Thermodynamic Analysis of Organic Rankine Cycle for Waste Heat Recovery at Sorong Power Plant

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Abstract. Indonesia remains highly dependent on fossil fuels and non-renewable energy sources, which contribute to global warming. On the other hand, the country has yet to fully develop waste heat utilization, especially through organic Rankine cycle (ORC) systems, to help reduce reliance on fossil fuels. Take an example, Sorong Gas Engine Power Plant uses diesel engine in which the exhaust gas can produce up to 369°C of flue gas which get released directly into the atmosphere. This paper presents a thermodynamic calculation and analysis of Organic Rankine Cycle using waste heat from the exhaust gas. This paper includes calculation of the net power output, thermal efficiency, mass flow rate among several choices of refrigerant. Among 20 refrigerants available in Indonesia, R600 offers zero ODP, GWP number of 4, and the lowest refrigerant mass flow rate that can reach up to 13% of Rankine system efficiency. These factors provide valuable strong starting points in designing ORC using waste heat recovery promoting sustainable energy for communities

Keywords: Thermodynamic, Organic rankine cycle; Waste heat; Flue gas; Power plant.

1 INTRODUCTION

In recent decades, energy consumption has surged significantly due to technological advancements and rapid economic growth. This increase has driven higher fossil fuel usage, leading to environmental problems like air pollution, global warming, and ozone layer depletion [1].

Governments, industries, academic institutions, and other stakeholders globally, in both developed and developing nations, have adopted strategies to promote the shift toward a low-emission, environmentally sustainable society. Likewise, the Indonesian

M. A. Muflikhun et al. (eds.), *Proceedings of the 10th International Conference on Science and Technology (ICST 2024)*, Advances in Engineering Research 268,
https://doi.org/10.2991/978-94-6463-772-4_4

government has enacted policies aimed at reducing carbon emissions, including a commitment to reach net zero emissions by 2060 and gradually eliminate the use of fossil fuels [2].

Indonesia is rich in geothermal energy resources, providing a clean and renewable power source. This energy, which is naturally generated and stored as heat beneath the Earth's surface, produces significantly lower greenhouse gas emissions compared to fossil fuels. It is estimated that Indonesia holds about 40% of the world's geothermal energy reserves [3], making it the country with the largest reserves worldwide. The majority of these reserves are located in western Indonesia, particularly in regions such as Sumatra, Java, and Bali, where energy demand is notably high.

Despite Indonesia's significant reserves, their utilization has not been fully optimized. An example, Sorong gas engine power plant has five gas engines in which the engine can produce up to 369°C of exhaust gas per engine. With the high temperature of the flue gas in the engine exhaust, waste heat energy can be reused for various purposes, including electricity generation using Organic Rankine Cycle (ORC) technology.

To recover waste heat from flue gas of gas engine power plant. The ORC system operates by utilizing low grade heat from the exhaust gases, which would otherwise be lost, to generate electricity. This process enhances the overall energy efficiency of the power plant. implementing ORC in a gas engine power plant maximizes the use of exhaust heat, improving the efficiency, reducing emissions, and offering an economical way to increase power output without extra fuel consumption.

This paper aims to conduct a preliminary assessment of the net power output produced by an Organic Rankine Cycle (ORC) system that leverages the waste heat potential from the Sorong gas engine power plant. The goal of this system is to effectively convert low-grade heat sources into electricity. The research utilizes a mathematical framework based on the

thermodynamic principles of the ORC cycle to determine the flue gas flow, refrigerant flow, thermal efficiency of the system, and ultimately the net power output. Furthermore, the selection of the working fluid is analysed in terms of its availability within the country and its thermal and transport properties, as these elements are crucial for optimizing the heat transfer process in the system [4], [5] and their environmental aspects like Ozone Depletion Potential (ODP) and Global Warming Potential (GWP).

