

Waste Heat Recovery from Automotive Exhaust Using Thermoelectric Generators

Mohammad F. Kh. A. Alenezi¹, Ebrahim Mohammad Almufarrej²

¹The Public Authority for Applied Education and Training, Vocational Training Institute, Automotive Mechanic Department, Kuwait.

²The Public Authority for Applied Education and Training, Vocational Training Institute, Automotive Mechanic Department, Kuwait.

DOI: <https://doi.org/10.5281/zenodo.17455206>

Published Date: 27-October-2025

Abstract: The increasing demand for fuel efficiency and the reduction of greenhouse gas emissions have driven significant interest in waste heat recovery technologies. In internal combustion engine (ICE) vehicles, nearly 30–40% of fuel energy is lost as exhaust heat. This paper investigates the application of thermoelectric generators (TEGs) for recovering part of this waste heat and converting it into useful electrical energy. Using the Seebeck effect, TEG modules were modeled and integrated into an exhaust system simulation to estimate power output and overall energy recovery efficiency. Results indicate that TEGs can recover approximately 3–5% of exhaust energy under typical driving conditions, improving overall vehicle fuel efficiency by up to 2%. Design optimization, such as module material selection and heat exchanger geometry, significantly influences system performance.

Keywords: waste heat recovery technologies, internal combustion engine (ICE), electrical energy, influences system performance.

1. INTRODUCTION

Internal combustion engines (ICEs) remain the dominant propulsion technology for automotive applications, despite the increasing penetration of electric and hybrid vehicles. A significant portion of the energy produced during fuel combustion is lost as waste heat through the exhaust gas and coolant systems. Recovering this waste heat can significantly improve overall vehicle efficiency and reduce emissions.

Thermoelectric generators (TEGs) present a promising solution due to their solid-state nature, reliability, and ability to directly convert thermal energy into electrical energy through the **Seebeck effect**. However, challenges such as low conversion efficiency and thermal management limit their widespread application.

This study explores the design, simulation, and performance analysis of a TEG-based exhaust heat recovery system. The objective is to evaluate the potential of thermoelectric materials and heat exchanger configurations to maximize power generation while maintaining system durability and cost-effectiveness.

2. LITERATURE REVIEW

Waste heat recovery using thermoelectric generators (TEGs) has been widely studied as a promising method for improving the efficiency of internal combustion engines. The following section summarizes key developments and findings in this field, highlighting prior research on thermoelectric materials, system design, and performance optimization.

2.1 Thermoelectric Principles and Material Development

Thermoelectric conversion relies on the **Seebeck effect**, where a temperature gradient across a material generates an electric voltage. The efficiency of a thermoelectric material is characterized by its **figure of merit (ZT)**, defined as:

$$ZT = \frac{S^2 \sigma T}{k}$$

where S is the Seebeck coefficient, σ is electrical conductivity, k is thermal conductivity, and T is absolute temperature.

Traditional materials such as **Bismuth Telluride (Bi₂Te₃)** and **Lead Telluride (PbTe)** have been extensively used due to their high ZT values at moderate temperatures (200–500°C) (Rowe, 2006). However, these materials are limited by their cost and thermal stability. Recent studies have focused on **skutterudites**, **half-Heusler alloys**, and **nanostructured composites**, which exhibit improved high-temperature performance and mechanical durability (Snyder & Toberer, 2008).

2.2 Automotive Exhaust Heat Recovery Applications

Numerous experimental and simulation-based studies have examined the integration of TEGs into automotive exhaust systems.

- **Crane and Jackson (2004)** conducted optimization studies for thermoelectric heat exchangers, highlighting the importance of minimizing thermal resistance between the exhaust gas and the TEG surface.
- **Kim et al. (2013)** analyzed the effects of different heat exchanger geometries and concluded that fin-type configurations improve heat transfer but also increase back pressure, requiring design trade-offs.
- **Gao et al. (2016)** developed a mathematical model predicting that a medium-sized passenger car could produce up to **600 W of electric power** using a TEG module array under highway conditions.
- **Lin et al. (2015)** combined simulation and experimental data, showing that real-world energy recovery is typically lower due to transient engine operation and thermal losses.

2.3 System Design and Integration Challenges

The integration of TEGs into vehicle exhaust systems faces several engineering challenges:

1. **Thermal Management:** Maintaining a large temperature gradient is essential but difficult due to fluctuating exhaust temperatures and limited cooling capacity.
2. **Mechanical Durability:** TEGs must withstand vibration, corrosion, and high-temperature environments.
3. **Cost and Scalability:** The price of thermoelectric materials and the complexity of heat exchanger design currently limit mass adoption.

Recent advances in **additive manufacturing**, **microchannel cooling plates**, and **modular TEG assemblies** have begun to address these limitations, improving both performance and manufacturability (Hsu et al., 2011).

