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Analysis of Electrical Potential in a Thermoelectric Generator Utilizing Cooking Stove Waste Heat

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Abstract

The need for sustainable alternative energy sources drives the exploration of waste heat utilization, including from domestic and commercial sectors such as cooking stoves. This study analyzes potential for electricity generation from waste heat of commercial restaurant stoves using a multi-module Thermoelectric Generator (TEG) system based on Peltier modules (TEC1-12706 and TEG 1848) equipped with cooling. The experimental method was conducted by testing the module characteristics on a controlled heat source and directly applying it to an LPG stove with specific distance variations according to temperature requirements. Characterization results show a strong nonlinear relationship between temperature difference (ΔT) and output voltage, with optimal performance in the ΔT range of 40–65°C. In stove testing, the system was able to generate power up to 804 mW (at ΔT ~53°C). This study concludes that utilizing stove waste heat with serially scaled TEG modules and active thermal management is a viable strategy for generating DC electricity in waste-heat recovery applications, although overall efficiency is still limited by internal module resistance and thermal contact instability in real operating environments.

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Abstrak

Kebutuhan akan sumber energi alternatif yang berkelanjutan mendorong eksplorasi pemanfaatan panas terbuang, salah satunya dari sektor domestik dan komersial seperti kompor masak. Penelitian ini menganalisis potensi pembangkit listrik dari panas buang kompor restoran komersial menggunakan sistem generator termoelektrik (TEG) multi-modul berbasis Peltier (TEC1-12706 dan TEG 1848) yang dilengkapi dengan pendingin. Metode eksperimen dilakukan dengan menguji karakteristik modul pada sumber panas terkontrol dan mengaplikasikannya secara langsung pada kompor LPG dengan variasi jarak tertentu sesuai kebutuhan suhu. Hasil karakterisasi menunjukkan hubungan non-linier yang kuat antara beda suhu (ΔT) dan tegangan keluaran, dengan performa optimal pada rentang ΔT 40–65°C. Pada pengujian kompor, sistem mampu menghasilkan daya hingga 804 mW (pada ΔT ~53°C). Studi ini menyimpulkan bahwa pemanfaatan panas buang kompor dengan TEG berskala modul seri dan manajemen termal aktif merupakan strategi yang layak untuk menghasilkan listrik DC dalam aplikasi waste-heat recovery, meskipun efisiensi keseluruhan masih dibatasi oleh resistansi internal modul dan ketidakstabilan kontak termal dalam lingkungan operasi riil.

1. Introduction

Two inseparable issues arise as the global demand for energy increases: so too does concern for environmental damage. This has intensified the search for and innovation in sustainable and renewable energy sources. The process of primary energy conversion in power plants, industrial processes, and everyday equipment partially results in losses as waste heat (Forman, 2016). The recovery of this low-temperature waste heat presents a highly promising

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opportunity to improve overall energy efficiency. One source of waste heat is stoves, which are widely used in households, restaurants, and the food industry. A substantial amount of thermal energy is radiated into the environment, most of which remains untapped.

Various studies indicate that the combustion process in household gas stoves has a relatively low thermal efficiency, it means a large portion of the heat energy from the flame is not absorbed by the cooking vessel but is lost to the environment through radiation, convection, and exhaust gases; for instance, experimental measurements on an LPG burner recorded flame temperatures reaching 500–700 °C, while the stove walls (inner and outer) remain in the range of 60–160 °C, indicating a high level of unused residual heat (Rahmadsyah, 2022; Wae-Hayee et al., 2021). This phenomenon of wasted heat presents a significant opportunity for waste-heat recovery systems, one of which is through the application of thermoelectric generators (TEGs) capable of converting temperature gradients into electrical energy; several studies have demonstrated that TEG modules placed on hot areas of a stove—for example, on the top plate or heat spreader—can generate sufficient electrical power for light loads such as lighting or charging small batteries (Atmoko et al., 2021; Shimanuki et al., 2019). Thus, waste heat that has previously gone unused can be converted into an alternative energy source, improving the overall efficiency of the gas stove system while adding value in the context of energy sustainability.