2 METHODOLOGY

2.1 Cycle Description

The Organic Rankine Cycle (ORC) is a thermodynamic process designed to convert low-temperature heat sources into electrical energy. It is particularly useful in scenarios where high-temperature steam is not available, such as in geothermal power plants, waste heat recovery systems, and solar thermal applications. Similar to the conventional Rankine cycle used in steam power plants, the ORC utilizes organic fluids with lower boiling points rather than water. These fluids, which may include refrigerants or hydrocarbons, enhance heat transfer at lower temperatures and pressures, thus improving the efficiency of energy conversion within ORC systems. The ORC cycle is typically represented on a temperature-entropy diagram, as illustrated in Figure 1.

The ORC process starts with the working fluid being pumped to a heat exchanger (state 2 – 1), where it collects heat from a low-temperature source, such as waste heat from an industrial process, in the preheater (state 2 – 3). As the fluid absorbs heat, it vaporizes in the evaporator (state 3 – 4) and then expands through a turbine (state 4 – 5s), generating mechanical power as it drives the turbine. Once the vapor exits the turbine, it is condensed back into a liquid form in a separate heat exchanger called the condenser, releasing heat that can be dissipated or repurposed for other uses (state 5s – 1). The liquid is then pumped back to the heat exchanger, allowing the cycle to begin anew.

The key benefit of the ORC system is its ability to produce electricity from low-temperature heat sources that would otherwise go unused. By tapping into these often-overlooked renewable or waste heat sources, the ORC improves energy efficiency and helps cut greenhouse gas emissions. Additionally, the use of organic fluids with minimal global warming and ozone depletion potential makes the ORC an eco-friendly option for energy conversion. In summary, the organic Rankine cycle is a flexible and efficient method for generating electricity from low-temperature heat, offering a sustainable solution for power generation and waste heat recovery across a range of applications.

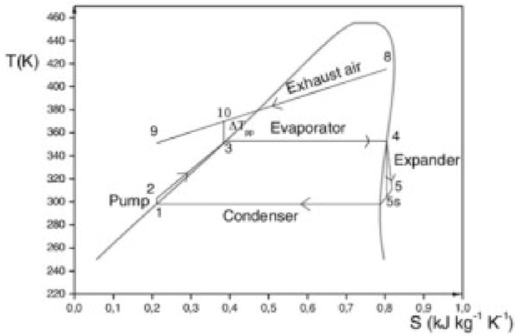

Fig. 1. Typical T-s diagram of ORC system.

2.2 Working Fluid Selections

Unlike traditional Rankine cycle that use water or specifically steam as a working fluid, organic Rankine Cycle (ORC) use refrigerant instead as working fluid. The source of heat can be waste heat from all type of power plants, geothermal with relatively low heat temperature, and waste heat from industrial process. To identify a suitable working fluid that can be used for ORC, the working fluids should be fit with the temperature from the waste heat. The refrigerant candidates in this paper are presented in Table 1.

Table 1. Comparison between present work and literature.

No	Refrigerant	Refrigerant Type	GWP	ODP
1	R600	HC	4	0
2	R600a	HC	3	0
3	R245fa	HFC	1030	0

Refrigerants are ideal working fluids in ORC systems because of their relatively low critical temperature and pressure, allowing them to effectively absorb low-grade heatfrom waste sources. These refrigerants can be categorized into three main types: dry, wet, and isentropic, with each category fulfilling a specific role based on its adiabatic behaviour during turbine expansion. In the selection process, it is crucial to evaluate the properties of the working fluids, focusing on their thermophysical characteristics such as pressure, temperature, specific volume, latent heat, flash point, specific heat, and thermal conductivity. The critical temperature and pressure of the selected fluid should align with the temperature of the heat source. Two key environmental considerations when selecting a refrigerant for ORC applications are Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). GWP measures the potential of a refrigerant to trap heat in the atmosphere, contributing to global warming over a specified time period (usually 100 years). Lower GWP values are preferable to minimize the environmental impact. ODP quantifies the refrigerant's potential to destroy the ozone layer. Refrigerants with high ODP, such as CFCs and HCFCs, have been phased out or are being restricted due to their harmful effects on the ozone layer. Selecting refrigerants with low GWP and zero ODP is crucial to minimizing the environmental footprint of ORC systems and ensuring compliance with global environmental protocols.

