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Perspective

Waste heat recovery technologies in modern internal combustion engines

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ABSTRACT

Waste heat recovery (WHR) technologies in internal combustion engines (ICEs) outline various methods to harness wasted energy for improved efficiency and reduced emissions. The discussion covers heat exchangers, turbo-compounding, bottoming cycles, thermoelectric generators (TEGs), thermochemical recuperation (TCR), thermoacoustic conversion, and absorption refrigeration. Each technology's principles, applications, benefits, and challenges are explored, highlighting advancements and innovations from industry leaders. This paper underscores the ongoing efforts to maximize energy efficiency and minimize environmental impact in ICEs across diverse vehicle types and applications.

1. Introduction

The quest for more efficient and environmentally friendly transportation has been a driving force behind ongoing innovation in internal combustion engine (ICE) technology. Despite significant advancements, a substantial portion of the energy produced by ICEs is lost as waste heat, representing a missed opportunity for improved efficiency and reduced emissions. Waste heat recovery (WHR) technologies emerge as a promising solution to capture and utilize this untapped energy, offering the potential to enhance the performance of ICEs across various applications [1]. Waste heat recovery (WHR) in internal combustion engines (ICEs) reflects a growing interest in optimizing energy efficiency and minimizing environmental impact. Researchers and engineers have explored a diverse array of WHR technologies, each with unique principles, applications, benefits, and challenges. Heat exchangers have long been utilized to recover heat from exhaust gases, with advancements such as finned plate heat exchangers and variable-geometry turbochargers mitigating challenges like pressure reduction and backpressure. Turbo-compounding, whether mechanical or electrical, offers significant potential for fuel savings and emissions reduction, as demonstrated by Volvo's pioneering D13TC engine. Bottoming cycles, including the Rankine, Brayton, and Kalina cycles, present opportunities to convert waste heat into mechanical or electrical energy, with different working fluids and engine conditions dictating their effectiveness. Meanwhile, thermoelectric generators (TEGs) offer scalability and fast response but face challenges such as low efficiency and high cost [2]. Thermochemical recuperation (TCR) seeks to enhance fuel's lower heating value (LHV) by utilizing waste heat to sustain fuel steam reforming reactions, promising improvements in engine efficiency and emissions reduction [3]. Thermoacoustic conversion, employing the Stirling cycle, shows potential for high efficiency but grapples with challenges like transient response and additional weight [4]. Finally, absorption refrigeration cycles utilize waste heat for cooling systems, offering benefits such as pre-cooling intake air and reducing engine load. Despite challenges like low coefficient of performance (COP), absorption refrigeration holds promise for operating with low-grade energy [5]. Overall, the literature underscores the multifaceted efforts to maximize energy efficiency and minimize environmental impact in ICEs through the advancement and application of WHR technologies.

2. WHR

Waste heat recovery (WHR) plays a pivotal role in optimizing the efficiency of internal combustion engines (ICEs) by reclaiming energy lost during combustion. Despite significant technological advancements, a substantial portion of the energy derived from engine combustion dissipates as thermal and kinetic energy, with only about 30% converted into useful power. This underscores the critical importance of WHR mechanisms in enhancing combustion efficiency and overall engine performance [1]. Figure 1. shows the power flow diagram in ICEs, indicating the importance of waste heat recovery (WHR) to enhance combustion efficiency.

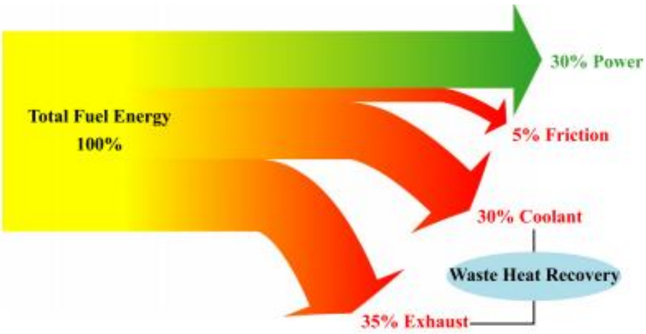


Figure 1. Power flow diagram in ICEs [6]

