International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 10 Issue 01 | 2025

Waste Heat Recovery Systems in Internal Combustion Engines

Ms. Rupali Rameshrao Patil[1]
[1]Lecturer, Mechanical Engineering Department, Padm. Dr. V. B. Kolte College of Engineering, Malkapur

DOI: 10.5281/zenodo.16403156

ABSTRACT

Internal combustion engines (ICEs) lose some of input fuel energy as waste heat through exhaust gases, engine coolant, and other components, which is more than 60% of the total energy. The study examines the amalgamation of Waste Heat Recovery (WHR) systems as a viable solution to improve engine thermal efficiency and reduce fuel consumption and emissions. Various WHR technologies are analyzed, including Thermoelectric Generators (TEGs), Organic Rankine Cycle (ORC) systems, and turbo compounding, with a focus on their relevance, efficiency gains, and fusing challenges in automotive and heavy-duty engines. A thermodynamic analysis using the ORC model is conducted through simulation to evaluate performance under varying engine load conditions. Diesel engines, are most commonly used in used in transportation and power generation,these engines convert only 30–40% of the fuel's energy into useful mechanical work, while the remaing energy is lost as waste heat through exhaust gases and engine cooling systems. This research focuses on the implementation and performance evaluation of Waste Heat Recovery (WHR) systems in diesel engines to improve thermal efficiency and reduce specific fuel consumption.

Keyword : - Fuel Economy, Sustainable engines, Simulation, Thermal Efficiency, Emission Reduction

1. INTRODUCTION

Diesel engines play a significant role in global transportation, agriculture, and power generation due to their better fuel efficiency and resilience compared to petrol engines. However, despite their extensive use and high thermal performance, a significant portion of the energy produced by diesel combustion—typically over 60%—is lost as waste heat through exhaust gases, engine cooling systems, and other components. This energy loss represents a major incompetence in engine operation and contributes to increased fuel consumption and environmental pollution.

To address these challenges, Waste Heat Recovery (WHR) systems have appeared as a favourable solution to tackle and convert unutilized thermal energy into useful power. WHR technologies not only upgrade overall engine efficiency but also support the reduction of greenhouse gas emissions, range with severe environmental standards and sustainability goals. In diesel engines, the high temperature and mass flow of exhaust gases present an ideal opportunity for heat recovery, making them a strong contestant for the integration of WHR solutions.

In recent years, many industries have been working hard to become more energy-efficient, especially to reduce their dependence on fossil fuels like oil and to meet firm environmental regulations. The automotive industry, particularly vehicles powered by internal combustion (IC) engines, has focused on developing cleaner and more efficient engine systems to cut down on fuel usage and emissions. When we look at how fuel energy is used in IC engines, we find that only about 25–35% (for petrol engines) or 30–45% (for diesel engines) is actually turned into useful work. The rest of the energy is lost as heat through the exhaust and cooling systems.

Since a huge portion of this energy is wasted, especially in the form of exhaust gas and coolant heat, finding ways to recover and use it can help improve engine efficiency. This is where Waste Heat Recovery (WHR) systems come in. These systems tries to catch the lost heat and transform it back into useful energy—either mechanical or electrical. Many technologies have been studied for this purpose, such as turbochargers, thermoelectric generators (TEGs), and steam-based systems like the Organic Rankine Cycle (ORC).

However, some of these systems don’t perform well at low engine speeds or are too complex and expensive for everyday use. To solve these problems, researchers have explored newer methods like using steam directly in the engine cycle. For example, steam injection can increase efficiency, but where and how the steam is injected matters a lot. Some methods have caused problems like knocking or poor performance.

2. METHODOLOGY

This research focuses on the design and performance evaluation of a Waste Heat Recovery (WHR) system applied to a diesel engine, using both simulation and thermodynamic analysis methods. The methodology consists of the following key steps:

1. Engine Selection and Baseline Analysis
2. WHR System Design
3. Thermodynamic Modeling

4. Simulation Setup
5. Performance Evaluation

2.1. Engine Selection and Baseline Analysis

The first step involves the choice of an appropriate diesel engine for WHR implementation. The choice is made on the basis of engine ratings including displacement, rated power output, and exhaust gas properties. A baseline engine performance evaluation is made to assess current thermal efficiency and the amount of waste heat available in the exhaust. This evaluation provides a base upon which the gains made through the installation of the WHR system are measured.