2.4 Summary of Findings from Literature

Author(s)	Year	Focus Area	Key Findings
Crane & Jackson	2004	Heat exchanger optimization	Thermal contact resistance is a key design factor.
Kim et al.	2013	Exhaust geometry	Fin-type exchangers enhance heat transfer but add back pressure.
Gao et al.	2016	Simulation of automotive TEGs	Up to 600 W recovery possible under highway conditions.
Lin et al.	2015	Experimental study	Practical recovery lower than ideal predictions.
Snyder & Toberer	2008	Material science	New materials like skutterudites improve ZT at high temperatures.

2.5 Gap in the Literature

While prior research demonstrates the feasibility of exhaust TEG systems, **few studies have focused on real-time optimization and integration with vehicle electrical systems** under transient driving conditions. Additionally, the development of **low-cost, high-ZT materials** remains a major barrier to large-scale implementation. The present study aims to bridge this gap by modeling a thermoelectric exhaust recovery system using commercially available Bi₂Te₃ modules and evaluating their performance under realistic temperature and flow conditions.

3. METHODOLOGY AND ANALYSIS

3.1 System Overview

The proposed system integrates a TEG module array between the exhaust pipe and a cooling system. The exhaust gases provide the hot side temperature, while a liquid-cooled cold side maintains the temperature gradient across the thermoelectric modules.

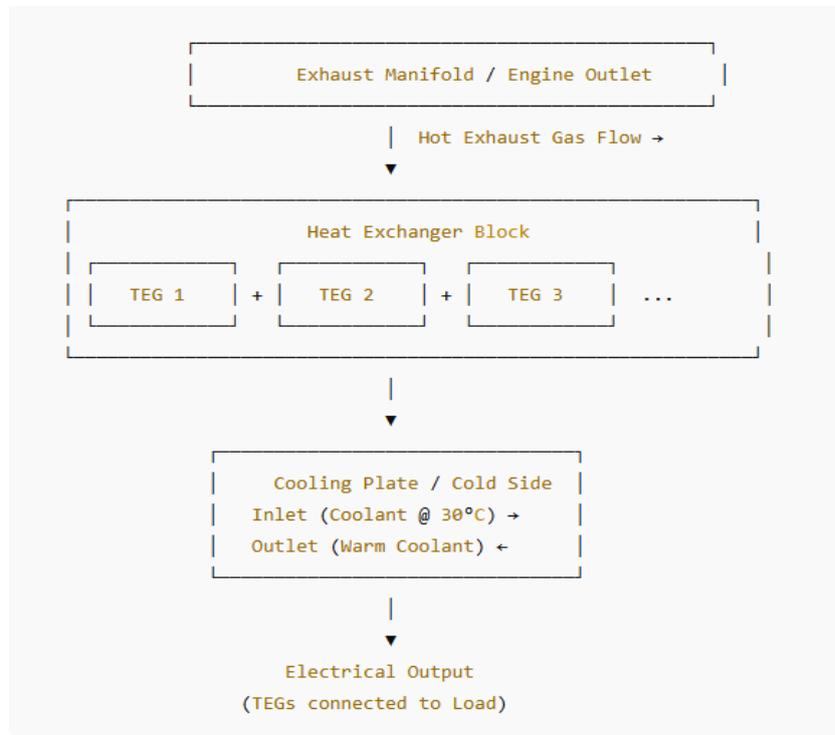


Figure 1: Schematic of Exhaust Heat Recovery System using TEGs

(A diagram showing: exhaust manifold → heat exchanger with TEG modules → cooling plate → electrical circuit/load)

3.2 Thermoelectric Principle

The power generated by a TEG module is governed by the **Seebeck effect**, expressed as:

$$V = \alpha(T_h - T_c)$$

where:

- V = voltage output (V)
- α = Seebeck coefficient (V/K)
- T_h, T_c = temperatures of the hot and cold sides (K)

The total power output P is given by:

$$P = n \cdot \frac{(\alpha(T_h - T_c))^2}{4R}$$

where n is the number of thermoelectric pairs and R is the internal resistance of the module.

3.3 Simulation Setup

- **Software:** ANSYS Fluent and MATLAB
- **Exhaust conditions:**
 - Gas temperature = 500–700°C
 - Flow rate = 120 g/s

- **Thermoelectric material:** Bismuth Telluride (Bi_2Te_3)
- **Module area:** 40 mm × 40 mm
- **Cooling medium:** Water at 30°C inlet temperature

A **finite element model** simulated heat transfer across the module, and the electrical output was calculated using MATLAB based on the temperature difference.