Thermoelectric generators, both TEC and TEG types, offer an attractive solution for the direct conversion of heat into electrical energy through the Seebeck effect. These solid-state devices are characterized by their reliability, silent operation, minimal moving parts, and scalability (Champier, 2017; He, 2015). However, widespread adoption of TEG technology is hindered by relatively low conversion efficiency and high material costs, especially for applications involving small temperature gradients (< 100°C) (Kandar, 2021).

Previous research has explored the application of TEGs for waste heat recovery. For example, studies have been conducted to integrate TEGs with biomass cookstoves (Bustomy, 2020) and portable gas stoves (Nithyanandam and Mahajan, 2018). Most of these studies use commercial Bismuth Telluride (Bi_2Te_3) modules (Peltier TEC1-12706) due to their availability and moderate performance at low temperatures. Although promising, these systems often produce limited power output, primarily due to inadequate thermal management and suboptimal system design. Active cooling by flowing water on the cold side of the TEG is known to dramatically increase the temperature differential (ΔT), thereby enhancing voltage and power output according to the fundamental relationship $V = \alpha\Delta T$, where α is the Seebeck coefficient (Zhang & Zhao, 2015). Nevertheless, comprehensive studies on the influence of variations in heat source distance combined with active cooling in real-world cooking environments remain limited.

This study provides a systematic experimental analysis of a multi-module TEG system based on Peltier TEC1-12706 modules compared with TEG 1848 modules (12 connected in series), integrated with a flowing active cooling system.

2. Research Methods

2.1. Materials and Equipment

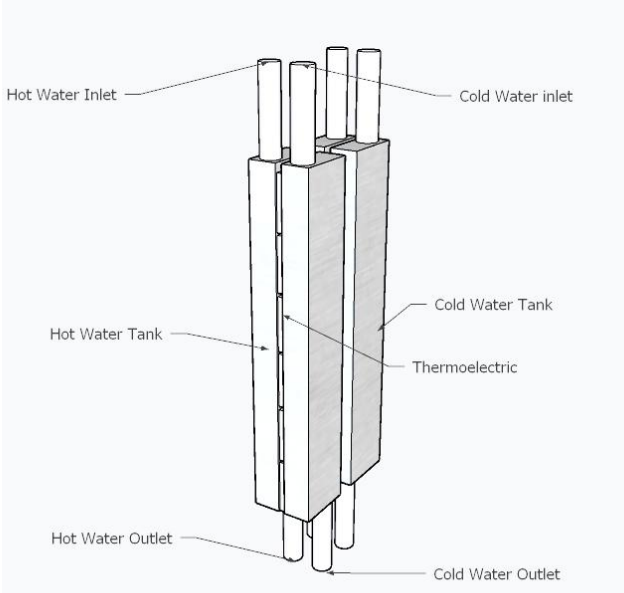
The materials and equipment used in this study are listed in **Table 1**.