In the powertrain, energy loss is primarily attributed to the engine itself, accounting for 60%, with braking contributing the remaining 40% [6]. Hybrid electric vehicles (HEVs) employ supercapacitors and flywheels to capture energy during braking, while Formula 1 vehicles utilize sophisticated energy recovery systems (ERS), including MGU-H and MGU-K electric motors, to harness exhaust energy and braking waste heat, yielding an additional 160 horsepower. While previous discussions have focused on brake WHR in supercapacitor and flywheel systems, this section delves into the complexities of engine WHR. Key sources of heat loss in ICEs include the charge air cooler (intercooler), engine coolant, exhaust gas recirculation (EGR) cooler, and exhaust. The effectiveness of WHR from these sources depends on factors such as temperature, heat quantity, and availability, often referred to as exergy. Although exhaust and EGR energy are the primary sources for WHR, charge air cooler and engine coolant can also possess valuable energy, especially under high load conditions. The selective catalytic reduction (SCR) system, commonly used in the exhaust path to reduce NOx emissions, operates at a lower temperature compared to EGR due to the pressure drop applied to the EGR gas, resulting in higher exergy [7].

3. Heat exchangers

Heat exchangers play a ubiquitous role in waste heat recovery (WHR) technologies, often integrated as essential components rather than standalone systems. While research on their independent applications as WHR methods is limited, WHR shell-tube and finned plate heat exchangers have been strategically positioned along the exhaust line to warm engine lubricant oil during cold start conditions. This innovative approach not only yields fuel-saving benefits but also contributes to emissions reduction. By reducing engine warm-up time, the application of heat exchangers leads to a drop in cooling fluid temperature and duration, resulting in improved efficiency and a net reduction in fuel consumption of up to 2.6%. Furthermore, this implementation has been shown to reduce CO, CO_2, HC, PM, and NO_x emissions by approximately 7%, 3.6%, 3%, 2%, and 3%, respectively. However, the integration of heat exchangers into the exhaust pathway presents significant challenges, notably related to pressure reduction and backpressure. Pressure reduction can result in a decrease in mass flow rate, while backpressure may undermine the turbocharging effect. To address these challenges, advancements such as the adoption of more efficient finned plate heat exchangers instead of shell-tube configurations and the utilization of variable-geometry turbochargers (VGT) have been proposed. These technological enhancements offer promising prospects for mitigating the inherent challenges associated with heat exchanger integration into the exhaust system [8].

4. Turbo-compounding

Turbo-compounding is a concept that involves integrating a power turbine into the turbocharger assembly, offering a straightforward yet effective means of enhancing engine performance. This integration can take two primary forms: mechanical turbo-compounding and electrical turbo-compounding. In mechanical turbo-compounding, the power turbine is connected directly to the crankshaft to generate additional torque and power. Conversely, in electrical turbo-compounding, the power turbine is linked to a generator to produce and store electrical energy. The application of electrical turbo-compounding is particularly justified in scenarios where the electrical load exceeds 50 kW or in hybrid electric vehicles (HEVs), especially Range-Extended Electric Vehicles (REEVs) and series HEVs aimed at battery charging. Moreover, electrical turbo-compounding finds utility in competitive arenas such as Formula 1, where it helps reduce turbo lag and extend driving range. Mechanical turbo-compounding can be further categorized into two configurations: series and parallel. In the series turbo-compound system, priority is given to turbocharging when exhaust flow energy is limited, with excess energy subsequently powering the turbine. Conversely, the parallel turbo-compound system provides additional torque and power when exhaust energy exceeds the demand for turbocharging. Figure 2 introduces the architecture of both series and parallel turbo-compounding. Volvo stands out as a pioneer in the application of turbo-compound systems in heavy-duty diesel engines. For instance, the 2022 Volvo D13TC engine, equipped with turbo-compounding, achieves notable fuel savings of up to 6% compared to its predecessor, the 2020 Volvo D13 VGT engine equipped with variable-geometry turbochargers. Turbo-compounding systems can extract a substantial portion of exhaust energy, up to 25.7%, leading to enhancements in brake-specific fuel consumption (BSFC) by 1.9% and output power by 11.4%, while simultaneously reducing NO_x, soot, and CO_2 emissions by approximately 5%, 2%, and 5%, respectively, compared to non-compounded systems. These benefits are particularly pronounced in heavy-duty diesel engines operating predominantly at high loads. Although turbo-compounding offers modest fuel savings for SI (spark ignition) engines, it presents challenges for medium-duty vehicles and urban driving scenarios characterized by medium to low engine loads, where it may result in additional weight and increased back pressure, thereby potentially compromising engine performance. Nevertheless, turbo-compounding systems have demonstrated significant fuel savings, ranging from 10% to 12.5%, 44% to 61%, and 43% to 53% compared to non-turbo-compounded, series diesel-HEV, conventional diesel engine, and SI-HEV configurations with battery packs, respectively, especially in supercapacitor-based series diesel-HEVs [9].

