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Performance analysis of a thermoelectric generator (TEG) for waste heat recovery

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Abstract

In this study, the potential of thermoelectric generators (TEGs) for converting waste heat into electrical energy was investigated as a solution to increasing energy demand and environmental challenges. The performance of a TEG module, based on fundamental thermoelectric principles such as the Seebeck and Peltier effects, was analyzed through a detailed theoretical modeling that incorporated temperature-dependent material properties as well as electrical and thermal contact resistances. The analysis was conducted for a module consisting of 127 Bismuth Telluride (Bi_2Te_3) elements, and the performance was evaluated as a function of the load resistance to internal resistance ratio (R_L/R_{el}). Simulation results confirmed that maximum power output is achieved when the load resistance equals the internal resistance ($R_L/R_{el} = 1$). Under this condition, the module delivered approximately 2.50 W of power with a thermal efficiency of 4.05%. Moreover, it was observed that maximum efficiency occurred at a load resistance ratio higher than that corresponding to maximum power. These findings indicate a trade-off between power and efficiency in TEG design, highlighting that the optimal operating point should be determined according to specific application objectives. The developed model provides a reliable tool for the efficient design and optimization of TEG systems.

1. Introduction

In conventional energy generation systems, a significant portion of the energy released from fuel combustion is dissipated into the environment as unrecovered waste heat. This waste heat originates from industrial facilities, automotive exhaust systems, and power plants, and it is estimated to account for nearly two-thirds of global energy consumption. Therefore, the efficient recovery of waste heat presents a critical potential for enhancing energy efficiency and reducing environmental impact [1,2]. Among the promising solutions to these challenges, thermoelectric generators (TEGs) have attracted considerable attention due to their ability to directly convert thermal energy into electrical energy.

Fundamentally, TEGs convert a temperature difference between the hot and cold junctions into electricity through a physical phenomenon known as the Seebeck effect. This conversion requires the careful selection of material properties and the proper optimization of system operating parameters. In this context, extensive research has been conducted to enhance the performance of TEG technology and to integrate it into practical applications. Among these studies, numerous investigations have employed numerical modeling to evaluate TEG performance. For example, Araby et al. [3] presented the modeling of an HZ-20 TEG module using MATLAB/Simulink and analyzed its performance based on sea surface temperatures in different regions of Egypt. Their results indicated that under conditions of 230 °C on the hot side and 30 °C on the cold side, the module produced a maximum power of 19 W at 2.38 V, while field simulations showed that the annual power output varied between 0.037 and 3.04 W across regions. Similarly, Mahmat et al. [4] experimentally and theoretically examined a TEG system powered by concentrated solar energy collected through linear Fresnel lenses and solar glass tubes. According to their experimental findings, a maximum open-circuit voltage of 3.41 V and a maximum output power of 1.558 W were obtained in a heat pipe using pure water, whereas the corresponding values for a system using acetone were 3.03 V and 1.136 W; the maximum electrical efficiency of the system was measured as 2.08%. Moreover, good agreement was achieved between the numerical model and the experimental results, with error ranges of 7.5–11.1% for the open-circuit voltage and 4.5–8.4% for the cold-side temperature.

To further enhance the efficiency and power output of TEGs, the design of hybrid energy conversion systems has become an important research focus. These approaches involve the integration of TEGs with other energy harvesting technologies. For instance, Shan et al. [5] numerically investigated the performance of a hybrid energy conversion system combining a novel near-field thermophotovoltaic (NFTPV) device with a TEG. Their results showed that at an emitter temperature of 1000 K, the efficiency of the hybrid system was 3.5–9.5% higher and the optimum power output increased by 6–16% compared to a stand-alone NFTPV; at 2000 K, the system efficiency reached 45.8%, which was 6% higher than that of the single NFTPV. They demonstrated that optimal ranges of parameters such as cell temperature and applied voltage simultaneously ensured high efficiency and power output for the hybrid system. In another study, Riahi et al. [6] experimentally and theoretically analyzed the performance of concentrated photovoltaic-thermal (CPVT) systems integrated with TEGs. Their findings indicated that the CPVT-TEG system increased the daily electrical efficiency by 7.46% compared to CPVT alone, and for an aperture area of 39 m^2, the annual electricity generation increased from 5930 kWh to 6289 kWh, yielding an additional 359 kWh. Similarly, Zhang et al. [7] investigated the experimental performance of a low-concentration photovoltaic/thermal (LCPV/T) collector integrated with a TEG. Their results revealed that during summer, the system produced domestic hot water with an average temperature of 52.96 °C, while the PV module achieved an average electrical power output of 436.13 W with an efficiency of 14.34%, and the TEG contributed an additional 1.68 W (0.285% of the total).