2.3 Mathematical Equations

Designing ORC cycle system is developed after base cycle parameters is determined. To determine these parameters, calculation using thermodynamic principles is nece sary. These are formulas which are used to determine those parameters needed.

Pump work is calculated as,

$$\dot{W}_{pump} = \dot{m}_{ref}(h_2 - h_1) \tag{1}$$

Turbine work is defined as,

$$\dot{W}_{turbine} = \dot{m}_{ref}(h_3 - h_4) \tag{2}$$

The heat transfer required for the evaporator is calculated as,

$$\dot{Q}_{eva} = \dot{m}_{ref}(h_3 - h_2) \tag{3}$$

The heat transfer released from the flue gas is expressed as,

$$\dot{Q}_{fg} = \dot{m}_{fg} \times CP_{fg}(T_8 - T_9) \tag{4}$$

Heat transfer required for the preheater is defined as,

$$\dot{Q}_{ph} = \dot{m}_{ref} \times CP_{ref}(T_3 - T_2) \tag{5}$$

The heat transfer of preheater flue gas is expressed as,

$$\dot{Q}_{phfg} = \dot{m}_{fg} \times CP_{fg}(T_{10} - T_9) \tag{6}$$

The energy balance at preheater is shown by,

$$\dot{Q}_{ph} = \dot{Q}_{phfg} \tag{7}$$

And the mass flow rate of the flue gas calculated by,

$$\dot{m}_{fg} = \rho \times A \times v \quad (8)$$

The net power in this ORC system is calculated as,

$$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump} \quad (9)$$

The overall efficiency of the system is calculated as,

$$\eta_r = \frac{\dot{W}_{net}}{Q_{fg}} \quad (10)$$

3 RESULT AND DISCUSSION

In this calculation, T_8 the inlet flue gas temperature was set at 363°C meanwhile T_9, the outlet of flue gas temperature was set at 54°C, As for the number of T_8 were obtained from data taken on July 2024. T_9 obtained from the water saturation temperature at a partial pressure of 15.116 kPa. T_3, temperature of evaporator is varied from 100°C up to130°C with an increment of 5°C for each variation. This method of calculation is used to decide the best performance of each refrigerant at certain temperature. As for the heat transfer released from the flue gas will always has the same value of 2291 kW.

3.1 Pump Work

Figure 2 provides data of pump work using refrigerant R600, R600a, and R245fa in the Organic Rankine Cycle. After examining the data, pump's work tends to increase with the rising temperature. It shows that using refrigerant R600a has the largest pump work varies between 20.93 kW to 44.56 kW depending on the temperature. Meanwhile pump operation using refrigerant R245fa has the lowest number varies between 10.09 kW to 19.97 kW. The pump performance using refrigerant R600 is positioned between refrigerant R245fa and refrigerant R600a varies between 14.07 kW to 26.98 kW. A higher pump work typically meaning higher energy usage in which can reduce the overall efficiency of the system.

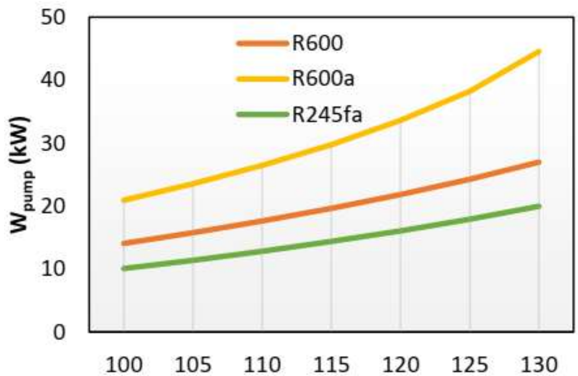

Fig. 2. Pump work for different refrigerant.

3.2 Turbine Work

Figure 3 illustrates the turbine performance for three refrigerants, R600, R600a, and R245fa with varying temperatures. For all three refrigerants, turbine work increases as the evaporator temperature rises from 100°C to 130°C. This is a typical result since higher temperatures generally lead to greater energy input to the system, allowing the turbine to generate more work.

