Low Emission Power Plant Design Using R134a as Working Fluid

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Low Emission Power Plant Design Using R134a as Working Fluid Instead of Fossil Fuel to Mitigate Greenhouse Gas Effect

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ABSTRACT

This study investigates the potential of using R134a as a working fluid in a low-emission power plant instead of the conventional power plant to mitigate the greenhouse effect. The study explores the thermodynamic properties of R134a and its suitability for use in an Organic Rankine Cycle (ORC) power plant. A simulation model was developed using Aspen Hysys to evaluate the power plant's performance using this working fluid. The results indicate that the ORC power plant can significantly reduce greenhouse gas emissions compared to conventional power plants while maintaining high energy efficiency. About 18.17 kW of electric power can be obtained at a working condition of 10 bar and an evaporator temperature of 130 ºC with the highest thermal efficiency of 3.43%. The study provides valuable insights into the potential of R134a as a sustainable working fluid for low-emission power generation.

Keywords: low-emission, waste thermal, Aspen Hysys, R134a, greenhouse gas emissions, organic Rankine cycle, thermal efficiency.

INTRODUCTION

Global warming refers to the long-term increase in the ambient temperature primarily due to human activities that release greenhouse gases into the atmosphere (Hosseini, 2022). These greenhouse gases trap heat in the atmosphere, causing the earth's temperature to rise, which has various negative impacts on the environment and human well-being, which leads to the cause of death factors (Agius et al., 2021)

The primary greenhouse gases responsible for global warming include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases are released into the atmosphere through various human activities, including burning fossil fuels for energy, deforestation, and industrial processes. The burning of fossil fuels for energy production is the main cause of the greenhouse effect, for example, in Bangladesh, an amount of 0.90 kg CO2/kWh is produced from power plants coal-based (Karmaker et al. 2020).

To mitigate global warming, it is essential to reduce greenhouse gas emissions by transitioning to renewable energy sources, such as wind, hydroelectric power plants, and solar power, improving energy efficiency, and implementing policies that support sustainable practices. Biomass is also known as a low-emission energy source and is even called zero emission. In

Indonesia, biomass power plants (PLTBm) have grown rapidly in the past 5 years, utilizing a variety of waste resources such as palm shells, rice husk, corncob, bagasse, bamboo, sawdust, and off-cut furniture wood (Simanjuntak et al., 2022). In addition, Indonesia also has the potential to obtain energy from biomass through the gasification process (Simanjuntak et al., 2018).

However, the utilization of biomass gasification technology is still very limited, while direct biomass combustion in boilers is still the dominant method for waste conversion into electricity.

For this reason, researchers continue to improve the performance of biomass combustion incinerators, because, theoretically that the high performance of incinerator lead to a decrease the emission. Increasing the incinerator performance can be done by increasing the air distribution in the combustor zone. Introducing an internal air plenum to equally distribute the required air for combustion leads to improve significantly the incinerator's performance (Simanjuntak et al., 2021).

Another way is energy diversification, which is to develop power plants that utilize wasted thermal energy. This can be done by utilizing a thermal energy absorption system and converting it into electrical energy. Usually, the working fluid used is refrigerant, that do not release greenhouse gases into the atmosphere. Simple energy storage has been thermally designed by researchers. By using water as a medium, a thermal design has been carried out and can be used as a means of storing thermal energy (Simanjuntak et al., 2021).

The method of differentiating energy by utilizing wasted energy has begun to be developed today. Wasted energy ranging from low to highest levels can be used to generate electrical energy. For this reason, a working fluid is used that must meet the requirements that are friendly to the environment. One of them is refrigerant (Escalante et al., 2022).

Refrigerants are categorized as low-emission fluids when used as working fluids in Organic Rankine Cycle (ORC) power plants due to their relatively low global warming potential (GWP) and ozone depletion potential (ODP) compared to traditional refrigerants like CFCs and HCFCs. The use of low-emission refrigerants in ORC systems helps to reduce the overall environmental impact of the power plant by minimizing greenhouse gas emissions and other harmful pollutants. In addition, ORC systems can use waste heat from industrial processes, geothermal sources, or solar thermal collectors to generate electricity with high efficiency and low emissions.

