

Waste Heat Recovery Technologies for IC Engines: A Comparative Review of Thermoelectric and Organic Rankine Cycle Systems

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Abstract

Internal combustion (IC) engines, widely used in automotive, marine, and industrial applications, are inherently inefficient due to significant thermal energy losses. A substantial portion of the energy generated from fuel combustion is expelled as waste heat through the exhaust system and cooling fluids. With increasing emphasis on energy efficiency and environmental sustainability, Waste Heat Recovery (WHR) technologies have garnered considerable attention for their potential to enhance overall engine performance and reduce fuel consumption and emissions. Among the various WHR methods, Thermoelectric Generators (TEGs) and Organic Rankine Cycle (ORC) systems have emerged as leading solutions due to their adaptability and effectiveness in different thermal regimes. This review provides a comparative analysis of TEG and ORC systems for IC engine waste heat recovery. TEGs are solid-state devices that convert thermal gradients directly into electrical energy using the Seebeck effect. Their advantages include compactness, absence of moving parts, and silent operation, although they suffer from low conversion efficiency and material limitations. In contrast, ORC systems use organic working fluids to generate mechanical power via an expansion process, making them more efficient at converting medium-grade heat but at the cost of increased complexity, size, and maintenance. The paper explores the fundamental working principles, recent advancements in materials and system architectures, integration strategies with IC engines, and the performance metrics of each technology. A detailed comparison highlights their respective benefits and trade-offs in terms of efficiency, scalability, cost, and system complexity. Emerging trends, such as hybrid systems and smart control technologies are also discussed, offering insights into future integration prospects.

Keywords: Waste heat recovery, internal combustion engines, thermoelectric generators, organic Rankine cycle, energy conversion efficiency, thermal energy utilization

INTRODUCTION

Internal combustion (IC) engines have been the backbone of transportation, industrial machinery, and power generation for more than a century. Despite significant technological advancements over the years, the thermal efficiency of these engines remains relatively low. On average, only about 30–40% of the fuel's chemical energy is converted into useful mechanical work, while the remaining 60–70% is lost as waste heat through exhaust gases, engine cooling systems, and other parasitic losses [1–3]. This inefficiency not only limits fuel economy but also contributes to increased greenhouse gas emissions and environmental degradation. As global efforts intensify to improve energy efficiency and reduce carbon footprints, the recovery and utilization of waste heat from IC engines have emerged as critical areas of research and development [4, 5].

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Waste Heat Recovery (WHR) technologies aim to capture this lost thermal energy and convert it into useful power, either in the form of mechanical work or electricity. The potential benefits of WHR systems are multifaceted: they can enhance the overall efficiency of engine systems, reduce fuel consumption, lower emissions, and improve sustainability across various sectors, including automotive, marine, and stationary power generation. Furthermore, integrating WHR technologies into existing systems provides a means to achieve energy efficiency gains without the need for radical changes in engine architecture or operational methodology [6–8].

Among the various WHR technologies under investigation, two stand out due to their adaptability and promising performance – Thermoelectric Generators (TEGs) and Organic Rankine Cycle (ORC) systems. These technologies are particularly attractive for mobile applications, such as vehicles and locomotives, where size, weight, and system integration are critical design considerations. TEGs utilize solid-state materials to convert temperature gradients directly into electrical energy based on the Seebeck effect, offering the advantages of no moving parts, silent operation, and compact design. On the other hand, ORC systems employ an organic working fluid with a low boiling point to operate a thermodynamic cycle, like the conventional Rankine cycle, making them well-suited for medium-grade waste heat recovery [9–12].

Despite their shared objective, TEG and ORC systems differ significantly in their design, operating principles, efficiency ranges, and practical challenges. TEG systems are generally easier to integrate and maintain but suffer from low conversion efficiency and high material costs. In contrast, ORC systems can achieve higher efficiencies and power outputs, especially in high-load applications, but their mechanical complexity and cost can be limiting factors. Therefore, a comparative review of these two technologies is essential to understand their respective strengths, limitations, and prospects [13–15].

