The Evaluation of Thermodynamics and Environmental Impact of Waste Heat Recovery System Using Alternative Refrigerants

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Abstract. Diesel engines play a critical role in numerous sectors due to their robustness and efficiency but contribute significantly to environmental pollution through exhaust emissions. These emissions contain substantial thermal energy, which, if not harnessed, exacerbates air quality issues and global climate change. The Organic Rankine Cycle (ORC) offers a promising solution for recovering this waste heat and converting it into mechanical or electrical power. This study conducts thermodynamic simulations using MATLAB to analyze ORC systems for diesel engine exhaust heat recovery, focusing on thermal efficiency, power generation potential, and environmental impact of different refrigerants, specifically R-141b, R-245fa, and R-123. Results indicate that ORC performance is significantly influenced by the refrigerant's critical temperature. R-141b demonstrates the highest thermal efficiency at 13.13% with a heat source temperature of 120°C but also has the highest environmental impact, contributing 3,090 kgCO2 eq/year. In contrast, R-123 shows the lowest environmental impact at 231 kgCO2 eq/year for direct TEWI and 7.73 kgCO2 eq/year for indirect TEWI, with a slightly lower thermal efficiency of 12.73%. R-245fa, with the lowest efficiency at 12.14%, also has a substantial environmental impact. This research provides insights into optimizing energy recovery from diesel engine waste heat and advancing sustainable energy solutions.

1 Introduction

Diesel engines play a pivotal role in various sectors due to their robustness and efficiency, yet they are also notable contributors to environmental challenges [1]. The exhaust gasses emitted from diesel engines contain significant thermal energy, which, if not recovered, contributes to both local air quality issues and global climate change through greenhouse gas emissions. Harnessing this waste heat presents a compelling opportunity to improve overall

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https://doi.org/10.1051/e3sconf/202560501002

energy efficiency and mitigate environmental impact by utilizing advanced technologies such as the Organic Rankine Cycle (ORC).

The ORC is a widely recognized technique for transforming low to medium-temperature waste heat into practical mechanical or electrical energy [2], [3], [4]. Operating on the same principle as the traditional Rankine Cycle but using organic fluids as the working fluid, ORC systems are particularly suitable for recovering waste heat from sources like diesel engine exhaust, where temperatures typically range from 300°C to 500°C. This cycle has garnered significant attention in recent years due to its versatility and effectiveness in various industrial and transportation applications [2].

Previous research has extensively explored the application of ORC systems for waste heat recovery from diesel engine exhaust. The Organic Rankine Cycles (ORCs) are promising technologies for energy-intensive industries, which account for 5% of global energy consumption [5]. For instance, Jones and Brown [6] investigated the integration of ORC systems with heavy-duty diesel engines, highlighting improvements in fuel efficiency and reductions in CO2 emissions by up to 10%. Additionally, Varshil P. & D. Deshmukh [7] explores waste heat recovery from internal combustion engines (ICE) utilizing the Organic Rankine Cycle (ORC). This study employs fourth-generation coolants such as Hydro Fluoro Olefin (HFO) and Hydro Fluoro Ether (HFE). Additionally, Rijpkema J. et al. [8] examined the application of the ORC system in heavy-duty trucks, demonstrating potential enhancements in engine energy efficiency and significant reductions in greenhouse gas emissions.

Despite these advances, the selection of appropriate working fluids remains a critical factor in optimizing the thermodynamic efficiency and environmental impact of ORC systems. Recent studies have highlighted the need for a deeper understanding of how alternative refrigerants, with varying thermodynamic properties, interact with the ORC cycle to influence overall system performance. This intersection of thermodynamics and environmental considerations presents a novel research opportunity: the potential to not only enhance energy recovery from diesel engine waste heat but also minimize the environmental footprint of these systems.

This paper aims to advance the current understanding of ORC systems by conducting comprehensive thermodynamic simulations that evaluate the performance of different alternative refrigerants. Using MATLAB software, the study will assess key system performance metrics, including thermal efficiency and power generation potential, alongside an environmental impact analysis of various refrigerants. The novelty of this research lies in its dual focus on thermodynamic optimization and environmental sustainability, aiming to identify refrigerants that offer both high efficiency and reduced environmental impact.