The common finding of the above studies is that TEGs, whether operating alone or as part of hybrid systems, possess significant potential for harnessing waste heat and other thermal sources. However, to optimize TEG performance, there is a need for a comprehensive theoretical model that simultaneously accounts for practical factors such as element geometry, material properties, and thermal/electrical contact resistances.

The aim of this study is to develop a comprehensive and reliable theoretical model for analyzing the performance of TEG. The proposed model not only relies on fundamental physical equations but also incorporates practical factors that more accurately reflect the behavior of a real module. These factors include the temperature-dependent variation of material properties, losses arising from electrical and thermal contact resistances, and scaling effects associated with the series configuration of the module. Within the modeling methodology, the operational characteristics of the TEG module were evaluated particularly as a function of the ratio of load resistance to internal resistance. In this way, the model demonstrates how current, voltage, power, and thermal efficiency vary, thereby enabling the identification of design parameters that optimize TEG performance for specific applications. The findings provide a robust engineering basis for the practical deployment of TEG systems.

2. Material and Method

A TEG is essentially a power generator that directly converts thermal energy into electrical energy. In this study, the performance of a TEG module was analyzed using an electrical circuit model composed of series-connected p-type and n-type semiconductor elements (Figure 1). The conversion of heat into electricity is governed by the Seebeck, Peltier, Joule, and Thomson effects. These effects are associated with the temperature difference between the hot and cold junctions, the electric current passing through the system, and the properties of the semiconductor elements. Table 1 summarizes the parameters that define the operating conditions and physical structure of the modeled TEG module.

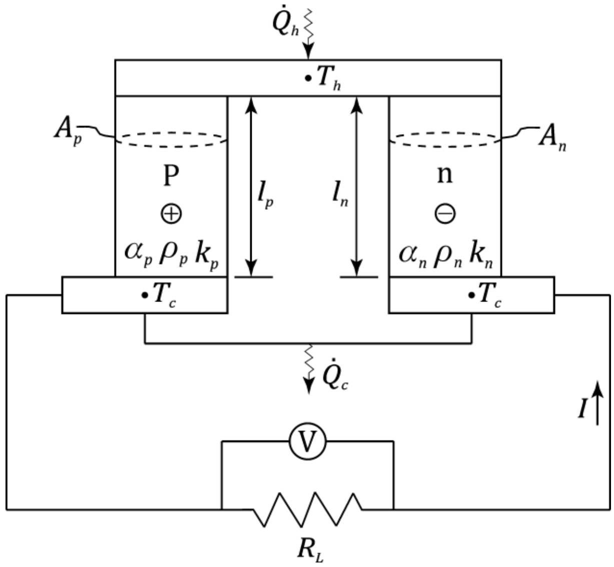

Figure 1. Electrical circuit model of the TEG.

Table 1. Properties of the TEG module.

Description	Value	Unit
Hot junction temperature, T_h	400	K
Cold junction temperature, T_c	300	K
Number of p–n thermocouple elements, n	127	piece
Length of the thermocouple element, $l_p = l_c$	1	mm
Cross-sectional area of the thermocouple element, $A_p = A_c$	1.2	mm^2
Thermal contact conductivity ratio, r	0.2	-
Electrical contact resistivity ratio, s	0.1	mm
Ceramic plate thickness, l_c	0.7	mm

2.1. Thermoelectric modeling

The total internal resistance of the TEG includes the resistance of n p–n thermocouple pairs as well as the electrical contact resistances at the junctions. This resistance is expressed by Equation (1):

$$R_{el} = n\left(\frac{\rho_p l_p}{A_p} + \frac{\rho_n l_n}{A_n}\right)\left(1 + \frac{s}{l_p}\right) \tag{1}$$

Here, l, A and ρ denote the element length, cross-sectional area, and resistivity, respectively. The subscripts p and n represent the p-type and n-type semiconductor elements. The electrical contact resistance is incorporated into the ideal resistance of the element pair by applying the correction factor $1 + s/l_p$, where s is the electrical contact resistance coefficient.