WASTE HEAT RECOVERY: AN OVERVIEW

Waste Heat Recovery (WHR) technologies focus on capturing thermal energy that is typically lost to the environment during the operation of internal combustion engines. This otherwise wasted heat represents a significant energy source that, if efficiently reclaimed, can substantially improve overall system efficiency. The recovered thermal energy can be converted into useful forms, such as electrical power or mechanical energy, which can then be utilized to operate auxiliary components, recharge vehicle batteries, or directly assist the engine’s propulsion system. This not only enhances fuel economy but also contributes to reducing harmful emissions by lowering fuel consumption. For application in mobile and automotive environments, WHR systems must meet stringent design criteria. These include a compact and lightweight form factor to avoid adding excessive bulk, the ability to operate efficiently across a wide range of engine loads and temperatures, robust durability to withstand harsh operating conditions, and cost-effectiveness to justify their integration into commercial vehicles. Achieving the optimal balance among these factors remains a key challenge in WHR technology development.

THERMOELECTRIC GENERATOR (TEG) SYSTEMS

Working Principle

Thermoelectric Generators (TEGs) function on the principle of the Seebeck effect, which occurs when a temperature gradient across two different conductors or semiconductors generates an electric voltage. In a TEG, this effect is utilized by arranging multiple thermocouples – pairs of p-type and n-type thermoelectric materials – into modules. These thermocouples are connected electrically in series to build up voltage and thermally in parallel to maximize heat flow. When a heat source, such as engine exhaust, creates a temperature difference between the hot and cold sides of the module, electricity is produced because of charge carrier movement. TEGs can continuously generate power if the temperature gradient is maintained.

Materials

Common thermoelectric materials include Bismuth Telluride (Bi_2Te_3), Lead Telluride (PbTe), and Skutterudites due to their high thermoelectric efficiency. Current research aims to improve the figure of merit (ZT) using nanostructured composites, doped materials, and hybrid structures to increase conversion performance and reduce thermal losses.

Advantages

- Solid-state operation with no moving components, enabling noise-free and low-maintenance systems.
- Small size and lightweight design allow for easy integration into existing engine exhaust setups.
- Modular architecture offers flexibility for scaling power output across different applications.

Limitations

- Typically, low energy conversion efficiency, often below 5% under practical conditions.
- High material costs and the need for effective heat dissipation systems increase implementation challenges.
- Requires a substantial and stable temperature difference for optimal performance, limiting effectiveness in fluctuating thermal environments.

ORGANIC RANKINE CYCLE (ORC) SYSTEMS

Working Principle

The Organic Rankine Cycle (ORC) functions on the same basic thermodynamic principles as the conventional Rankine cycle but employs organic working fluids, such as R245fa, R123, or Toluene. These fluids possess lower boiling points and higher vapor densities compared to water, making ORC systems particularly effective for recovering energy from low- to medium-temperature heat sources like exhaust gases. During operation, the working fluid absorbs thermal energy from the waste heat source in the evaporator, changes phase into vapor and then expands through a turbine or positive displacement expander to generate mechanical or electrical energy. The vapor is subsequently condensed and pumped back to the evaporator to complete the cycle.

System Components

A complete ORC setup typically consists of an evaporator (heat exchanger), an expander, a condenser, and a feed pump. Ongoing research is focused on compact system designs that can be efficiently integrated into automotive platforms.

Advantages

- High energy conversion efficiency at moderate temperatures.
- Scalable for applications requiring larger power outputs.
- Wide selection of organic fluids adaptable to various temperature ranges.

Limitations

- Increased system complexity due to mechanical components
- High capital and maintenance costs compared to simpler WHR systems
- Organic fluids may degrade over time or leak under fluctuating thermal loads

COMPARATIVE ANALYSIS

Thermoelectric Generator (TEG) systems and Organic Rankine Cycle (ORC) systems differ significantly in their design philosophy, performance characteristics, and application suitability. TEGs, being solid-state devices, offer simplicity with no moving parts, making them highly reliable and suitable for compact installations. However, their energy conversion efficiency is relatively low, typically in the range of 2–5%, and their power output is limited. In contrast, ORC systems are mechanically more complex due to the presence of turbines, pumps, and heat exchangers but can

achieve higher efficiencies (8–15%) and generate significantly more power – up to tens of kilowatts. Maintenance demands are also greater for ORCs, owing to fluid handling and component wear. While both systems are costly, the nature of expenses differs TEGs involve expensive materials, whereas ORCs incur costs from fluids, mechanical components, and system integration. Integration flexibility is another key distinction, with TEGs being more modular and adaptable, whereas ORC systems require more installation space and careful thermal design (Table 1).

