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ENERGY AND EXERGY ANALYSIS OF A THERMOELECTRIC GENERATOR: INFLUENCE OF HEAT SINK GEOMETRY UNDER NATURAL CONVECTION

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Abstract: The electrical performance of a thermoelectric generator (TEG) cooled by air convection was studied under two different heat sink configurations: pin-fin and parallel-plate. Notably, while the pin-fin heat sink produced a greater temperature difference across the TEG, it also yielded lower electrical power output and reduced energy and exergy efficiencies. Entropy generation analysis provided information on the thermodynamic irreversibilities of the energy systems and indicated an optimal energy conversion rate for the parallel-plate configuration. Taken together, these findings demonstrate that thermoelectric performance is determined not only by the temperature difference between the hot and cold sides of the TEG but also by the absolute operating temperature and the heat transfer effectiveness between system components.

Keywords: thermoelectric generator, heat sink, entropy generation, natural convection

INTRODUCTION

The increasing worldwide demand for energy has intensified efforts to improve energy production efficiency and increase the adoption of renewable sources [15]. During the conversion of primary energy resources, particularly fossil fuels, a substantial portion of input energy—often up to 70%—is lost as waste heat [6]. Therefore, the effective utilization of this thermal loss presents a significant opportunity to enhance overall energy conversion efficiency. Waste heat recovery technologies mitigate this issue by converting surplus thermal energy into usable forms, including electricity.

Thermoelectric generators (TEGs) directly convert heat into electrical energy and are increasingly used in waste heat recovery applications. They offer notable advantages, including low system cost, extended service life, minimal noise, and environmental benefits [11]. The electrical energy produced by thermoelectric power systems can supply various direct current (DC) loads directly or, through a DC-DC converter, meet specific current and voltage requirements [13]. The relatively low energy-conversion efficiency and output power of single TEG modules limit their widespread adoption in energy systems [20]. As a result, TEGs are often utilized as low-power sources, such as for circuit controllers in environmental monitoring systems measuring air temperature, humidity, and Sulphur dioxide (SO₂) concentration [14].

The performance of a TEG is influenced not only by material properties, such as the thermoelectric figure of merit, which measures a material's efficiency in converting heat to electricity, but also

by the thermal interaction between the heat source, the thermoelectric module, and the heat sink. In practical applications, heat exchangers, which facilitate heat transfer between two fluids or surfaces, significantly affect temperature distribution and heat flow, impacting electrical output and overall efficiency [9].

Various heat sink geometries, including plate-fin and pin-fin configurations, have been extensively studied. Although pin-fin heat sinks offer a larger surface area, their performance under natural convection can be constrained by flow interference and boundary layer interactions [19]. In comparison, plate-fin heat sinks may facilitate more organized buoyancy-driven airflow, thereby enhancing heat transfer efficiency [3].

A common assumption is that increasing the temperature gradient between the hot and cold plates of a thermoelectric generator (TEG) device enhances its performance. Pujol et al. [17] showed that increasing heat transfer intensity in TEG systems does not always result in higher power output, as system performance depends on the interaction between thermal conditions and electrical characteristics.

Thermoelectric efficiency is also influenced by absolute temperature levels and thermodynamic irreversibilities, which are unavoidable losses of useful energy due to real-world inefficiencies. Entropy generation analysis, a method for assessing lost energy and system inefficiency, serves as a valuable tool for evaluating these effects by quantifying exergy destruction, the loss of potential to perform work within the system. Lamba et al. [12] demonstrated that both internal

and external irreversibilities significantly affect thermoelectric performance, and the increased heat transfer does not necessarily reduce entropy generation.

This study experimentally investigates the influence of heat sink geometry on the thermodynamic performance of a TEG operating under natural convection. Two heat sink configurations, parallel-plate and pin-fin designs, are compared in terms of temperature distribution, electrical output, energy and exergy efficiencies, and entropy generation. The findings demonstrate that a larger temperature difference does not necessarily result in improved thermoelectric performance.

