Waste Heat Recovery Systems for Improved Engine Efficiency: A review

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Abstract - *This review examines new trends in heat recovery systems (WHRS) that consistently improve engine efficiency in almost all internal combustion engines applied. The addressed survey takes into account technology aspects, namely thermoelectric generators (TEGs), organic rankine cycles (ORCs), turbo-compounding and exhaust gas recirculation (EGR) systems. A careful assessment of the benefits and drawbacks, as well as the operational effectiveness and implementation concerns for each technology, is what is carried out. Furthermore, the text highlights the cutting-edge techniques and methods directed to materials selection, system combination, and optimization. The integration of these abstracts offers a wide appeal on the recent advances in WHRS technologies and their main aim of enhancing the efficiency of engines as well as lowering emissions.*

Keywords - WHRS, Efficiency, review, TEG, ORC

1. INTRODUCTION

The significant improvements in fuel efficiency and reduced emissions, as for internal combustion engines, has caused WHRS (Waste Heat Recovery Systems) to gain unprecedented attention for the last few years. These systems prove to be a valuable means of utilising heat energy that otherwise is discharged without any use to produce power thereby compensating the overall propulsion. In this review paper, undeniably research WHRS technologies meant for different IC engines applications. Waste heat recovery systems are one of the key technologies that have got a lot of attention for improving internal combustion engine efficiencies, especially in car and industrial applications. Indeed, it is estimated that as much as 50% to 70% of the energy being produced in engines is lost in exhaust gases and cooling systems [1]. That is a huge loss, and there should thus be designs that can capture such waste heat and convert it into a useful form, perhaps mechanical or electrical energy. WHR systems with their waste heat recycling have a very good potential toward the attainment of fuel consumption reductions, reduction in greenhouse gas emissions and sustainability in consuming energy. For many years, research has been carried out in the exploration of efforts to recover and utilize waste heat, including Organic Rankine Cycles (ORC), thermoelectric generators and turbocharger by Kumar & Kanjilal [2]. The latest developments in materials, energy storage integration into a system have, therefore improved the feasibility and efficiency of such technologies. In a more future-bound global effort at emission reduction and fuel efficiency, WHR systems will become increasingly necessary. This review discusses several technologies for WHR, their implications on engine efficiency, the challenges involved in integrating these systems with existing architectures of engines, such as cost, complexity, and optimization of thermal management, among others [3].

The Organic Rankine Cycle is often wrongly named or misunderstood as the "Organic Carnot Cycle (OCC). However, the organic word itself refers to the Organic Rankine Cycle (ORC). This is a cycle based on a thermodynamic process that converts heat into work just like a standard Rankine cycle except that it uses an organic fluid, which has a much lower boiling point than water. In this case, it is more suitable to low-temperature sources of heat. Fig.1 represents schematic diagram of the organic Rankine cycle (ORC) waste heat recovery system.

Alternative fluid: Hydrocarbons, refrigerants, or silicon-based fluids rather than water. Organic fluids have a relatively low boiling point and are ideally used for low-grade geothermal, biomass, solar thermal, or waste heat sources. Low-Temperature Efficiency: ORC is tailored for low to medium-temperature applications wherein the Rankine cycle using water/steam would be inefficient.

Organic Rankine Cycle Components

Evaporator (Boiler): Working fluid is heated up by an external source, so it can get evaporated.

Expander (Turbine): High-pressure vapor expands in the expander, usually a turbine, to work by producing electricity in a generator.

Condenser: The expanded vapor then moves through the condenser where it cools down and condenses into liquid.

Pump: Liquid is pumped back to the evaporator to start again.

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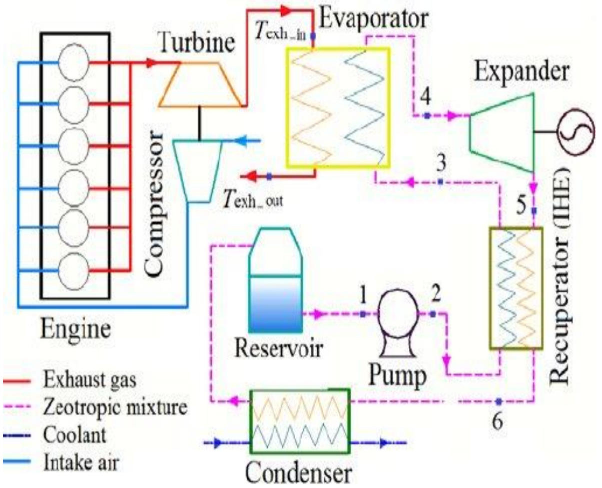

Figure 1. Schematic diagram of the organic Rankine cycle (ORC) waste heat recovery system.