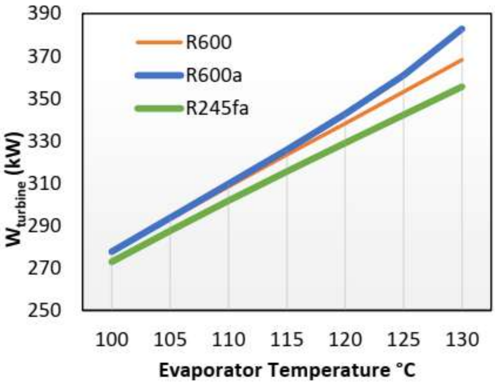

Fig. 3. Turbine work for different refrigerant.

Analysing the data, it is apparent that the turbine performance between three refri erants is not much different. R600 shows the highest turbine work at all temperature levels, starting from 277.7 kW at 100°C and reaching 382.8 kW at 130°C. This ind cates that R600 is the most effective at converting thermal energy into mechanical work in the temperature range tested. R600a follows closely behind R600, with slightly lower turbine work values, starting at 277.6 kW at 100°C and reaching 368.2 kW at 130°C. It performs similarly to R600 but with a slight reduction in efficiency. R245fa exhibits the lowest turbine work among the three, starting at 272.9 kW at 100°C and reaching 355.5 kW at 130°C. This refrigerant has consistently lower work output, suggesting it is less effective in this particular temperature range compared to R600 and R600a. Tu bine work output change following the temperature increase form 100°C to 130°C because it will also increase the enthalpy in the evaporator. The turbine performance along with pump performance is a crucial parameter in Organic Rankine Cycle as it directly affects the system's overall performance as well as the system's efficiency. The larger the turbine work and the smaller the pump work, the better the overall performance and system efficiency.

3.3 Heat Transfer of the Condenser

Figure 4 compares the value heat rejection from the condenser using different refrigerants. R600a has the highest Q' Condenser values as the evaporator temperature increases, especially above 115°C. This suggests that R600a requires more heat rejection at higher temperatures, which may negatively affect system efficiency as more energy is dissipated as waste heat. R600 has the most consistent heat rejection across the temperature range, showing stability in its thermal behaviour. This suggests that R600 maintains a balanced and efficient heat rejection profile, making it a more stable choice in systems where temperature changes are common. R245fa shows the lowest heat rejection overall, with a slight decline as temperature increases, indicating it might be more efficient in managing the heat load at higher evaporator temperatures.

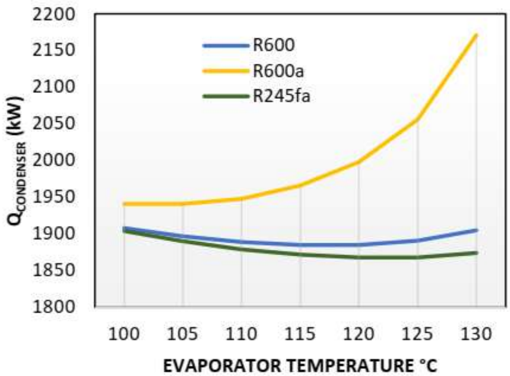

Fig. 4. Heat rejection of condenser using different refrigerants.

Upon analysing the data, we find that for applications where consistent and stable performance is required, R600 seems to offer the best balance, with minimal variation in heat rejection. R600a may be less efficient at higher temperatures due to its increasing heat rejection, which could place more demand on the condenser. R245fa appears to be more efficient in managing heat rejection at higher temperatures, though it shows slight instability in heat rejection as the temperature changes.