R134a is a common refrigerant that has been widely studied as a working fluid for ORC systems due to its favorable thermodynamic properties and low environmental impact. Several studies have investigated the performance of ORC systems using R134a as the working fluid for small-scale electricity generation plants. For instance, a study by Peng et al. (2020) proposed a low-temperature ORC system using R134a for waste heat recovery from a diesel engine. The study showed that the ORC system could generate up to 3.7 kW of electricity with a maximum thermal efficiency of 5.8%. Another study by Arslan et al. (2021) investigated the performance of an ORC system using R134a for waste heat recovery from a small-scale biomass boiler. The study showed that the ORC system could generate up to 4.2 kW of electricity with a maximum thermal efficiency of 8.4%.

However, further research is needed to optimize the cycle performance and improve the economic feasibility of ORC systems for widespread adoption. Aspen Hysys is a process simulation software widely used in the chemical and energy industries for the design and optimization of various process plants.

In this study, Aspen Hysys is used for the design and simulation of a low-emission power plant using R134a as the working fluid. The system is optimized by variable simulation of evaporator temperature and working fluid flow rate.

MATERIALS AND METHODS

Material

R134a was used as the working fluid in this study. The characteristics of this fluid include the chemical formula: CF3CHCl2; colorless gas at room temperature and pressure; has a boiling point of -26.2°C and a freezing point of -112.4°C; has a low ozone depletion potential (ODP) and a low global warming potential (GWP). Overall, R134a is considered to be a more environmentally friendly refrigerant compared to some other refrigerants that have higher ODP and GWP. However, it is essential to handle it with care and follow proper safety protocols as they can be hazardous if not handled correctly. Whereas, ORC systems are commonly used for power generation from low-grade heat sources. R134a is a suitable refrigerant for use in ORC systems due to its favorable thermodynamic properties.

Method

This study was carried out with the following steps: Design and construction of the model simulation setup using Aspen Hysys V 12.1 to include an evaporator, economizer, turbine, condenser, and pump. The system model is designed to operate with R134a as the working fluid. After the model is completed, a simulation is carried out using predetermined parameters that correspond to the character of the working fluid R134a. To get data, simulations are carried out based on models that have been built. Data including the duty of the evaporator, cooler, and turbine power output are collected. After that, data analysis is carried out to evaluate the performance of the system. The performance parameters will include thermal efficiency. The last step is that the result of the simulation will be summarized and conclusions drawn regarding the potential of using R134a as a working fluid in an ORC system for low-emission power generation.

The studied system diagrams

The ORC system diagram studied in this article is shown in Figs 1 and 2. Heat sources as the energy input to the system can be a variety of low-grade heat sources such as geothermal, waste heat from industrial processes, or solar thermal energy.

There were two models studied; a simple model that does not use an economizer and a model that uses an economizer. This is done because, at the operational temperature of the evaporator 60 °C, the exit temperature of the turbine is relatively high which can be used as a preheater of the working fluid before it is inserted into the evaporator. This can be done using an economizer. The thermal efficiency of an ORC system can be improved by using an economizer (Nazerifard et al., 2022).

The basic components of this system include; (1) organic working fluid as the heat transfer medium from the heat source to the system, (2) a heater where the organic working fluid is vaporized by the heat from the heat source, (3) turbine as the component that converts the kinetic energy of the expanding organic vapor into mechanical energy, (4) economizer which is used to preheat the working fluid before entering the heater using waste heat from the turbine. (5) cooler where the organic vapor is condensed back into a liquid, (6) pump is used to circulate the liquid organic working fluid from the condenser back to the heater, completing the cycle, and (7) generator as the component that converts the mechanical energy from the turbine into electrical energy. The model system is simulated using operational parameters as shown in Table 1.