2 Methodology

2.1 Refrigerant Selection

The choice of refrigerant is crucial in ORC systems as it directly impacts system performance, efficiency, and safety. In this study, R245fa, R123, and R141b have been selected, which are commonly used refrigerants in ORC applications due to their favorable thermodynamic properties and operational characteristics, as seen in Table 1.

 https://doi.org/10.1051/e3sconf/202560501002

Table 1. Selected Refrigerant Properties

No	Parameter	R245fa	R123	R141b
1.	Critical Temp (°C)	154.01	183.7	204.2
2.	Critical Pressure (MPa)	3.651	36.62	4.240
3.	Global Warming Potential (GWP)	1030	77	725
4.	Ozone Depletion Potential (ODP)	0	0.02	0.11
5.	Safety Group	B1	B1	B1

The refrigerants selection should take into account some factors including thermodynamic characteristics (critical temperature, pressure, heat capacity), environmental impact (global warming potential, ozone depletion potential), safety (flammability, toxicity), and total equivalent warming impact. R245fa is known for its high critical temperature and good efficiency in medium to high-temperature ranges. Meanwhile, R123 and R141b have the highest critical temperature but have a small amount of ozone depletion potential.

2.2 System Description

The ORC system is a thermodynamic cycle that converts heat from a lower-temperature heat source into mechanical or electrical power. It operates on principles similar to the conventional Rankine Cycle but uses organic fluids with lower boiling points as working fluids. This research involves an ORC system with components such as an evaporator, turbine, condenser, and pump, as depicted in Figure 1.

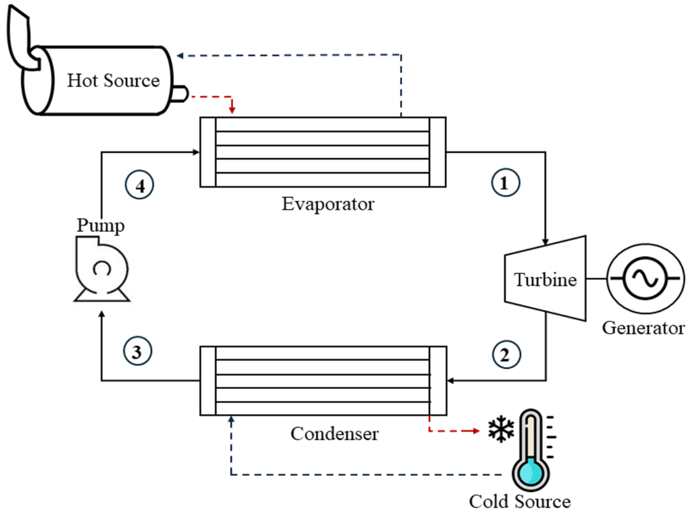

Fig. 1. ORC System

Evaporator is where heat is transferred from the hot exhaust of the diesel engine to the working fluid. In this case, exhaust from a diesel engine which is approximately 100 – 200°C heats the working fluid, causing it to vaporize and expand. This phase change extracts thermal energy from the exhaust gas, cooling it down in the process. Then, the working fluid enters the turbine. As the vapor expands through the turbine blades, it rotates the turbine shaft, generating mechanical power. This mechanical energy is then used to drive a generator to produce electricity or directly power mechanical equipment. The vapor in the condenser is cooled and condensed back into liquid form by transferring heat to a cooling medium (e.g., ambient air or water). This phase change releases latent heat energy, which is rejected to the environment. The pump circulates the liquid working fluid from the condenser back to the evaporator. The pump increases the pressure of the liquid working fluid to maintain a continuous cycle. This ensures that the working fluid can absorb heat in the evaporator and repeat the cycle efficiently.

