.

[21] Ragupathi P, Barik D, Pradeep S and Lakshan L 2018 A Review on Waste Heat Recovery Technologies in Internal Combustion Engines International Journal of Research in Advent Technology 270-276.
[22] Chen WH, Huang SR and Lin YL 2015 Performance analysis and optimum operation of a thermoelectric generator by Taguchi method Applied Energy 158 44-54.

[23] Kishore RA, Sanghadasa M and Priya S 2017 Optimization of segmented thermoelectric generator using Taguchi and ANOVA techniques Scientific reports 7 11-15.

[24] Rezania A, Atouei SA and Rosendahl L 2020 Critical parameters in integration of thermoelectric generators and phase change materials by numerical and Taguchi methods Materials Today Energy 16 100376.

[25] Ji D, Wei Z, Mazzoni S, Mengarelli M, Rajoo S, Zhao J, Pou J and Romagnoli A 2018 Thermoelectric generation for waste heat recovery: Application of a system level design optimization approach via Taguchi method Energy Conversion and Management 172 507-516.

[26] Kishore RA, Kumar P and Priya S 2018 A comprehensive optimization study on Bi 2 Te 3-based thermoelectric generators using the Taguchi method Sustainable Energy & Fuels 21 175-190.

[27] Anant Kishore R, Kumar P, Sanghadasa M and Priya S 2017 Taguchi optimization of bismuth-telluride based thermoelectric cooler Journal of Applied Physics 122 2025109.