Table 1. Criteria for TEG & ORC system.

Criteria	TEG Systems	ORC Systems
Energy Conversion Efficiency	2–5%	8–15%
Mechanical Complexity	Low (solid-state)	High (moving parts)
Maintenance Requirements	Minimal	Moderate to high
Power Output	Low (watts to a few kW)	Moderate to high (up to 30 kW+)
Response to Load Changes	Fast	Moderate
Integration Flexibility	High (compact and modular)	Medium
Cost	High (materials)	High (components and fluid)

INTEGRATION STRATEGIES IN IC ENGINES

Effective integration of WHR technologies into internal combustion engine systems is essential to maximize energy recovery without compromising engine performance or packaging constraints.

- *TEG Systems:* Thermoelectric generators are typically integrated either directly into the engine's exhaust manifold or mounted along the exhaust pipe, where the temperature gradients are most significant. These locations allow TEGs to utilize high-grade thermal energy efficiently. To enhance thermal conductivity and ensure mechanical durability, thermal interface materials (TIMs), such as graphite sheets or phase-change compounds, are applied between hot surfaces and thermoelectric modules. Additionally, advanced heat spreaders and finned heat sinks are employed to optimize heat distribution and cooling on the cold side of the modules. Their modularity and compact size make TEGs suitable for both light and heavy-duty vehicle applications.
- *ORC Systems:* Organic Rankine Cycle systems demand more space due to their complex components, including evaporators, expanders, condensers, and fluid circulation pumps. Effective layout planning is crucial, especially in mobile platforms. Compact ORC units with integrated control systems are currently being designed for hybrid electric vehicles, trucks, and marine engines, where sufficient installation space and higher power output requirements justify the additional complexity.

Advanced Materials and Designs

Significant research is being directed toward enhancing the efficiency of TEG systems by developing advanced thermoelectric materials. Innovations, such as nanostructured composites, quantum dot arrays, and hybrid thermoelectric modules are being employed to improve the figure of merit (ZT) while minimizing thermal conductivity and increasing electrical output. Simultaneously, ORC systems are witnessing advancements in compact and high-efficiency micro-expanders, as well as the development of environmentally benign organic fluids that perform well under a wide range of temperatures. Enhanced cycle designs and control algorithms are being created to maximize energy recovery and system responsiveness.

Hybrid WHR Systems

Researchers are also investigating integrated WHR systems that combine the benefits of both TEG and ORC technologies. These hybrid systems aim to improve thermal utilization across different temperature ranges and engine operating conditions, providing higher overall efficiency and adaptability.

Smart Control and IoT Integration

Modern WHR systems increasingly leverage IoT-based sensors and control technologies to enable dynamic performance optimization. By integrating with vehicle control units, these systems can adapt to real-time load changes, engine states, and driving patterns, thereby improving reliability and overall energy recovery.

CONCLUSIONS

Thermoelectric Generators (TEGs) and Organic Rankine Cycle (ORC) systems represent two of the most promising technologies for harnessing waste heat from internal combustion (IC) engines. TEGs stand out due to their solid-state design, compact size, and ease of integration, making them highly suitable for recovering low-grade heat to power auxiliary systems or charge onboard batteries. In contrast, ORC systems can deliver significantly higher energy conversion efficiencies and power outputs, especially when recovering heat from exhaust gases. However, their increased mechanical complexity, need for precise thermal management, and higher cost of implementation present certain challenges. Despite their respective limitations, ongoing advancements in thermoelectric materials, working fluids, micro-expanders, and smart control systems are steadily enhancing the performance and applicability of both technologies. As the demand for cleaner, more efficient engine systems continue to grow, especially in hybrid and heavy-duty vehicles, the role of TEG and ORC systems in improving overall energy efficiency is likely to become increasingly critical.

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