2.3 Thermodynamics Analysis

To assess the efficiency of the ORC system in converting waste heat into usable work or electricity, performance indicators such as thermal efficiency and irreversibility are calculated. The following formulas are used to calculate the thermal efficiency and irreversibility of each system's components:

1. Evaporator

The process of heat absorption takes places when the refrigerant assimilates heat from the waste heat produced by the diesel engine. The rate at which heat is transferred in the evaporator of the ORC system is as follows:

$$Q_{evap} = \dot{m}\ (h_1\text{-}h_4) \tag{1}$$

Where, $\dot{m}$ is the refrigerant mass flow rate, h_1 is the refrigerant enthalpy at the evaporator's inlet, while h_4 represents the refrigerant's enthalpy at the evaporator's outlet.

The rate of irreversibility of the evaporator can be expressed as:

$$I_{Evap} = T_0\dot{m}\frac{(s_1-s_4)(h_1-h_4)}{T_H} \tag{2}$$

Where T_0 is the environment temperature and T_H is the heat source temperature. While s_1 and s_1 are the entropy at outlet and inlet evaporator respectively.

2. Turbine

In the turbine, the expansion of saturated steam results in the rotation of the turbine, which produces work. The power generated by the turbine is determined by:

$$\dot{W}_{Turbine} = \dot{m}\ (h_1 - h_2)\ \eta_t \tag{3}$$

Where, η_t is the turbine's efficiency, while h_1 and h_2 for enthalpy at inlet and outlet of turbine.

The rate of irreversibility for turbine is given by:

$$I_{Turbine} = T_0\dot{m}\ (s_1\text{-}s_2) \tag{4}$$

Where, s_1 and s_2 express entropy at inlet and outlet of turbine.

3. Condenser

The condenser heat transfer rate can be described as:

$$Q_{cond} = \dot{m}\ (h_2\text{-}h_3) \tag{5}$$

Where, h_2 is the refrigerant enthalpy at condenser's inlet, while h_3 is the refrigerant enthalpy at condenser's outlet.

The rate of irreversibility of the condenser can be expressed as:

$$I_{Cond} = T_0\dot{m}\frac{(s_2-s_3)(h_2-h_3)}{T_L} \tag{6}$$

Where T_L is the temperature at a cold source.

4. Pump

The refrigerant is transferred from low pressure to high pressure by a pump. The power required for the pump in ORC can be described as:

$$\dot{W}_{Pump} = \dot{m}\,(h_4 - h_3)\,\eta_p \quad (7)$$

Where, η_p is the pump's efficiency, while h_3 and h_4 express enthalpy at inlet and outlet of pump.

The rate of pump irreversibility is given by:

$$I_{Pump} = T_0\dot{m}\,(s_4\text{-}s_3) \quad (8)$$

Where, s_3 and s_4 express entropy at inlet and outlet of pump.

2.4 Environmental Analysis

To evaluate how effectively TEWI (Total Equivalent Warming Impact) analysis is a methodology used in this study to assess the total environmental impact of ORC systems, considering both direct and indirect greenhouse gas emissions throughout the entire lifecycle of the equipment. TEWI analysis is a valuable tool for policymakers, manufacturers, and consumers. It helps in making informed decisions about systems that balance performance with environmental considerations. It underscores the importance of adopting sustainable practices and technologies to mitigate climate change and reduce overall environmental footprint. TEWI analysis considers two key aspects:

a. Direct Emissions:

To evaluate the direct emission of the system, there are two aspects that need to be considered: refrigerant leakage and refrigerant charge. Direct emissions occur during the operation of the equipment when refrigerants leak into the atmosphere. Refrigerants have varying Global Warming Potentials (GWPs), which measure their relative impact on global warming compared to CO_2 over a specific time frame (typically 100 years). While Refrigerant Charge represents the amount of refrigerant contained within the system that directly influences direct emissions. Systems with higher refrigerant charges typically have a greater potential for emissions.

Direct TEWI accounts for emissions directly associated with refrigerant leakage during operation. It is calculated using the formula [9]:

$$TEWIdirect = GWP \times L \times N \quad (9)$$

Where,

GWP = Global Warming Potential of refrigerant (unitless, relative to CO_2)
L = Annual leakage rate of refrigerant ii (in kg/year)
N = system duration (year)

b. Indirect Emissions:

Indirect emissions includes electricity usage for compressors, fans, pumps, and other components. And the environmental impact of indirect emissions depends on the source of the electricity used (e.g., fossil fuels versus renewable energy sources).