2. LITERATURE REVIEW

Recovering waste heat from engine cavities (i.e., WHRS) is attracting high interest as an endeavour that may help present day internal combustion engines to be more efficient while simultaneously leading to diminution of emissions. Hundreds of technical paper-contents have been dedicated to the study of the wide kinds of WHRS technologies applied for various engine types and applications.

Thermoelectric generators (TEGs) are a widely used technology in waste heat recovery applications from engines of automobiles. Developments of TEG technology have touched various aspects ranging from material development, system integration, to optimization of performance, among others, as [4], [5] describe. Through these studies, the harnessing of exhaust gas waste heat through TEGRs can be maximized as electricity for optimized productivity in engines.

Besides TEGs, another system widely focused on in the automobile and heavy-duty vehicle industry is Organic Rankine Cycle (ORC) systems. For instance, Li et al. [6] and Wang and Liu [7] measured the performance of the ORC systems under various operating conditions such as engine and exhaust waste heat cooling. The overall efficiency of ORC systems develops by cooling the engine. In addition, Garcia et al. [8] evaluated ORC systems applied for the recovery of waste heat in heavy-duty vehicles. An important point, according to the authors, is that the efficiency of a system depends heavily on optimization during design to achieve the maximum recovery of energy from waste heat.

It also appears to be promising in regard to the problem of extractible exhaust heat in marine diesel engines. Kim and Park [9] studied the possibilities of using turbo-compounding systems for the exhaust gas energy recovery purpose to drive additional turbine whose output is transferred back into the crankshaft. In the results presented, such researchers claimed a potential of this technology for increasing the efficiency of an engine and providing savings of fuel in marine propulsion systems.

Besides the application of WHRS, EGR systems have also gained attention due to the fact that they are a means of capturing the waste heat with reducing the emissions produced by the internal combustion engines (ICE). Zhang and Li [10] analyzed EGR systems for turbocharged engines, which showed that EGR systems lower combustion temperatures and minimize heat leakage improving engine efficiency.

Therefore the review of literature has covered a wide scope of WHRS as shown in table 1 and has shown that it can be an effective tool for dramatically improving internal combustion engine operational performance and consequently emissions reduction across many engine applications. Nevertheless, the research focuses on integration, materials development, and optimization including performance testing of WHRS systems is inevitable to achieve overall successful implementation of renewable energy sources in real life situations.

Table1. Review of literature for WHRS.

Sr. No.	Title	Authors	Year	Focus	Result
1	Modelling and Evaluation of Waste Heat Recovery Systems in the Case of a Heavy-Duty Diesel Engine	A. F. M. Arif et al.[11]	2021	Modelling - Compares different WHR systems for a specific engine type	This paper compares the waste heat recovery technologies for the heavy-duty diesel engine and sees both Steam Rankine and Organic Rankine Cycles noticeably rising efficiency.
2	Impact of waste heat recovery systems on energy efficiency improvement of a heavy-duty diesel engine	Wang et al.[12]	2018	Analysis - WHR systems impact on EEDI for container ships	Investigates the impact of WHR systems on improving the Energy Efficiency Design Index (EEDI) of container ships.