THERMOELECTRIC MODEL. ENERGY-EXERGY ANALYSIS

A thermoelectric couple (TC) functions as an electrical power generator and comprises two semiconductor legs: one p-type and one n-type. Heat flux induces the redistribution of charge carriers, resulting in an excess of electrons in the n-type leg and a deficit in the p-type leg. Multiple thermoelectric couples, denoted as N , are electrically connected in series and thermally arranged in parallel to form a thermoelectric module.

Supplying heat to the upper ceramic plate (the hot side) creates a temperature difference ΔT between the hot and cold sides of the module. Under these conditions, the device functions as a thermoelectric generator utilizing the Seebeck effect. When the TEG module terminals are connected to an external electrical load R_L , an electric current I_{TEG} flows through the circuit.

The mathematical formulation applied in this study relies on several simplifying assumptions [20]:

- thermal contact resistance between the heat source and the thermoelectric module is neglected;
- the cross-sectional areas of the semiconductor legs are constant;
- the heat transfer process is steady-state; and
- heat transfer is considered one-dimensional.

The model incorporates temperature-dependent properties of thermoelectric materials, including electrical resistivity, thermal conductivity and the Seebeck coefficient.

The electrical behaviour of the thermoelectric generator is characterized by Ohm's law, where the output voltage U_{TEG} (V) determines the output current I_{TEG} (A), as expressed by the following relation [5]:

$$I_{TEG} = \frac{U_{TEG}}{R_L} \quad (1)$$

The heat rate absorbed at the hot side of the thermoelectric generator, $Q_{h,TEG}$ (W), is expressed by relation [4]:

$$Q_{h,TEG} = N \left[\alpha_{TEG} T_H I_{TEG} + K_{TEG} (T_H - T_C) \right] - \frac{1}{2} I_{TEG}^2 R_{IN,TEG} \quad (2)$$

Details regarding the evaluation of the internal resistance of the TEG module, $R_{IN,TEG}$, are presented in other research studies [4,5].

Relation (2) accounts for multiple physical contributions. The first term represents the combined effect of the Seebeck effect and heat conduction, as described by Fourier's law. The second term reflects Joule heating, a loss mechanism within the system. Notably, only half of the Joule heat is transferred to the hot side, while the other half is dissipated to the cold side.

In this formulation, the overall Seebeck coefficient of the TEG module is defined as [21]:

$$\alpha_{TEG} = \alpha_p - \alpha_n \text{ (V/K)} \quad (3)$$

where α_p and α_n are the Seebeck coefficients of the p-type and n-type materials, respectively. These coefficients are temperature-dependent and are evaluated using the following correlation [21]:

$$\alpha_p = -\alpha_n = (22224 + 930.6T_m - 0.9905T_m^2) \times 10^{-9} \text{ V/K} \quad (4)$$

TEG module is also characterized by a thermal conductance K_{TEG} (W/K), defined as [5]:

$$K_{TEG} = k_p \frac{A_p}{L_p} + k_n \frac{A_n}{L_n} \quad (5)$$

The thermal conductivities of the p-type and n-type materials, denoted as k_p and k_n , are determined using the temperature-dependent expressions given in relation [21]:

$$k_p = k_n = (62605 - 277.7T_m + 0.4131T_m^2) \times 10^{-4} \text{ W/mK} \quad (6)$$

The operation of the thermoelectric generator requires maintaining the cold side of the module at a lower temperature, T_C , typically achieved through natural or forced convection. Under these conditions, the heat rejected at the cold side, $Q_{c,TEG}$ is expressed by relation [4]:

$$Q_{c,TEG} = N \left[\alpha_{TEG} T_C I_{TEG} + K_{TEG} (T_H - T_C) \right] + \frac{1}{2} I_{TEG}^2 R_{IN,TEG} \quad (7)$$