Table 1. List of materials and equipment

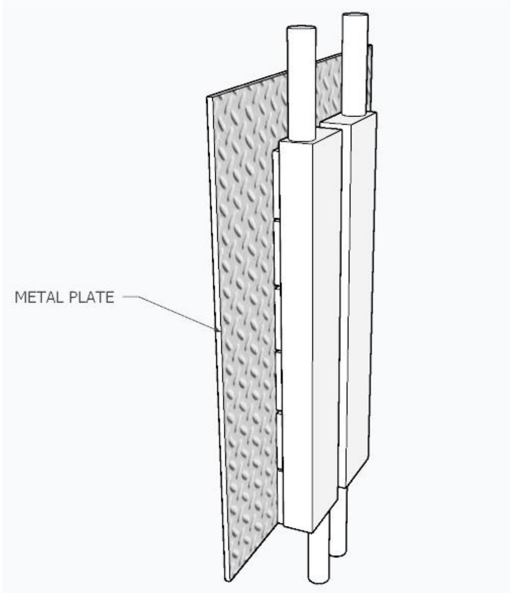
Category	Item	Specification / Details
TEG Components	Peltier Module	TEC1-12706 dan TEG 1848 masing-masing 12 buah (40 mm × 40 mm, max ~150°C)
	Heatsink	Aluminum Holow, 40 mm × 20 mm × 250 mm (L×W×H)
	Thermal Interface	Silicone-based high-temperature adhesive (Silen pipe glue)
	Thermal Conductors	Iron plates (2 mm thickness x 200 mm x 300 mm),
Measurement	Temperature Sensor	K-type Digital Thermocouple (Accuracy: ±0.5°C, Range: -50°C to 1300°C)
	Electrical Meter	Digital Multimeter (Voltage: ±0.5%+2 digits, Current: ±1.0%+3 digits)
	Load	8 W DC incandescent lamp (Nominal: 12 V, 0.67 A)
Heat Source	Cooking Stove	Commercial restaurant LPG stove (single burner)

2.2. Fabrication of System

The system was designed to maximize the temperature gradient across the modules by actively cooling the cold side. Twelve TEC1-12706 and TEG-1848 modules were electrically connected in series to increase the output voltage. The cooling system was constructed using a sealed aluminium hollow block, connected to inlet and outlet pipes (**Figure 1(a)**). System testing to achieve a temperature gradient was conducted by attaching the setup to an iron plate. The plate's purpose was to store heat longer from the stove flame. The assembly was then placed near the stove flame, as illustrated in **Figure 1(b)**.



(a)



(b)

Figure 1. Schematic of thermoelectric voltage characteristic tests (a) and thermoelectric tests on stoven (b)

2.3. Experimental Procedure and Data Acquisition

Testing was conducted using two methods. First, to determine the thermoelectric characteristics, a controlled heat source inside a hot water tube was used. The cold side was set to a temperature of 28°C. Subsequently, the temperature was allowed to decrease continuously until a balance between the hot side temperature (T_h) and cold side temperature (T_c) was reached. Twelve TEC modules were arranged in series and operated in TEG mode. The hot side temperature (T_h) was varied from 100°C down to 28°C, while the cold side temperature (T_c) was maintained constant at room temperature, 28°C, resulting in a temperature difference (ΔT) range of 0–72°C. The output voltage generated was observed for each ΔT condition. The fundamental principle is the Seebeck effect, where a thermal gradient across a thermoelectric material generates an electrical voltage (Rowe, 2018).

Second, direct testing was performed on a stove using a plate heated by the stove flame at a specific distance, primarily focusing on achieving a constant temperature.

3. Results and Discussions

The measurement data results for the characterization of TEC modules arranged in series and operated in TEG mode are presented in **Figure 2**.