3.4 Refrigerant Mass Flow Rate

Figure 5 provides data for different working mass flow rate of three refrigerants on several evaporator temperatures. Starting with R600, this refrigerant maintains a nearly constant mass flow rate throughout the entire temperature range. At 100°C, the mass flow rate is 5.446 KG/s, and at 130°C, it changes only slightly to 5.437 KG/s. The very small variation indicates that R600 is relatively unaffected by changes in evaporator temperature. This suggests that R600 has a stable flow behavior, with minimal sensitivity to temperature fluctuations. Its near-constant mass flow rate means that systems using R600 can expect consistent performance over a broad range of temperatures. In contrast, R600a demonstrates a clear increase in mass flow rate as the evaporator temperature rises. At 100°C, the mass flow rate starts at 5.391 KG/s, and it climbs steadily, reaching 6.837 KG/s at 130°C. This suggests that R600a is much more sensitive to changes in temperature compared to R600. As the temperature increases, the mass flow rate rises significantly, indicating that R600a is responsive to thermal changes. This property could be useful in applications where a higher mass flow rate is needed at elevated temperatures, as the refrigerant adjusts its flow rate according to the system's thermal demands. Finally, R245fa, represented by the orange line, has the highest mass flow rate among the three refrigerants, but like R600, it remains relatively stable over the temperature range. At 100°C, the mass flow rate is 10.33 KG/s, and at 130°C, it decreases slightly to 10.17 KG/s.

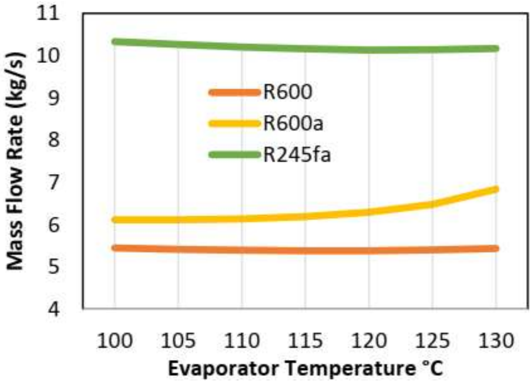

Fig. 5. Refrigerant mass flow rate for different evaporator temperatures.

It's important to recognize that higher mass flow rates may necessitate larger equipment and components, which could influence the cost and practicality of the ORC (Organic Rankine Cycle) system. Conversely, lower mass flow rates might lead to a more compact system design, but they could also restrict power output and reduce the overall efficiency of the ORC. Selecting the ideal refrigerant and its associated mass flow rate for an ORC system requires careful consideration of various factors, such as the temperatures of the heat source and sink, system efficiency, the properties of the working fluid, safety concerns, and economic viability.

3.5 Net Power Output

Figure 6 shows the net power output of Organic Rankine Cycle using three different refrigerants at varies evaporator temperature. Net power output is one of the most important parameters to see if Organic Rankine Cycle is viable to be created. Net Power itself depends on the value pump work and turbine work.

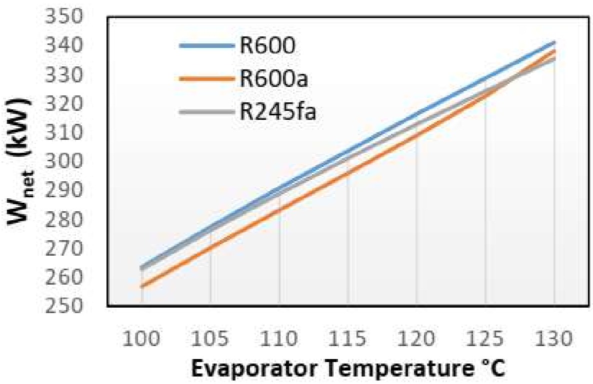

Fig. 6. Heat rejection of condenser using different refrigerants.

Analysing the data, it is apparent that R600 consistently delivers the highest net power output across the temperature range. At the lowest temperature of 100°C, R600 generates a power output of 262.8 kW, and by 130°C, this value increases to 341.2 kW. R600a starts with the lowest net power output at 100°C, producing 256.8 kW. However, like the other refrigerants, R600a's net power output increases steadily as the temperature rises, reaching 338.2 kW at 130°C. Although R600a consistently delivers slightly less power compared to R600, the difference is relatively small. Meanwhile R245fa starts with a power output of 263.5 kW at 100°C. This makes it initially more powerful than R600a at lower temperatures. However, as the temperature increases, R245fa's performance lags slightly behind the other two refrigerants. At 130°C, its net power output is 335.5 kW, making it the least efficient at the highest temperature in the comparison.