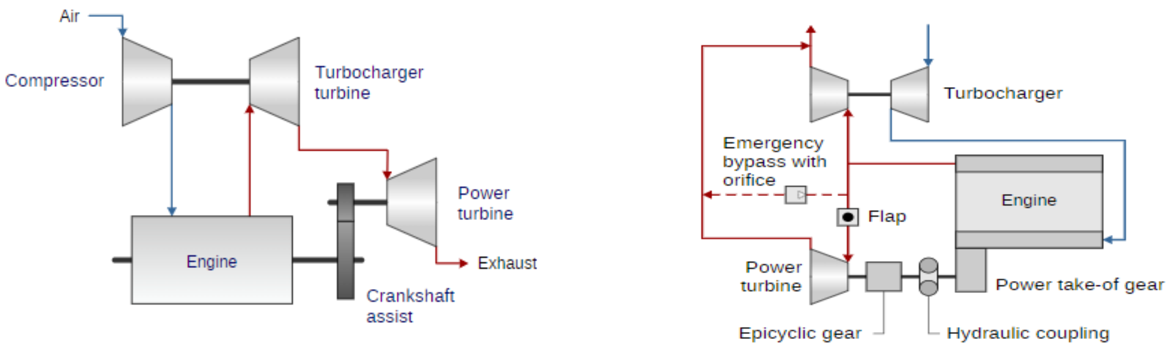
5. Bottoming cycle

A thermodynamic cycle, such as the Rankine, Brayton, and Kalina cycles, represents a transformative process wherein thermal energy undergoes conversion into mechanical form to drive a turbine to produce mechanical or electrical energy. The choice of working fluid, whether air, steam, or organic fluid, significantly influences the efficacy of energy recovery from exhaust gases, making it a pivotal parameter in determining the suitability of different cycles for specific applications. The steam Rankine cycle (SRC) offers an advantage in engine cooling compared to the organic Rankine cycle (ORC), boasting a 41.8% advantage. However, in terms of electrical output and fuel improvement, the SRC lags the ORC, with figures of 2% against 4.9% and 9.5% against 24.7%, respectively [10]. A cascaded SRC/ORC system proposed for waste heat recovery (WHR) from diesel engines yielded a notable 5.6% improvement in power compared to basic diesel engines. Furthermore, hybrid electric vehicles (HEVs) equipped with an ORC system demonstrated a significant output power improvement of 5.4% (2.2 kW), leading to 1.0% and 1.2% fuel savings for NEDC and WLTP driving cycles compared to powertrains without an ORC. The efficacy of SRC and ORC systems is heavily contingent upon exhaust temperature and engine load, as the working fluid must attain its boiling and saturated temperatures. Hence, heavy-duty applications are deemed ideal platforms for these systems.

The Kalina cycle (KC) was introduced to overcome the challenge of low heat source temperatures, demonstrating substantial efficiency improvements of 25%-40% versus 8%-13% and fuel savings of 20%-30% versus 8%-10% in comparison with ORC systems in a light-duty M15GS engine. In contrast, the Brayton cycle (BC) is less dependent on engine load and exhaust temperature and boasts simpler implementation compared to SRC, ORC, and KC systems. With no need for a condenser, BC systems do not impose additional weight, vibration, or maintenance on the powertrain. Plug-in series hybrid electric vehicle configurations equipped with intercooled BC exhibited improvements of 5.5%, 5.7%, and 2% in fuel economy, powertrain efficiency, and brake power, respectively, compared to similar configurations lacking BC integration [11].

6. Thermoelectric generators

Various direct electrical conversion devices, such as thermoelectric, piezoelectric, thermionic, and thermophotovoltaic devices, offer alternatives that eliminate the need for mechanical and moving parts found in traditional technologies. Among these, the thermoelectric generator (TEG) stands out as a widely employed solution in transportation applications. TEGs function by converting the temperature difference between two junctions into electrical energy through the Seebeck effect. TEGs offer several notable advantages, including scalability for low load ranges, rapid response times, precise temperature control, absence of moving parts, and the elimination of the need for refrigerants. However, they face challenges in handling high load capacities, achieving high efficiency, managing costs, and maintaining a low coefficient of performance (COP). Unlike bottoming cycles, which are typically more suited for Range-Extended Electric Vehicles (REEVs) and series hybrid electric vehicles (HEVs), TEGs can find application across various types of HEVs. In addition to their ability to generate excess power, TEGs offer benefits in terms of fuel savings and efficiency improvements. Figure 3 illustrates a simplified diagram of a single TEG system [12]. Several major automotive manufacturers, including General Motors, Volkswagen, BMW, Fiat, Toyota, and Honda, have actively pursued the development of thermoelectric generators (TEGs) for their passenger and commercial vehicles.