The TEG output power P_{TEG} (W) is expressed with relation [18]:

$$P_{TEG} = \frac{U_{TEG}^2}{R_L} \quad (8)$$

The energy conversion efficiency of TEG is defined as the ratio between the electrical power output and the heat input at the hot side of the module [4,18]:

$$\eta = \frac{P_{TEG}}{Q_{h,TEG}} \quad (9)$$

An energy analysis based solely on the first law of thermodynamics, which addresses energy

conservation, does not fully capture the efficiency of power conversion processes [16]. The concept of exergy, however, facilitates the evaluation of both energy quality and its degradation during thermodynamic transformations [7]. Consequently, applying the second law of thermodynamics in conjunction with exergy analysis provides a more comprehensive framework for identifying system losses and inefficiencies in energy conversion.

Thermodynamic irreversibilities significantly influence the performance of energy systems and require careful consideration. In thermoelectric systems, this type of irreversibility results in exergy destruction, thereby reducing the amount of useful work that can be extracted. Internal irreversibilities originate from Joule heating, conductive heat transfer within thermoelectric elements, and thermal losses through structural materials. External irreversibilities are associated with heat transfer at interfaces involving the heat source, heat sink, and surrounding fluid [2].

The *exergy destruction* associated with heat transfer between the hot and cold plates of the thermoelectric module, $Ex_{dest,TE}$, is given by the following expression [2]:

$$Ex_{dest,TE} = \left(1 - \frac{T_a}{T_H}\right) \cdot Q_{h,TEG} - \left(1 - \frac{T_a}{T_C}\right) \cdot Q_{c,TEG} - P_{TEG} \quad (10)$$

Knowing that the TEG module generates a useful electrical power $P_{TEG} = Q_{h,TEG} - Q_{c,TEG}$, the relation (10) will become:

$$Ex_{dest,TE} = T_a \cdot \left(\frac{Q_C}{T_C} - \frac{Q_H}{T_H} \right) \quad (11)$$

From relation (11), the entropy generation rate of the thermoelectric module can be identified with relation:

$$S_{gen} = Q_C / T_C - Q_H / T_H \quad (12)$$

The reversible work output of the thermoelectric generator-based energy conversion system can be described by the following relation [2]:

$$W_{rev} = P_{out} + T_a S_{gen} \quad (13)$$

Finally, the exergy efficiency, also known as the second-law efficiency, was determined with expression [1]:

$$\eta_{ex} = \frac{P_{out}}{W_{rev}} = \frac{P_{out}}{P_{out} + T_a S_{gen}} \quad (14)$$

EXPERIMENTAL SET-UP

Figure 1 presents the experimental setup and identifies the primary components of the two thermoelectric generator (TEG) systems. Electrical energy was generated using two commercial TEC1-12706 modules (Hebei I.T., Shanghai, China), each measuring 40 × 40 × 3.8 mm and containing 127

thermocouples composed of n-type and p-type Bi₂Te₃ semiconductor materials.

Both systems utilized a 12 V heating element rated for 120 °C operation as the heat source. The heater included an NTC thermistor and was enclosed in an aluminium casing (Keenso, USA) with overall dimensions of 28.5 × 150 × 5 mm³. A 300 W MCH-K310D DC source provided electrical power to the heater, maintaining stable operating conditions.

The DC output voltage was measured across the TEG's terminals using two Voltcraft VC271 SE digital multimeters, each with an accuracy of ±1%. Temperatures T_H and T_C were monitored with a PerfectPrime TC0304 thermometer equipped with K-type thermocouples, providing a measurement accuracy of ±0.5%. Ambient air temperature (T_a) was recorded using a PeakTech USB multimeter and a K-type thermocouple, with an accuracy of ±1%.