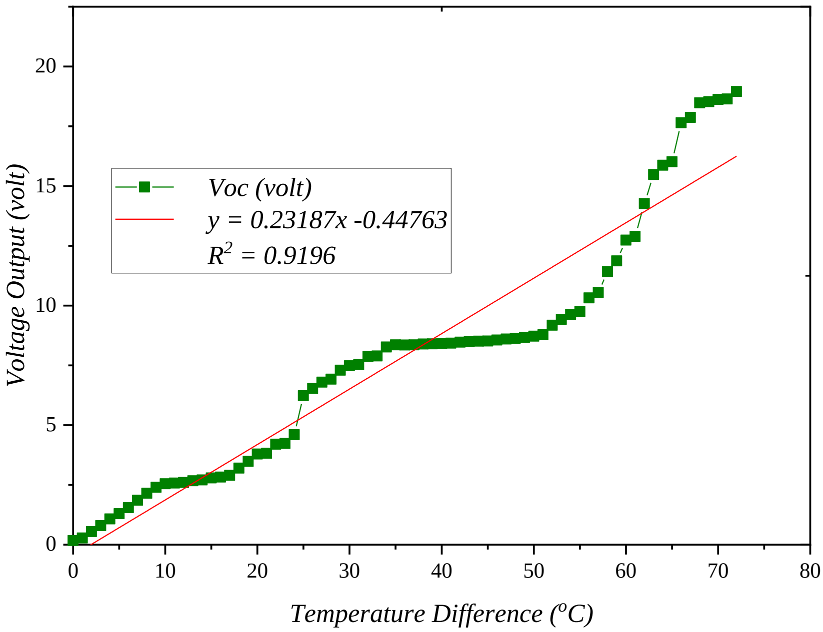


Figure 2. Test of TEC1-12706

Figure 2 data graph shows a strong non-linear relationship between *ΔT* and output voltage. At high *ΔT* (>60°C), the voltage reaches a maximum value of 18.95 V, but with significant fluctuations and a decreasing rate of increase. In the medium *ΔT* range (40–65°C), the voltage is relatively stable at around 8.4–8.5 V, forming a plateau that indicates an operating region with optimal voltage stability. Meanwhile, at low *ΔT* (<40°C), the voltage drops exponentially, approaching zero as *ΔT* close to zero. This pattern aligns with the characteristics of thermoelectric materials whose efficiency depends on the average temperature and the figure of merit (*ZT*) (Snyder & Toberer, 2008).

The non-linearity of the voltage response to *ΔT* can be explained by the temperature dependence of thermoelectric material parameters, primarily the Seebeck coefficient (*S*), electrical resistivity (*ρ*), and thermal conductivity (*κ*). The Seebeck coefficient is generally not constant but varies with temperature, often peaking at a specific operating temperature (Kim et al., 2015). Furthermore, the internal resistance of the module increases with temperature, which limits the increase in power even as voltage rises. At very high *ΔT*, parasitic heat conduction through the material and increased contact thermal resistance can reduce conversion efficiency, as observed in the declining rate of voltage increase at the upper end of the test range (Meng et al., 2019).

These results imply that operating the TEG at maximum *ΔT* is not always advantageous due to material performance degradation and thermal inefficiency. Conversely, the medium *ΔT* range (40–65°C) offers better voltage stability, which is crucial for waste heat recovery power generation applications requiring predictable output. For further optimization, current and power measurements are needed to determine the maximum power point (MPPT) and conversion efficiency. Precise control of the hot-side temperature and effective cooling of the cold side are also critical factors in maintaining system performance (Zhao & Tan, 2014).

Voltage Measurement from the Waste Stove

This measurement observed the voltage generated based on the stable temperature obtained during experiments on the TEC1-12706, as shown in **Figure 3**.