The current (I_{mp}) of the TEG module is obtained by dividing the open-circuit voltage (V_{oc}) by the total resistance. The open-circuit voltage is evaluated based on the Seebeck and Thomson coefficients, as given in Equation (2), while the current is subsequently calculated according to Equation (3).

$$V_{oc} = n[(\alpha_h T_h - \alpha_c T_c) - \mu(T_h - T_c)] \quad (2)$$

$$I_{mp} = \frac{V_{oc}}{R_{el} + R_L} \quad (3)$$

After computing the current, the voltage of the TEG module and its maximum output power are obtained from the electrical power relations, as expressed in Equation (4) and Equation (5):

$$V = I_{mp} R_L \quad (4)$$

$$W_{mp} = I_{mp}^2 R_L \quad (5)$$

2.2. Energy balance of the TEG

The thermodynamic balance of the TEG module was established by incorporating the effects of thermal contact resistance as well as the Peltier and Joule heat terms. The total thermal conductivity of the module (K_th) is calculated using a correction factor that accounts for the influence of thermal contact resistances, as expressed in Equation (6):

$$K_{th} = n\left(\frac{k_p A_p}{l_p} + \frac{k_n A_n}{l_n}\right)\left(\frac{1}{1 + r(l_c/l_p)}\right) \quad (6)$$

where k denotes the thermal conductivity difference, r represents the thermal contact resistance ratio, and l_c refers to the thickness of the ceramic plate.

The net absorbed heat flux on the hot side of the TEG module and the net dissipated heat flux on the cold side can then be determined according to Equation (7) and Equation (8), respectively.

$$\dot{Q}_h = \alpha_h I_{mp} T_h - \frac{I_{mp}^2 R_{el}}{2} + K_{th}(T_h - T_c) - \frac{\mu I_{mp}(T_h - T_c)}{2} \quad (7)$$

$$\dot{Q}_c = \alpha_c I_{mp} T_c + \frac{I_{mp}^2 R_{el}}{2} + K_{th}(T_h - T_c) + \frac{\mu I_{mp}(T_h - T_c)}{2} \quad (8)$$

Finally, the thermal efficiency (η_{mp}) is determined to assess the overall performance of the TEG, as shown in Equation (9):

$$\eta_{mp} = \frac{\dot{Q}_h - \dot{Q}_c}{\dot{Q}_h} = \frac{W_{mp}}{\dot{Q}_h} \quad (9)$$

In this model, the temperature-dependent properties of the Bi_2Te_3 thermoelectric material are represented by the set of relations given in Equation (10), Equation (11), Equation (12) and Equation (13), as proposed by Xuan et al. [8] and Lamba and Kaushik [9].

$$\alpha = [\alpha_p - (-\alpha_n)] = 2 \times (22224.0 + 930.6T - 0.9905T^2) \times 10^{-9} \quad (10)$$

$$\rho_n = \rho_p = (5112.0 + 163.4T + 0.6279T^2) \times 10^{-10} \quad (11)$$

$$k_n = k_p = (62605.0 - 277.7T + 0.4131T^2) \times 10^{-4} \quad (12)$$

$$\mu = [\mu_p - (-\mu_n)] = 2 \times (930.6T - 1.981T^2) \times 10^{-9} \quad (13)$$

3. Results and Discussions

Table 2 presents the steady-state electrical and thermal performance of the TEG module operating under maximum power conditions. According to the simulation results, the module produces a current of 0.88 A and a voltage of 2.85 V. The maximum output power of the module was calculated as 2.50 W. This power output is considered reasonable and expected for a module consisting of 127 elements with a length of 1 mm and a cross-sectional area of 1.2 mm^2. Such a power level may be sufficient for practical applications such as powering small electronic devices or charging a battery. This value was also obtained under the maximum power transfer condition, where the load resistance equals the internal resistance of the module (2.95 Ω). On the other hand, the total heat absorbed from the hot side of the module was 61.70 W, while the heat rejected from the cold side was 59.20 W. The fact that most of the absorbed heat is transferred to the cold side rather than converted into electricity is an inherent characteristic of TEGs. The thermal efficiency was calculated as 4.05%. In the model, accounting for contact resistances and other losses reduced the efficiency below the ideal theoretical value, thereby providing a more realistic result.

Table 2. Electrical and thermal performance parameters of the TEG module operating under maximum power condition.