The electrical load for both systems was provided by two resistance decade boxes: a PeakTech 3280 model and an Eisco model (±1% tolerance). To promote efficient heat transfer between components, thermally conductive double-sided adhesive tape was used to bond the heat source, TEG modules, and heat sinks. This adhesive exhibited a thermal conductivity of 1.2 W/m·K and an adhesion strength of 12-18 N/25 mm, thereby improving thermal contact and heat dissipation. The thermoelectric system was enclosed within an insulating structure composed of expanded polystyrene (EPS), which provided both mechanical support and thermal management by minimizing heat losses to the environment and enhancing overall energy conversion efficiency.

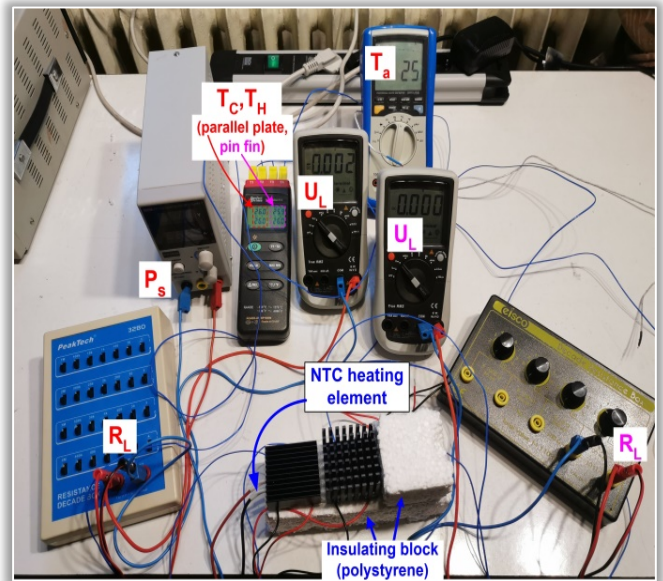


Figure 1. Experimental set-up for measuring TEG temperatures and output voltages U_L

Table 1 presents the main geometrical characteristics of the two heat sinks considered as heat-dissipation elements in thermoelectric energy systems.

Table 1. Basic geometrical specifications for the heat sinks

Case	Parallel plate HS	Pin – fin HS
Shape		
Size	50 x 45 x 18 (mm ³)	50 x 50 x 45 (mm ³)
Fin number	12	64
Thickness (fin/pitch)	1.55/2.85 (mm)	1.81/5.9 (mm)

RESULTS AND DISCUSSION

The external load resistance was selected as $R_L = 3 \Omega$, aligning with the temperature-dependent linear variation in the internal resistance of the TEC1-12706 module reported by Dziurdzia et al. [8], which ranges from 2.656Ω at 50°C to 2.876Ω at 70°C . This selection is validated by the Maximum Power Transfer Theorem, which states that maximum electrical power is achieved when the load resistance equals the thermoelectric generator's internal resistance [10].

Data analysis began following a 60-second warm-up period to minimize the influence of the heating element's transient negative temperature coefficient (NTC) behavior. During testing, the measured value of the surrounding air temperature (T_a) was 298 K.

As shown in Figure 2, the power supplied to the heating element (PS) decreased by approximately 10% during the 60-second transient period. A comparative analysis of the two cooling configurations shows that the pin-fin heat sink consistently produced a higher temperature gradient across the thermoelectric module than the parallel-plate heat sink.

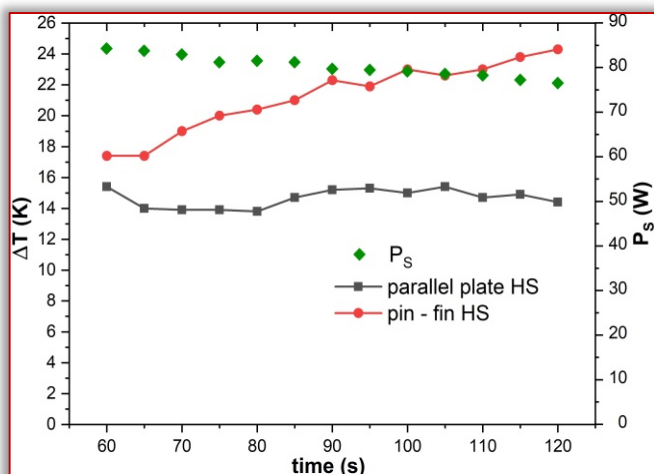


Figure 2. Variation of the TEG temperature gradient and heat-source power supply during the 1-minute testing period