3.6 Thermal Efficiency

Figure 7 shows the overall thermal efficiency of the system based on different refrigerants. Thermal Efficiency along with the net power output can be the main parameters to determine whether an Organic Rankine Cycle is feasible to build or not. The efficiencies of each refrigerant in the Rankine cycle are represented as percentages. These efficiency values indicate the fraction of thermal energy that the refrigerant can successfully convert into mechanical work within the cycle. A higher efficiency percentage signifies a more effective transformation of heat energy into usable work, resulting in enhanced power generation.

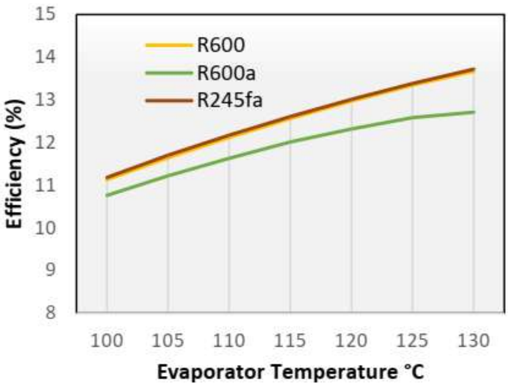

Fig. 7. Thermal efficiency of the ORC using different refrigerants.

Starting with R600, its efficiency increases steadily as the evaporator temperature rises. At 100°C, R600 has an efficiency of 11.13%, and this gradually increases to 13.67% at 130°C. R600a shows the most pronounced increase in efficiency as temperature rises. At 100°C, R600a has an efficiency of 10.76%, which is the lowest among the three refrigerants at this point. However, as the temperature increases, R600a's efficiency quickly improves, reaching 13.72% at 130°C. In contrast, R245fa starts with a relatively high efficiency of 11.18% at 100°C, placing it ahead of R600 and R600a at the lower temperature range. However, its efficiency increase is less dramatic compared to the other two refrigerants. By 130°C, R245fa's efficiency reaches 12.71%, which is lower than both R600 and R600a at this point.

4 CONCLUSION

This paper examines various refrigerants utilized in the Organic Rankine Cycle (ORC) and offers important insights for choosing the most suitable working fluid to achieve optimal performance and efficiency. Pump work increases as the temperature rises. Among the refrigerants, R600a has the highest pump work (20.93 kW to 44.56 kW), followed by R600 (14.07 kW to 26.98 kW), while R245fa has the lowest (10.09 kW to 19.97 kW). Greater pump work leads to higher energy consumption, which lowers overall efficiency. As temperatures increase from 100°C to 130°C, turbine work also rises for all refrigerants. R600 achieves the highest turbine work (277.7 kW to 382.8 kW), followed closely by R600a (277.6 kW to 368.2 kW), with R245fa producing the lowest turbine work (272.9 kW to 355.5 kW). This suggests that R600 is the most efficient at converting thermal energy into mechanical work.

R600a requires the most heat rejection at higher temperatures, which could reduce system efficiency. R600 shows stable and consistent heat rejection, while R245fa has the lowest heat rejection and performs better at managing heat loads at elevated temperatures. R600 maintains a nearly constant mass flowrate across the temperature range, indicating stable performance. In contrast, R600a's mass flow rate increases significantly with temperature, while R245fa has the highest but more stable mass flow rate, which could impact equipment size and cost.

In terms of net power output, R600 consistently produces the highest values (262.8 kW to 341.2 kW), followed by R245fa and R600a, which deliver similar outputs with slight variations across temperatures. Both R600 and R600a experience notable efficiency improvements as the temperature rises, with R600a reaching the highest efficiency at 130°C (13.72%). R245fa starts with a higher efficiency at lower temperatures but falls behind as the temperature increases, with 12.71% efficiency at 130°C.

In summary, R600 offers the best overall balance in terms of performance, stability, and efficiency, while R600a is more responsive to temperature changes, and R245fa performs better at lower temperatures but loses efficiency at higher ones. R600 selected as a favourable option for the ORC system because R600 offers the best overall balance in terms of performance, stability, and efficiency with highest network output, high thermal efficiency and lowest mass flow rate.

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