Table 1. Operational parameters of the model

Parameter	Set Value
Working fluid mass flow rate (kg/h)	3600-7200
Outlet pump pressure (bar)	10
Evaporator temperature (°C)	60-130
Phase fraction at the pump outlet	0
Phase fraction at the turbine inlet	1
Outlet turbine pressure (bar)	6.9
Turbine and pump efficiency (%)	75

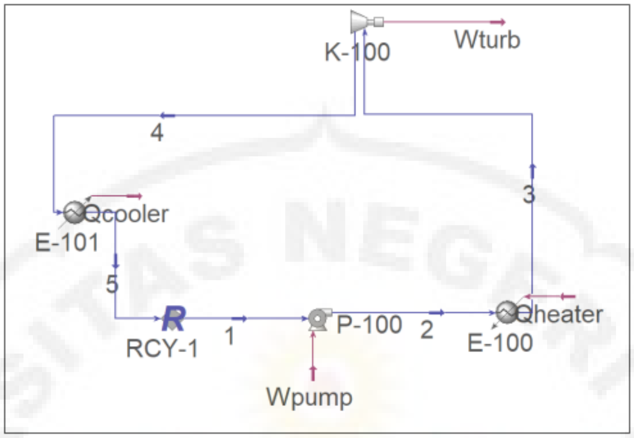

Figure 1. ORC system without an economizer

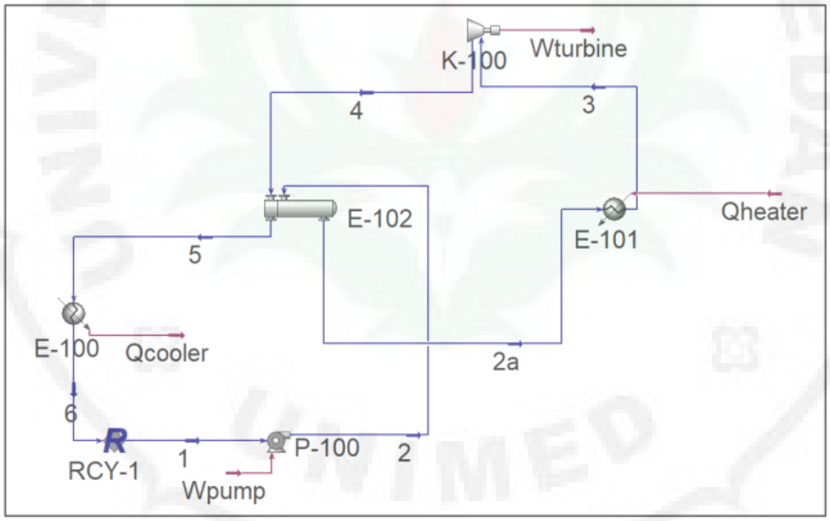

Figure 2. ORC system with an economizer

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RESULTS AND DISCUSSIONS

The effect of the evaporator temperature on the turbine output power

Figs 3 and 4 show graphs of the effect of evaporator temperature on the turbine output power of the system without the use of an economizer and the system using an economizer tested on three variations of the working fluid flow rate (Wf) while the pressure is maintained constant at 10 bar.

It can be seen that the temperature of the evaporator fluid affects the output power of the turbine in both systems with or without an economizer. This is in accordance with research on ORCs using geothermal as an energy source (Schifflechner et al., 2023). This is because the enthalpy of the working fluid increases with the temperature of the evaporator. For the increased temperature of the evaporator, the turbine output power also increases.