At steady state, after 120 seconds of testing, the temperature difference increased from 14.4 K in the parallel-plate configuration to 24.3 K in the pin-fin configuration (see Figure 2). This result indicates enhanced cold-side heat transfer for the pin-fin geometry. Similar effects of heat sink geometry on natural convection performance have been documented in the literature, where flow organization and boundary-layer interactions significantly influence heat dissipation [3,19]. However, the larger temperature gradient obtained with the pin-fin heat sink did not lead to a proportional increase in electrical power output. After 1 minute, at the end of the test, the electrical power increased by only about 20 mW, as shown in Figure 3. This behaviour confirms that TEG performance is not solely governed by the temperature difference. It is also determined by the overall thermal coupling between system components [17].

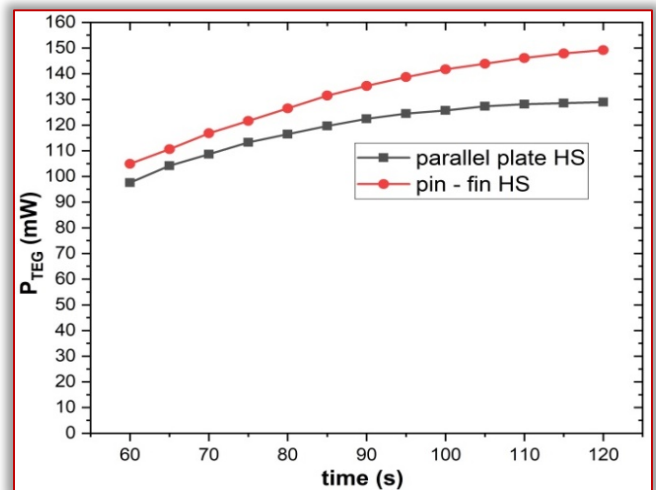


Figure 3. Evolution of the TEG output power during testing for the two systems with different heat sinks

The energy conversion efficiency was higher for the parallel-plate configuration, reaching 1.13% after 1 minute of testing, compared to 0.92% for the pin-fin heat sink (see Figure 4a). Despite the lower temperature gradient, the parallel-plate heat sink provided more effective energy conversion. This behavior is consistent with previous studies showing that excessive cooling may shift the operating point of the thermoelectric module away from optimal conditions [9,17].

Figure 4b shows a gradual decrease in exergy efficiency for the pin-fin heat sink configuration, which can be attributed to the progressive increase in thermodynamic irreversibilities during the one-minute transient regime, as shown in Figure 4c. For the pin-fin heat sink-based energy system, the energy destruction rate $E_{xdest,TE}$ ranged from 0.13 to 0.56 W.

As the thermodynamic system evolves over time, the enhanced cooling provided by the pin-fin geometry reduces the hot-side temperature by

about 11-14 K, thereby decreasing the thermodynamic quality of the heat input.