Indirect TEWI accounts for emissions from energy consumption during operation. It is calculated as:

$$TEWIindirect = Ea\ \beta\ n \tag{10}$$

Where, Ea = Energy consumption (KWh/year)
ββ= CO_2 emission factor (0.483 kg CO_2/KWh)
nn = System operational time in one year
The total TEWI combines both direct and indirect impacts to provide a comprehensive assessment of the system's environmental impact:

$$TEWI = direct\ emissions + indirect\ emissions = (GWP \times L \times N) + (Ea\ \beta\ n) \tag{11}$$

2.5 Designs and Simulation

The most important parameter to be adjusted is the exhaust gas temperature from diesel engines. This temperature typically varies depending on engine load, fuel type, and operating conditions. In this study, the exhaust gas temperatures range from 100°C to 200°C, covering a spectrum of heat sources commonly encountered in diesel engine applications:

- 110°C: Represents lower operating loads or conditions where the engine is not under heavy stress. This temperature range is relevant for light-duty diesel engines or during idle or low-speed operation.
- 130°C to 150°C: Typical temperatures during normal operating conditions of medium-duty diesel engines in various industrial and transportation applications. These temperatures reflect moderate to medium engine loads.
- 170°C to 190°C: Represents higher exhaust gas temperatures observed under heavy-duty or high-load conditions. This range is common in heavy-duty diesel engines used in construction equipment, trucks, and power generation applications.

Thus, the system is estimated to have the hot source temperature which is from diesel exhaust ranging from 100°C to 200°C.

Table 2. Operating Conditions

No.	Parameter	Value
1.	Heat source temperature (°C)	100-200
2.	Massflowrate (kg/s)	1
3.	Turbine isentropic efficiency (%)	85
4.	Pump isentropic efficiency (%)	80
5.	Condenser temperature (°C)	35
6.	Cooling water temperature (°C)	25

Simulation software, MATLAB is used to model the thermodynamic behavior of the ORC system. This includes developing mathematical models based on thermodynamic principles to simulate system performance. In addition, this study also carried out parametric studies, which conduct sensitivity analyses to evaluate the impact of varying heat source temperatures and different refrigerants on system performance. This helps in optimizing operational parameters to achieve maximum efficiency under different operating conditions.

3 Results and Discussions

 https://doi.org/10.1051/e3sconf/202560501002

3.1 Performance Evaluations

Refrigerant and operating conditions are key parameters which reflect the performance of ORC system. Figure 2 illustrates how system thermal efficiency varies with heat source temperature. It shows that as the temperature of the heat source increases, the thermal efficiency of the cycle also rises. This trend is consistent for all refrigerants, indicating that a higher heat source temperature raises the demand for evaporator heat and net power output, thus enhancing the overall thermal efficiency of the cycle. Additionally, Figure 2 highlights that R-141b achieves the highest thermal efficiency and can performed well at higher operating temperature (up to 200ºC). The results reveal that R-141b which has a critical temperature of 204.5°C, performs optimally at higher heat source temperatures approaching 200°C.