(a) (b)

Figure 2. System schematic representation of a) series turbo-compounding and b) parallel turbo-compounding

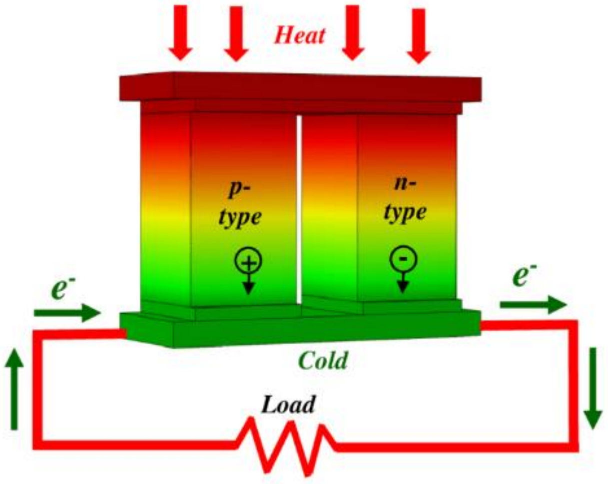


Figure 3. A simple structure of a thermoelectric generator system [6]

In 2008, BMW embarked on a TEG system integrated into the exhaust path, capable of generating 600 watts of electrical power. Subsequently, in 2009, they introduced an alternative design by implementing TEGs in the exhaust gas recirculation (EGR) system, resulting in 250 watts of electrical power and a 2% reduction in both CO_2 emissions and fuel consumption. BMW's innovative turbosteamer, based on the Rankine cycle, combined with the TEG system, achieved impressive results: up to 10 kW of power and 20 Nm of torque, leading to a 15% improvement in fuel consumption and a 10% increase in output power. Similarly, TEG applications in Fiat Iveco, Honda F1, and Toyota Prius-HEV demonstrated average fuel savings of 4%, 3%, and 11%, respectively [6].

7. Thermochemical recuperation

Thermochemical Recuperation (TCR) presents an innovative strategy for harnessing waste heat energy to drive fuel steam reforming reactions, thereby enhancing the lower heating value (LHV) of the fuel and ultimately improving engine efficiency and reducing emissions.

This paper delves into the intricacies of TCR, highlighting its key aspects and impacts on engine performance. Fuel transformation lies at the heart of TCR, involving the vaporization of liquid fuel utilizing waste heat energy. A critical consideration in TCR is the choice between gaseous and liquid fuels. Gaseous fuels offer higher specific energy (LHV) and release more energy during combustion, leading to lean-burn benefits and improved efficiency. Additionally, they exhibit shorter combustion durations and ignition delays, resulting in reduced emissions. Examining the efficiency and emissions impact of TCR reveals compelling results. High-pressure TCR coupled with Methanol Steam Reforming (MSR) demonstrates significant efficiency improvements ranging from 18% to 39% at lower loads, accompanied by notable reductions in emissions, including NOx (73-94%), CO (90-96%), and HC (85-97%). However, TCR with Ethanol Steam Reforming (ESR) yields modest efficiency gains of 2%, albeit with substantial reductions in CO and NO_x emissions compared to gasoline SI-ICE. Despite its potential, challenges loom on the path to TCR commercialization. These challenges encompass additional weight on the powertrain, uncertainties regarding efficiency at low-load conditions, and the prevalence of issues such as backfire, coke formation, and pre-ignition [13].

8. Thermoacoustic conversion

The intersection of thermoacoustic principles and Stirling engines offers a compelling avenue for waste heat recovery in automotive systems. By harnessing heat to induce sound waves and subsequently leveraging pressure fluctuations, this innovative approach embodies the efficiency and versatility of the Stirling cycle. Figure 4 introduces the Stirling cycle coupled with the engine exhaust pass and coolant fluid. Through cyclic compression and expansion of a working fluid across varying temperature gradients, Stirling engines facilitate energy conversion without the need for combustion, distinguishing them from traditional internal combustion engines.