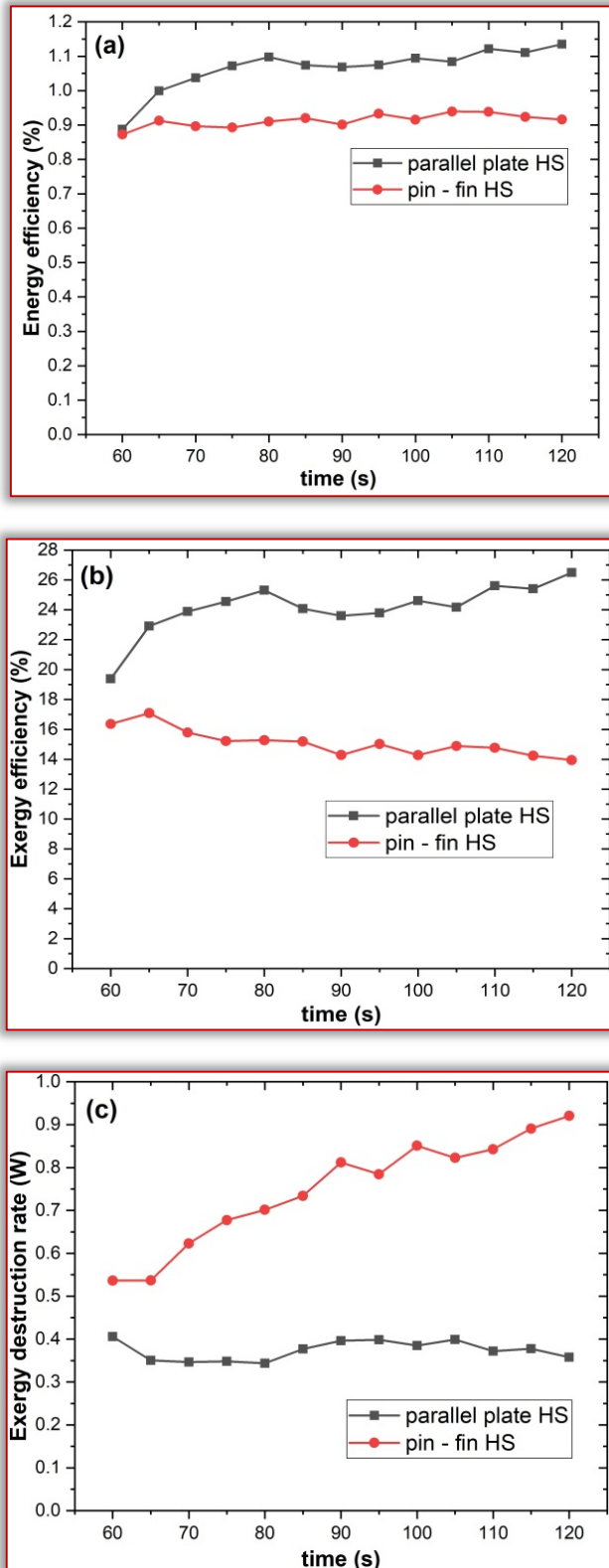


Figure 4. Evolution during testing of (a) energy efficiency, (b) exergy efficiency, and (c) exergy destruction rate

The parallel-plate heat sink achieved an exergy efficiency of 26.45% at the end of the test, compared to 13.95% for the pin-fin configuration (see Figure 4b). Since exergy efficiency reflects both energy quantity and quality, this result indicates that the parallel-plate configuration utilizes the available thermal potential more effectively. Such findings are consistent with

second-law analyses of thermoelectric systems, which report increased irreversibility due to enhanced temperature gradients and non-uniform heat transfer [12].

CONCLUSIONS

The present study compared the performance of pin-fin and parallel-plate heat sinks inside two energy systems with an identical thermoelectric module. The pin-fin heat sink increased the temperature gradient (ΔT) across the TEG module by about 68.8%, compared with the parallel-plate heat sink. However, this greater temperature differential resulted in only a 15.7% increase in electrical power after 1 minute of testing.

On the other hand, within the thermoelectric system, the parallel-plate heat sink exhibited superior thermal-to-electrical energy conversion efficiency, with improvements of 23.9% in energy efficiency and 19.2% in exergy efficiency. The pin-fin heat sink configuration produced substantially higher entropy production and exergy destruction, with irreversibility rates 32% to 157% higher than those of the parallel-plate configuration.

Analysis of both heat transfer mechanisms and thermodynamic compatibility within the system can optimize thermoelectric energy conversion, minimizing exergy destruction and maximizing net electrical power output.

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ISSN: 2067–3809



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