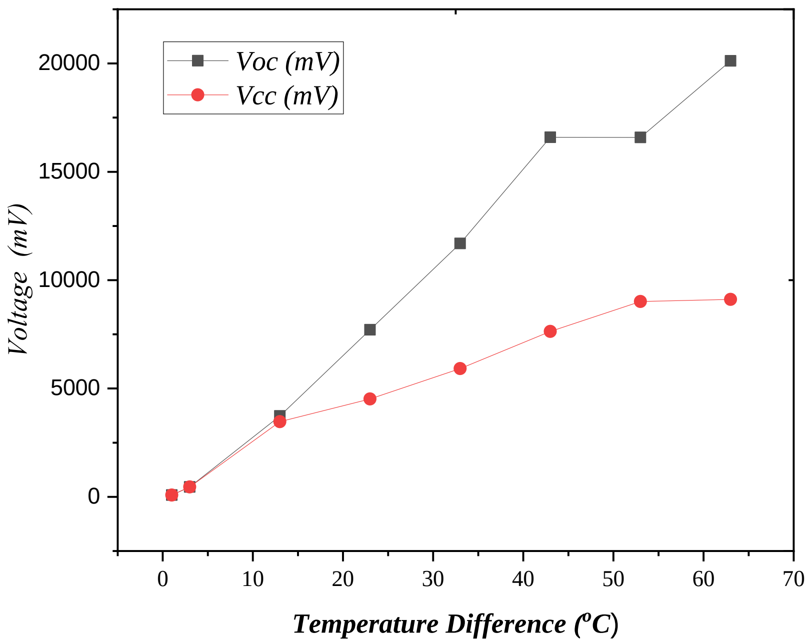


Figure 3. Waste Stove Heat Testing using TEC

Based on the measurement data of the TEC-12706 thermoelectric module conducted under very low current conditions (0.0xx mA) with a constant cold-side temperature (T_c) of 28°C, it can be observed that the open-circuit voltage (V_{oc}) and closed-circuit voltage (V_{cc}) are highly dependent on the temperature difference (*ΔT*). Higher values of V_{oc} and V_{cc} indicate a stronger Seebeck effect performance. For example, at the highest *ΔT* of 63°C (T_h=*90°C*), V_{oc} reaches a maximum value of approximately 23.75 mV, while at the lowest *ΔT* of 1°C (T_h=*28°C*), V_{oc} drops sharply to about 0.08 mV. This pattern is consistent with the fundamental principle of thermoelectric generators, where a larger temperature gradient produces a higher electromotive force (EMF). However, there is slight data variation for each repeated measurement at the same *ΔT*, likely due to factors such as temperature control instability or measurement noise.

Furthermore, at *ΔT* of 13°C (T_h=*40°C*), there are abnormally high and irregular V_{cc} and V_{oc} values (e.g., 538.09 mV) that deviate from the trend, indicating a possible transient anomaly during the experiment under those conditions. This result is not significant, as the power generated is minimal. For comparative data, the following are the test results for the TEG 1848, as shown in **Figure 4**.

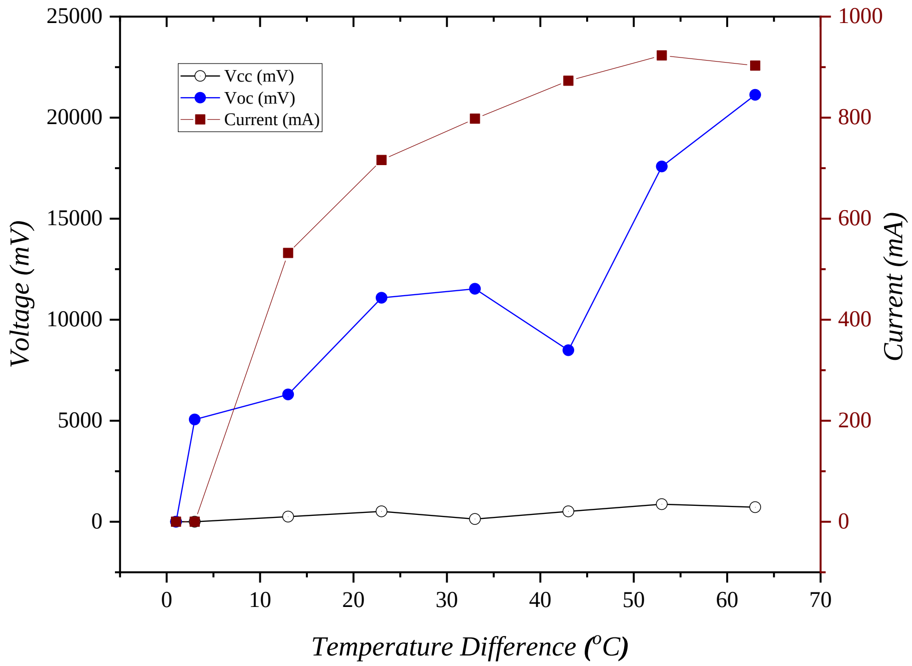


Figure 4. Characterization Testing of the TEG 1848 Module

Characterization testing of the TEG 1848 module across various temperature differences (ΔT) provides crucial experimental data on thermoelectric generator performance under realistic operating conditions. The systematically measured data of open-circuit voltage (V_{oc}), loaded voltage (V_{cc}), and load current (I) from ΔT 1°C to 63°C reveals a complex relationship between thermal gradient and electrical output. This study is relevant in the context of waste heat recovery, where understanding TEG characteristics in the intermediate temperature range (30-100°C) is critical for system optimization (Rowe, 2018).