Description	Value	Unit
Current, I	0.88	A
Voltage across load, V	2.85	V
Power, W_{mp}	2.50	W
Internal resistance, R_{el}	2.95	Ω
Heat absorbed, $\dot{Q}_h$	61.70	W
Heat dissipated, $\dot{Q}_c$	59.20	W
Thermal efficiency, η_{mp}	4.05	%

Figure 2 illustrates the variation of the current passing through the TEG module as a function of the load resistance ratio. As shown in the figure, the current reaches its maximum value when the load resistance ratio is zero. This condition represents a theoretical scenario in which the circuit is short-circuited and the load resistance is negligible. As the load resistance ratio increases, the total resistance of the circuit increases, and according to Ohm's law, the current decreases. When the load resistance ratio approaches infinity, the current theoretically tends toward zero. This behavior confirms that a TEG behaves as a voltage source, delivering current depending on the resistance of the connected circuit.

Furthermore, Figure 2 highlights the point at which the TEG module generates its maximum power. According to the maximum power transfer theorem, the power output is achieved when the load resistance equals the internal resistance ($R_L = R_{el}$), i.e., at $R_L/R_{el} = 1$. At this point, Figure 2 shows that the current is approximately half of the short-circuit current. Different applications may require different load resistance ratios, which directly affect the current output. Therefore, the design of a TEG system should be optimized according to the electrical characteristics of the intended load. Thus, the findings obtained from Figure 2 indicate that the evaluation of TEG performance should consider not only the maximum power point but also the significance of the operational load resistance range.

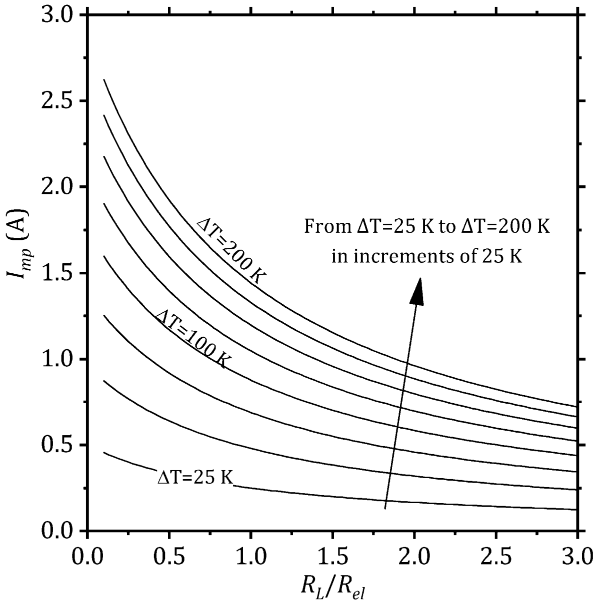

Figure 2. Variation of current in the TEG with respect to the load resistance ratio.

Figure 3 shows the variation of the electrical power generated by the TEG module as a function of the load resistance ratio. As illustrated in the figure, the power output of the TEG follows a parabolic curve, increasing with the load resistance ratio up to a certain point, after which it decreases. This behavior is in full agreement with the maximum power transfer theorem in electrical systems, which states that the maximum power delivered by a source to a load occurs when the load resistance equals the internal resistance of the source. Accordingly, the peak of the power curve corresponds to the point where the load resistance ratio equals unity ($R_L/R_{el} = 1$). At this point, the module achieves its theoretical maximum power output, which is of critical importance for TEG operation.

If the TEG is connected to a load resistance different from its internal resistance, the module operates below its maximum power capacity. For instance, as clearly observed in Figure 3, when the load resistance is twice the internal resistance ($R_L/R_{el} = 2$), the current decreases and consequently the power output is significantly reduced. These findings enable the identification of design parameters that maximize the targeted power output, thereby ensuring optimal performance of the TEG system.

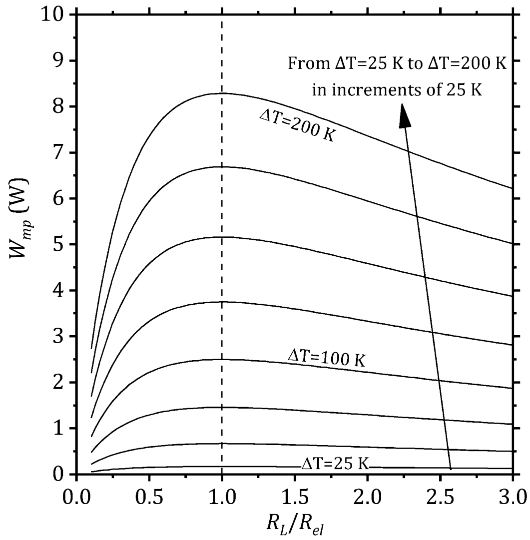

Figure 3. Variation of power output in the TEG with respect to the load resistance ratio.