3	Performance Analysis of a Waste Heat Recovery System for a Biogas Engine Using Waste Resources in an Industrial Complex	Liu et al.[13]	2023	Analysis - WHR system design for biogas engines	Analyses WHR system design for biogas engines in industrial complexes, focusing on efficiency of energy recovery.
4	Review on thermoelectric generators for waste heat recovery from internal combustion engines	Sun et al.[14]	2017	Review - Thermoelectric generators (TEGs) for WHR	Reviews the use of thermoelectric generators (TEGs) for WHR in internal combustion engines.
5	A review of organic Rankine cycle (ORC) waste heat recovery for internal combustion engine applications	Ghaebi et al. [15]	2017	Review - Organic Rankine Cycle (ORC) systems for WHR	Reviews Organic Rankine Cycle (ORC) systems for WHR in internal combustion engines.
6	Techno-economic analysis of waste heat recovery using Organic Rankine Cycles (ORCs) for engine applications	Ren et al. [16]	2020	Analysis - Techno-economic feasibility of ORC systems for WHR	Analyses the techno-economic feasibility of ORC systems for WHR in engine applications.
7	Exergetic and exergoeconomic analysis of a waste heat recovery system using organic Rankine cycle (ORC) for a heavy-duty diesel engine	Wu et al. [17]	2013	Analysis - Exergetic and exergoeconomic analysis of ORC-based WHR	Presents an exergetic and exergoeconomic analysis of an ORC-based WHR system for a heavy-duty diesel engine.
8	Waste heat recovery from spark ignition engines using thermosiphon heat pipes	Hajialigaht et al. [18]	2014	Analysis - Thermosiphon heat pipes for WHR in spark ignition engines	Investigates the use of thermosiphon heat pipes for WHR from spark ignition engines.
9	Potential of thermoelectric waste heat recovery for automotive applications	Li et al. [19]	2015	Analysis - Potential of TEGs for WHR in automotive applications	Evaluates the potential of TEGs for WHR in automotive applications.
10	A review of thermoelectric waste heat recovery: Materials, technologies, and applications	He et al. [20]	2012	Review - TEG materials, technologies, and applications for WHR	Reviews TEG materials, technologies, and applications for WHR.
11	Waste heat recovery from internal combustion engine exhaust using segmented heat pipes	Li et al. [21]	2010	Analysis - Segmented heat pipes for WHR from internal combustion engine exhaust	Studies the use of segmented heat pipes for WHR from internal combustion engine exhaust.
12	A review of exhaust heat recovery systems for automotive applications	Kitagawa et al. [22]	2006	Review - Exhaust heat recovery systems for automotive applications	Reviews exhaust heat recovery systems for automotive applications.
13	Design and optimization of a waste heat recovery system for a hybrid electric vehicle	Zhang et al. [23]	2011	Analysis - WHR system design and optimization for hybrid electric vehicles	Presents the design and optimization of a WHR system for a hybrid electric vehicle.
14	Kalina cycle for waste heat recovery from internal combustion engine exhaust	Yavuz et al. [24]	2013	Analysis - Kalina Cycle for WHR from internal combustion engine exhaust	Investigates the Kalina Cycle for WHR from internal combustion engine exhaust.

15	Economic feasibility study of waste heat recovery from a light-duty gasoline engine using an organic Rankine cycle	Oh et al. [25]	2015	Analysis - Economic feasibility of ORC-based WHR for light-duty gasoline engines	Analyses the economic feasibility of an ORC-based WHR system for a light-duty gasoline engine.

3. RESULTS AND DISCUSSION

This study provides a review on waste heat recovery systems (WHRS) for the enhanced performance of engines. The reviewed papers presented WHR technologies and applications from a variety of WHR sectors including marine, automotive, and industrial for internal combustion engines usage. The important findings include that the Organic Rankine Cycle (ORC) technology for WHR saw a rise in popularity among various engine types and fuel systems because of their excellent efficiency and scalability. Also, several studies analysed the techno-economic feasibility of WHR systems, highlighting potential fuel savings and emission reductions. Research also explored alternative WHR technologies like thermoelectric generators (TEGs) and Kalina Cycles, though these were less prevalent compared to ORCs. Specific features like WHR system design for biogas engines and flow rate measurement techniques were investigated in this study.

Despite the advancements in WHR technologies, a consistent research gap emerged across the reviewed papers: at present, no direct measurements of WHR plant operations and performance with experimental data. The majority of research aimed at simulation and analytical purposes or the introduction of some advanced existing solutions. A lack of clear lines linking potential effect to application is where there is a need for broader WHR system research.

This includes:

- Long - term performance evaluation: Research on outlined WHR systems performance and reliability over prolonged cycles with greater numbers of units and variables.
- Integration challenges: Research bringing into account WHR integration with existing engine designs and its usage of factors like weight, size, and price is to be deeply contemplated.
- Material advancements: Research and development of intelligent materials for WHR parts, especially for TERs, to enhance performance as well as to provide the ability to work at much higher temperatures.
- Optimisation and standardisation: Establishing best practices and standardised approaches for WHR system design and optimization across different engine types and applications.

4. CONCLUSIONS

WHR technology systems provide a promising route for improved engine efficiency and emission reduction. This review presented the prospects of ORC systems and discussed possible applications and technology solutions that are relevant to it. Nevertheless, a vital boundary of real-world performance data presents limits which prevent efficiently optimising and implementing WHR. Ongoing efforts in long-term testing, integration issues, materials development, and standardisation can be a stepping stone to sustainability for internal combustion engines in the future.

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