The data show that the open-circuit voltage (V_{oc}) generally increases with rising ΔT, in accordance with the fundamental Seebeck effect principle. However, significant variations are observed in the intermediate ΔT range (33-53°C), where Voc does not consistently follow an ideal linear trend. The calculated effective Seebeck coefficient (S_{eff} = $Voc/\Delta T$) ranges from 0.21-0.48 V/°C, indicating a strong dependence on the module's average operating temperature. This phenomenon is consistent with the characteristics of Bismuth Telluride thermoelectric material, whose electron transport properties are highly temperature-dependent (Snyder & Toberer, 2008). At low ΔT (<10°C), Voc measurements show anomalies likely caused by instrumentation offset or thermal contact instability.

The maximum power output of 804 mW was achieved at ΔT 53°C, not at the maximum ΔT of 63°C (653 mW), indicating a non-linear optimal operating condition. Analysis of internal resistance (R_{int}) shows variation between 9-23 Ω, with a tendency to increase at higher ΔT due to rising material resistivity. The mismatch between the low load resistance ($R_L = V_{cc}/I$) of 0.05-0.94 Ω and the relatively high Rint prevents the system from operating at its theoretical maximum power point. The principle of impedance matching ($R_L = R_{int}$) to maximize power transfer was not met in this test, explaining why the output power was not maximized despite a large ΔT (Kim et al., 2015).

Several anomalies are observed in the data, particularly in V_{oc} measurements at low ΔT (3°C) which show unrealistic values (~5 V), likely due to electrical noise or sensor calibration. High variability in repeated measurements at the same ΔT indicates experimental condition instability, such as fluctuating thermal contact or inconsistent cold-side cooling. Parasitic heat losses through conduction and convection, as well as contact thermal resistance, can reduce the effective ΔT across the module, especially at high-temperature gradients (Meng et al., 2019). This explains the performance drop at ΔT 63°C despite a larger nominal temperature difference.

The test results imply that designing a practical TEG system must consider: *first*: an optimal operating point around ΔT 50-55°C for this module type, *second*: the need for a maximum power point tracking (MPPT) system to adapt to changes in R_{int}, and *third*; the importance of effective thermal management to maintain a stable temperature gradient. For future research, it is recommended to conduct complete *I-V* curve measurements with variable loads, characterize the system's thermal properties, and analyze conversion efficiency while considering input heat flux (Zhao & Tan, 2014).

4. Conclusions

The multi-module thermoelectric generator (TEG) system (TEC1-12706/TEG 1848) installed on a commercial stove successfully converted waste heat into electrical energy, proving the feasibility of the waste-heat recovery concept for low-temperature heat sources. The system's power output has a non-linear relationship with ΔT. Optimal performance was not achieved at maximum ΔT but in the intermediate range (40–65°C), where voltage exhibited the highest stability. This indicates the importance of optimizing the operating point, not just maximizing the temperature difference.

The measurements show a significant mismatch between the high internal resistance of the modules and the low load resistance, causing the system to operate away from its Maximum Power Point (MPP). Implementing

Maximum Power Point Tracking (MPPT) is necessary to improve power transfer. Although the generated power (~804 mW) can already be utilized for very low-power electronic loads, real-world application requires more comprehensive thermal and electrical engineering design. Optimization should focus on improving thermal contact stability, reducing heat losses, and impedance matching to achieve more competitive system efficiency.

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