The thermal efficiency of a TEG module is the most critical performance metric, as it indicates the proportion of the total heat absorbed from the hot side that can be converted into useful electrical energy. Figure 4 illustrates the variation of thermal efficiency with respect to the load resistance ratio. As shown in Figure 4, the efficiency curve exhibits a different characteristic compared to the power curve. The efficiency starts at zero when the load resistance ratio is zero (short-circuit condition). This is because, although the current is at its maximum in the short-circuit case, the power dissipated in the load is zero. As the load resistance ratio increases, the efficiency rises rapidly and reaches its maximum at a certain point. This maximum efficiency point occurs at a load resistance ratio higher than that corresponding to the maximum power output. The underlying physical reason is that the increase in total circuit resistance reduces losses such as Joule heating, thereby allowing heat energy to be more effectively converted into electrical energy. When the load resistance ratio continues to increase beyond unity, the efficiency begins to decline again since the total generated power decreases. These results demonstrate that it is not possible to simultaneously achieve both maximum power and maximum efficiency. Hence, the optimal operating point of a TEG must be carefully selected depending on the intended application. For example, if the cost of the waste heat source is high or its availability is limited, operating near the maximum efficiency point may be economically more advantageous.

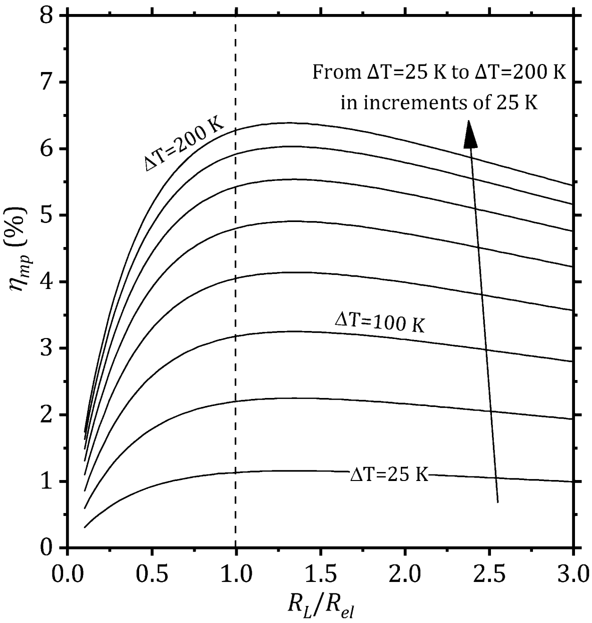

Figure 4. Variation of thermal efficiency in the TEG with respect to the load resistance ratio.

4. Conclusion

In this study, a theoretical model was developed to analyze the performance of a thermoelectric generator (TEG) for power generation from waste heat. The proposed model incorporates the temperature-dependent properties of semiconductor materials such as Bismuth Telluride (Bi_2Te_3), electrical and thermal losses due to contact resistances, and the fundamental principles of thermodynamics. The obtained results clearly revealed the dependence of the TEG module on the electrical load resistance. The model outputs demonstrated the steady-state performance of the TEG module under nominal operating conditions ($n = 127$, $l_p = 1$ mm, $A_p = 1.2$ mm^2, $T_h = 400$ K, and $T_c = 300$ K). Under these conditions, the module produced approximately 2.50 W of maximum electrical power. This power output is sufficient and expected for practical applications such as operating small electronic devices or charging a battery. The key finding is that the maximum power attainable from a TEG occurs when the load resistance equals the total internal resistance of the module ($R_L/R_{el} = 1$). This confirms a fundamental design principle regarding how the system should be optimized for maximum power output. On the other hand, while the power output reached its maximum at a load resistance ratio of unity, the efficiency curve peaked at a higher load resistance ratio. This indicates that a TEG designer must make a trade-off decision depending on the design priorities: if maximum energy conversion efficiency is targeted, the load resistance should be set greater than the internal resistance, whereas if the main objective is to achieve the highest possible power output, the load resistance should equal the internal resistance. In conclusion, the findings demonstrate the critical influence of design parameters, operating conditions, and load matching on the ultimate power output and efficiency of TEG modules.

Author contributions
Kaan Yaman: Conceptualization, Investigation, Writing - original draft, Data curation.
Sinan Dolek: Data curation, Writing-Original draft preparation, Formal analysis.
Gökhan Arslan: Writing - review & editing, Supervision, Methodology, Resources.

Conflicts of interest
The authors declare no conflicts of interest.

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