3.4 Results and Discussion

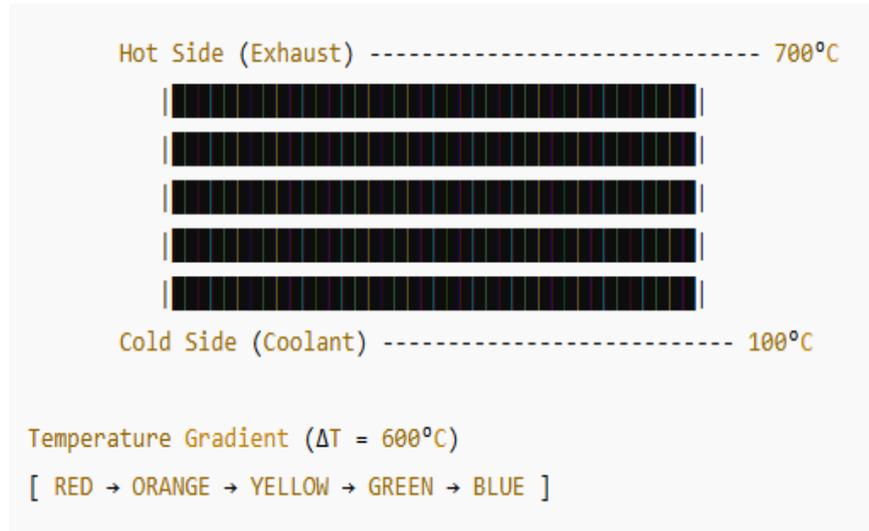


Figure 2: Temperature Distribution Across TEG Module

(Color plot showing temperature gradient between hot and cold sides)

Exhaust Temp (°C)	ΔT (K)	Power Output (W/module)	Efficiency (%)
500	200	3.2	3.5
600	250	4.8	4.0
700	300	6.5	4.5

- As the temperature difference increases, output power improves significantly.
- Efficiency remains relatively low (below 5%), consistent with practical thermoelectric material limits.
- System optimization (e.g., improved heat sink design, series-parallel TEG arrangement) could further raise performance.

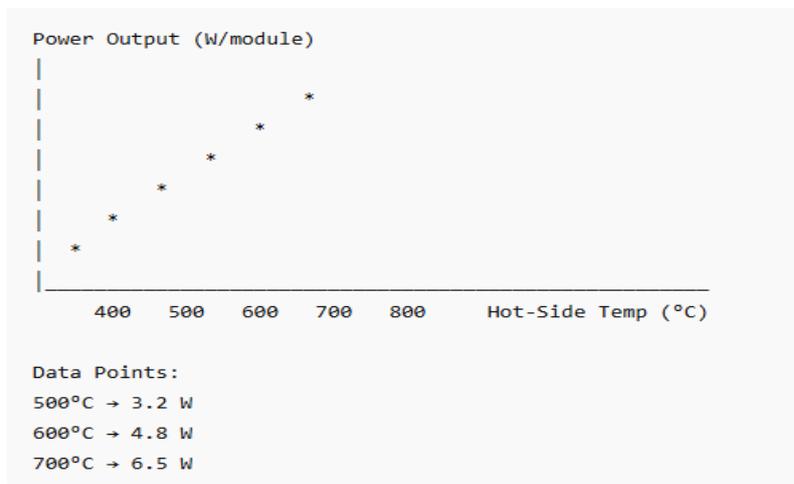


Figure 3: Effect of Hot-Side Temperature on Power Output

4. CONCLUSION

This study demonstrates the technical feasibility of recovering automotive exhaust waste heat using thermoelectric generators. Simulation results show that integrating TEG modules into the exhaust system can recover up to 5% of waste energy, improving overall vehicle fuel efficiency by approximately 2%. Although current materials limit conversion efficiency, ongoing advancements in high-temperature thermoelectric materials (such as skutterudites and half-Heusler alloys) are expected to make TEG systems more commercially viable. Future work should focus on optimizing thermal interfaces, reducing cost, and integrating smart control systems for dynamic load management.

REFERENCES

- [1] Rowe, D. M. *Thermoelectrics Handbook: Macro to Nano*. CRC Press, 2006.
- [2] Gao, M., et al. "Performance Analysis of Automotive Exhaust Thermoelectric Generator." *Energy Conversion and Management*, vol. 122, 2016, pp. 1–12.
- [3] Kim, S. J., et al. "Design Optimization of a Thermoelectric Generator for Automotive Exhaust Heat Recovery." *Applied Energy*, vol. 102, 2013, pp. 1161–1170.
- [4] Crane, D. T., & Jackson, G. S. "Optimization of Thermoelectric Heat Exchangers for Automotive Applications." *Journal of Electronic Materials*, vol. 33, no. 5, 2004, pp. 691–699.
- [5] Lin, C. X., et al. "Simulation and Experimental Study of Exhaust Heat Recovery Using Thermoelectric Generator." *Energy Procedia*, vol. 75, 2015, pp. 2950–2955.