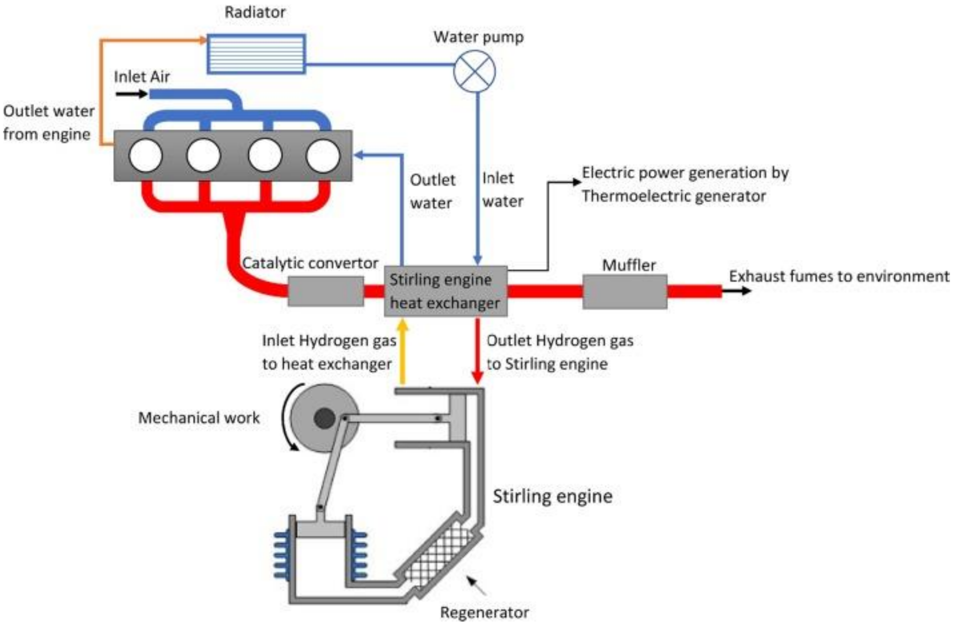


Figure 4. The Stirling cycle coupled with the engine for WHR

Within automotive applications, integration of Stirling engines has demonstrated notable benefits, such as a 1.3% increase in power output and 1% fuel savings in the Mercedes-Benz OM47 Euro VI Diesel Engine and a significant 5.2% enhancement in output power when coupled with the Iran Khodro EF7-NA SI Engine. Furthermore, the potential integration of Stirling and Otto cycles holds promise for unlocking up to 30% additional useful power. However, challenges related to transient response, lag time, and added weight necessitate careful consideration for widespread implementation. In summary, the synergy between thermoacoustic principles and Stirling engines presents a compelling frontier in automotive waste heat recovery, promising enhanced efficiency and reduced emissions with continued innovation and refinement [14].

9. Absorption refrigeration

Absorption refrigeration cycles offer a compelling departure from conventional vapor-compression systems, leveraging absorbent and refrigerant fluids to enhance engine efficiency through waste heat recovery. With a working principle reliant on heat rather than compressors, these cycles facilitate pre-intercooling, refrigeration, and air conditioning, thereby improving volumetric efficiency and engine performance. Caterpillar's application exemplifies their effectiveness in cooling intake air to boost power output and efficiency. Despite challenges like low coefficient of performance (COP), absorption cycles can recover up to 10% of waste heat, which is particularly beneficial in hybrid electric vehicles (HEVs), where waste heat from exhaust gases can yield an additional 8% power for cooling. Operating with low-grade energy sources and requiring minimal maintenance, absorption refrigeration cycles present an attractive avenue for enhancing engine efficiency and promoting sustainability in automotive contexts [15].

10. Conclusion

In conclusion, waste heat recovery (WHR) technologies represent a pivotal avenue for optimizing the efficiency and sustainability of internal combustion engines (ICEs) across diverse applications. From heat exchangers and turbo-compounding to bottoming cycles, thermoelectric generators, thermochemical recuperation, thermoacoustic conversion, and absorption refrigeration, a myriad of innovative approaches exist to harness and utilize wasted energy. While each technology presents its unique set of benefits and challenges, their collective impact underscores a shared goal: to maximize energy efficiency and minimize environmental impact in the automotive sector. As advancements continue to emerge and industry leaders drive innovation forward, the integration of WHR technologies into ICEs stands poised to revolutionize transportation, offering a pathway toward a more sustainable and greener future. Through collaborative efforts and continued research, the realization of more efficient and environmentally friendly ICEs appears within reach, promising to shape the future of mobility for generations to come.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

This paper does not involve data sharing since no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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