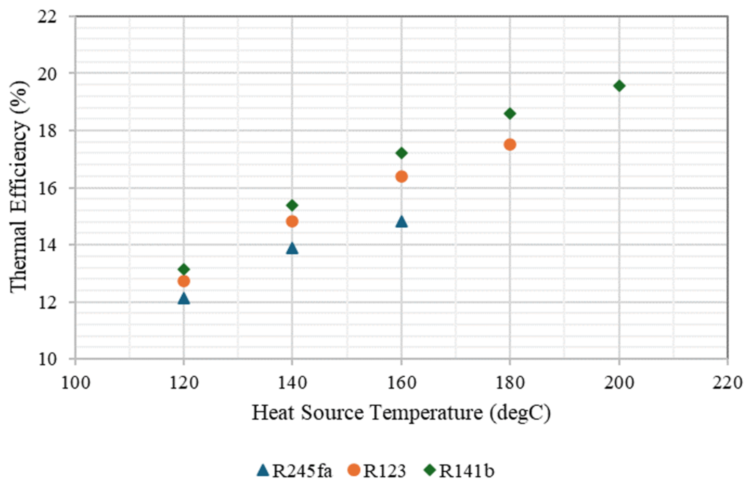

Fig 2. Impact of Heat Source Temperature on the System's Thermal Efficiency

The ORC system using R-141b exhibits an increase in efficiency ranging from 13.13% to 19.56% for the lowest and highest heat source temperatures, respectively. In contrast, R-245fa shows an efficiency increase of 12.14% to 14.83% for the same temperature range. Figure 3 shows that the thermal efficiency of the ORC is linked to the critical temperature of each refrigerant. The data indicates that R-141b has the highest critical temperature at 204.5°C, whereas R-245fa has the lowest at 154.01°C among the refrigerants examined. Sakinah [10] found that while various refrigerant properties minimally affect the thermal efficiency of the Organic Rankine Cycle, the critical temperature has a notable impact. Higher critical temperatures in refrigerants are strongly associated with improved system thermal efficiency.

Figure 3 depicts the relationship between the net power output of selected refrigerants and the heat source temperature. Similar to the previous trend, the net power output increases linearly with the rise in heat source temperature. Performance is notably enhanced when the heat source temperature approaches the refrigerant's critical point. It was found that R123 and R245fa consistently produced nearly the same amount of net power output with the lowest net power across all heat source temperatures, compared to R141b.

Based on the evaluation of both thermal efficiency and turbine work, under the same operating conditions, R245fa has the lowest thermal efficiency compared to the other three refrigerants, and R141b has the highest thermal efficiency at 13.13%, followed by R123 at 12.73%, and R245fa at 12.14% under operating conditions where the heat source temperature is 120°C.

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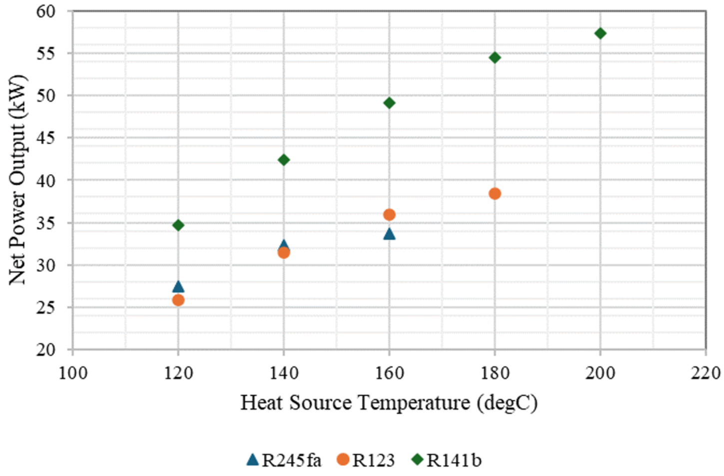

Fig 3. Effect of net power output with heat source temperature

Figure 4 illustrates the irreversibility of each system component. The refrigerant and operating conditions impact both irreversibility and efficiency, making it essential to select these factors carefully to achieve optimal system performance. As shown in Figure xx, the condenser exhibits the highest irreversibility, followed by the evaporator, turbine, and pump. The condenser contributes to 35% of the total system irreversibility, whereas the pump has the lowest, accounting for only 0.2%.

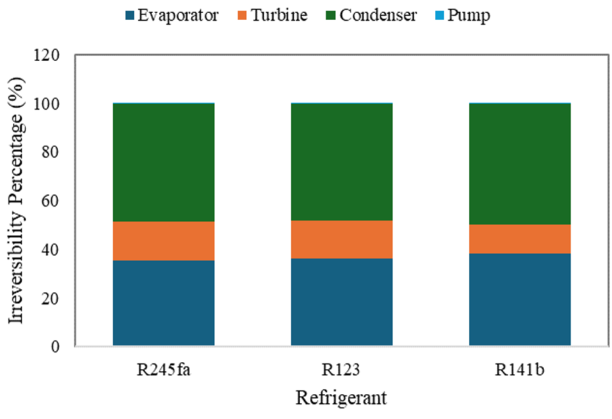

Fig 4. Irreversibility distribution of ORC at heat source temperature

Generally, most sources of irreversibility are tied to entropy, which is associated with flow and heat transfer. In the cycles, the components with significant irreversibility are the heat exchangers. This pattern is consistent across all heat source temperature variations. Typically, the evaporator experiences subcooled, evaporating, and superheated zones. Thus, the evaporator has the higher irreversibility.