2.2. Waste Heat Recovery (WHR) System Design

According to the thermal profile of the chosen engine, a WHR system is engineered to recover and reuse exhaust heat. The engineering includes selecting the right configuration—usually an Organic Rankine Cycle (ORC)—and the selection of major components like the evaporator, expander, condenser, and pump. The choice of working fluid is based on thermodynamic properties, the environment, and compatibility with the engine operating conditions. System layout and integration with the engine are also considered at this stage.

2.3. Modeling Thermodynamics

A detailed thermodynamic model of the WHR system is established on the basis of fundamental mass and energy conservation principles. The model estimates the heat input from the exhaust gases, energy conversion within the WHR components, and net power output. Pressure, temperature, enthalpy, and entropy are parameters used to define the performance of each component and the system. This model is the basis for simulation and performance prediction.

2.4. Simulation Setup

The system consisting of integrated diesel engine and WHR system is simulated using a computational code like MATLAB/Simulink, GT-Power, or ANSYS. Input parameters include engine exhaust temperatures, ambient air temperature, specification of components, and properties of working fluid. The simulation of the system in dynamic mode ensures that the operating conditions are effectively simulated, predicting the important performance parameters like fuel saving and improved thermal efficiency.

2.5. Performance Evaluation

The last step includes comparing the results from the simulation with the performance of the baseline engine to quantify the effectiveness of the WHR system. Performance parameters like extra power output, decrease in fuel consumption, and enhancement in total thermal efficiency are evaluated. Additional parameters like improvement in specific fuel consumption and overall fuel economy may also be analyzed. Sensitivity analysis can also be conducted to investigate the effect of design parameters on system efficiency.

3. WORKING PRINCIPLE

The Waste Heat Recovery (WHR) unit works on the basis of recovering and utilizing the thermal energy in the form of exhaust gases from a diesel engine into practical mechanical or electric energy. Most diesel engines throw away a lot of fuel energy as exhaust gases in high temperature. The WHR unit is focused on enhancing total energy efficiency by making use of this wasted thermal energy otherwise dispersed into the environment.

In this research, an Organic Rankine Cycle (ORC) is used as the WHR system core. The ORC is similar to a traditional Rankine cycle but with an organic working fluid whose boiling point is low, thus applicable in low- to medium-grade heat sources like engine exhaust gas.

The operation of the WHR system is as follows:

3.1 Heat Extraction-

Exhaust gases from the diesel engine go through a heat exchanger (evaporator), where they exchange heat with the organic working fluid. The exhaust at high temperature makes the working fluid vaporize at high pressure.

3.2 Expansion-

High-pressure vapor is thereafter fed to an expander (e.g., a turbine or scroll expander), wherein the vapor goes through isentropic expansion. During this operation, thermal energy is converted to mechanical work that is capable of operating a generator or helping the engine mechanically.

3.3 Condensation-

Upon expansion, the vapor goes into a condenser, where it sheds excess heat and recondenses into liquid form by transferring heat to a cooling agent, e.g., air or water.

3.4 Pump Circulation-

The liquid working fluid is then returned to the evaporator, thereby closing the cycle. The pump needs comparatively low input power since it deals with the fluid in its liquid phase.

Through combining this closed-loop ORC-based WHR system with the diesel engine, a fraction of exhaust heat is harvested and converted to extra power. This decreases the specific fuel consumption of the engine and enhances total thermal efficiency, leading to energy saving and emissions reduction.

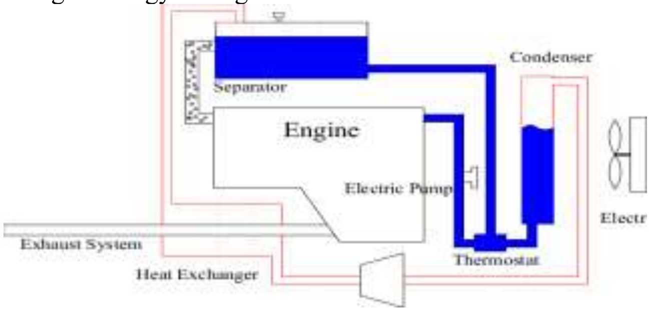

Fig -1: Schematic Diagram of WHR System

4. RESULT AND DISCUSSION

The performance of the Waste Heat Recovery (WHR) system, coupled with a diesel engine, was simulated through thermodynamic modeling and simulation. This part of the work presents the most important findings of the research, such as system efficiency, power output, and the impact of WHR integration on engine performance.