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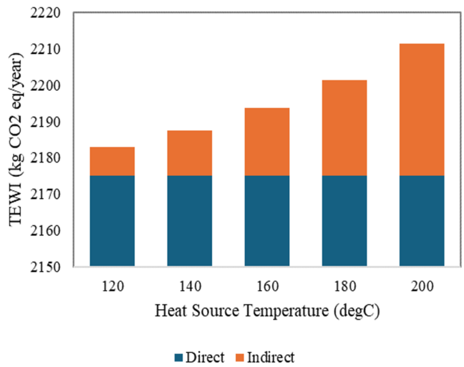
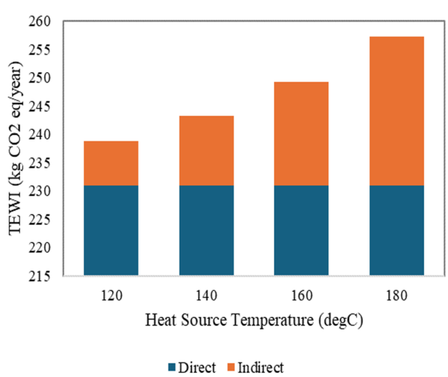
3.2 Environmental Impact Evaluation

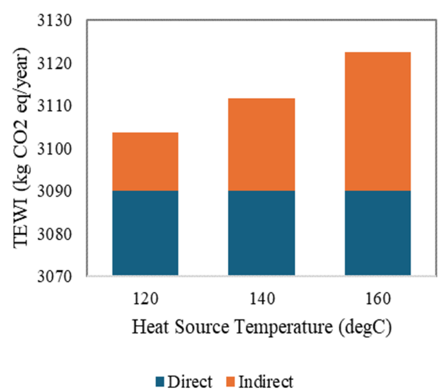
In addition, the environmental impact of each refrigerant is also investigated. The result from TEWI calculations is shown in Figure 5.



(a)



(b)



(c)

Fig 5. Total Equivalent Warming Impact (TEWI) for Each Refrigerants: (a) R141b (b) R123 (c) R245fa

Refrigerants are recognized for their environmental impact, encompassing both direct and indirect contributions. Based on calculations as seen in Figure 5, R245fa exhibits the highest direct contribution, amounting to 3090 $kgCO_2$ eq/year. This implies that if R245fa is employed in an ORC system, it would result in a negative environmental impact 3090 times greater than the other three refrigerants. In contrast, R123 presents the smallest direct contribution at 231 $kgCO_2$ eq/year. Regarding indirect environmental impact, R245fa again shows the highest contribution at 13.65 $kgCO_2$ eq/year, whereas R123 has the lowest value at 7.73 $kgCO_2$ eq/year.

4 Conclusions

This research explored the ORC performance for heat recovery, utilizing refrigerants: R-141b, R-245fa, and R-123. The key to enhancing performance lies in the critical temperature of each refrigerant; R141b demonstrates superior performance, while R245fa exhibits lower performance. The evaporator is the primary source of irreversibility in the ORC system. With a heat source temperature of 120°C, by using R141b, the ORC reaches a maximum thermal efficiency of 13.13%, but with also a high value of environmental impact which accounts for 3090 kgCO_2 eq/year. Among the refrigerants evaluated, R141b has the highest thermal efficiency but with high environmental impact, while R245fa and R123 result in the lowest efficiency which is about 12.14% and 12.73% respectively. But R123 has minimum impact for the environment, which is about 231 kgCO_2eq/year for direct TEWI and 7.73 kgCO_2eq/year for indirect TEWI. This study also reveals that increasing the heat source temperature enhances the thermal efficiency of the ORC and also increases their environmental impact.

The author expresses gratitude to Universitas Gadjah Mada for supporting and funding this research with the Academic Excellence Scheme C grant in 2024.

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