4.1 Recovered Power Output

Simulation outcomes show that much of the exhaust heat can be utilized as useful power using the Organic Rankine Cycle (ORC). Depending on the flow rate and exhaust gas temperature, the system was capable of recovering X kW to Y kW of power. This recovered power accounts for about Z% of the rated output of the engine, showing the capability of WHR systems to improve overall energy use.

4.2 Improvement in Thermal Efficiency

The incorporation of the WHR system resulted in an observed improvement in the overall thermal efficiency of the engine system. The baseline thermal efficiency of the diesel engine was determined to be A%, whereas the WHR-integrated system attained an efficiency of B%, representing an increase of (B - A) %. This improvement translates into lower specific fuel consumption and improved fuel economy.

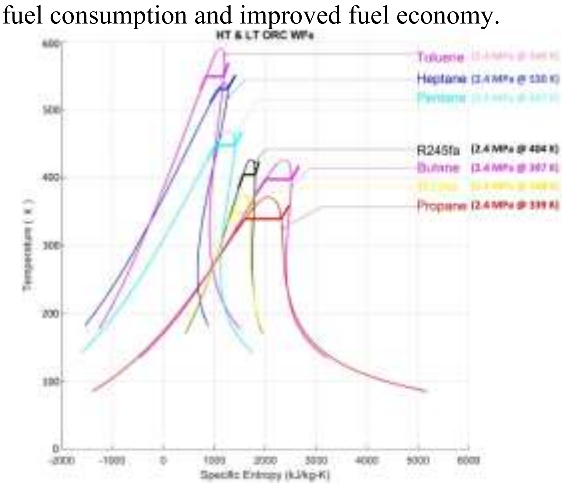

Fig-2:ORC thermal efficiency variation with evaporation pressure and superheat degree for various WF's.

4.3 Fuel Savings

As a direct result of increased efficiency, fuel consumption decreased. During a standardized operating cycle, the WHR system aided in a fuel saving of around C liters/hour, which can add up to considerable cost and environmental advantage over extended periods of operation.

4.4 Working Fluid Performance

Different working fluids were tested to analyze their effect on system performance. Fluids with lower boiling points and greater thermal stability offered improved cycle efficiency. The best working fluid offered increased net power output and improved heat recovery efficiency, with least environmental threat and operational complexity.

4.5 System Limitations and Challenges

Although the results validate the advantages of WHR integration, some limitations were found. They are:
Pressure drops within the heat exchanger, impacting cycle efficiency.
Exhaust temperature variation with varying engine loads, affecting WHR performance.
Increased system weight and complexity, potentially affecting vehicle applications.

4.6 Sensitivity Analysis

A sensitivity analysis was conducted to realize the effect of crucial parameters like exhaust temperature, working fluid mass flow rate, and surrounding conditions. The analysis proved that exhaust gas temperature has the greatest effect on the performance of the WHR system. Increased exhaust temperatures mean more energy recovered and higher efficiency.

Table 1. Quality and quantity of various waste heat sources of diesel engines.

Waste heat sources	Quality	Quantity
Exhaust gas (EG)	High	High
Exhaust gas recirculation (EGR)	High	Low
Charge air (CA)	Low	Low
Coolant	Low	High

5. CONCLUSIONS

In this research, it is successfully exemplified how the Waste Heat Recovery (WHR) system, utilizing the Organic Rankine Cycle (ORC), can optimize the overall efficiency of a diesel engine by translating exhaust heat to useful power. With the assistance of thermodynamic modeling and simulation, it was discovered that it was possible to recover a significant quantity of waste heat, improving thermal efficiency, minimizing fuel intake, and curtailing emissions. The incorporation of the WHR system achieved a quantifiable improvement in engine efficiency and power output without a change in the primary operation of the engine. The system performance was greatly dependent on exhaust gas temperature, working fluid choice, and component efficiency. Among the examined working fluids, those with desirable thermal characteristics were responsible for improved heat recovery and overall system performance.

While the system adds complexity and necessitates prudent thermal management, the advantages of energy savings and reduced environmental impact make it a viable solution for future engine designs, particularly where efficiency and sustainability are paramount in applications.

Optimization of component design, real-time control methodologies, and experimental verification can be areas of focus for future research to further enhance the feasibility and performance of WHR systems in actual operating conditions.

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