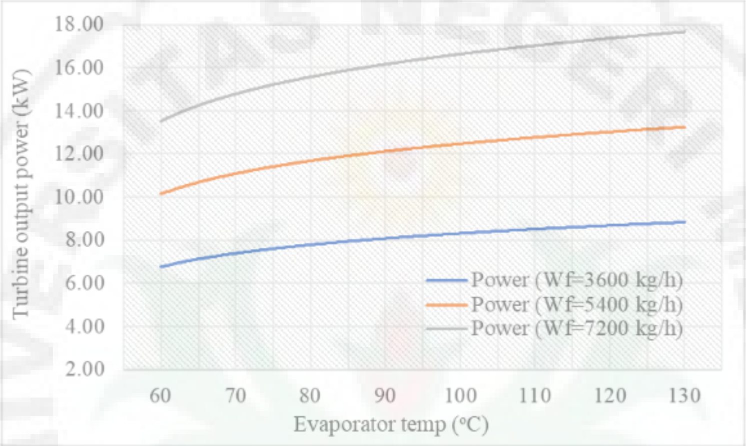

Figure 3. Effect of evaporator temperature at the system without an economizer

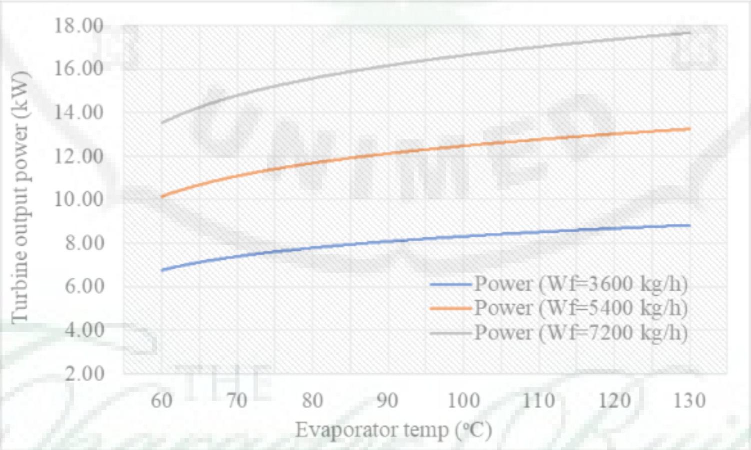

Figure 4. Effect of evaporator temperature at the system with economizer

The effect of the evaporator temperature on the thermal efficiency

Figs 5 and 6 illustrate the variation of the system's thermal efficiency with the evaporator temperature while keeping the turbine inlet temperature at saturated conditions. These graphs indicate that ORC in this study will be more thermally efficient if operated at a low temperature of the evaporator. This is an implication of the 2nd law of thermodynamics as proven in several tests of some organic fluids (Mago et al., 2007). It is theoretically that the enthalpy of the working fluid increases with temperature, but the ability of the turbine also greatly determines the thermal efficiency of the system (Song et al., 2017). For all of the working fluid flow rates that the increase in evaporator temperature resulted in a decrease in thermal efficiency. Thermal efficiency can still be increased again by utilizing wasted heat using other units.

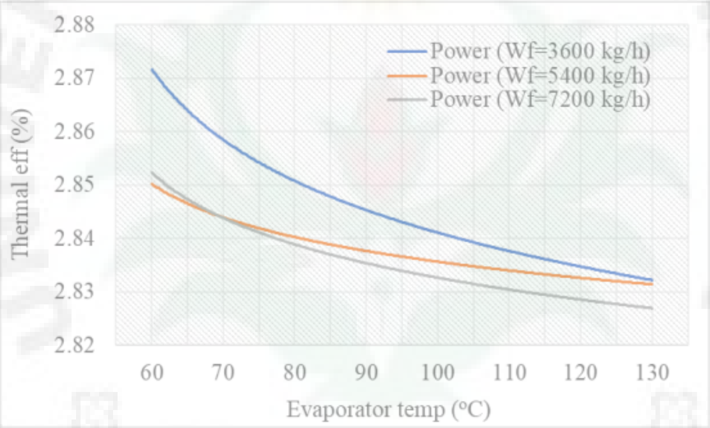

Figure 5. Thermal efficiency on the system without an economizer

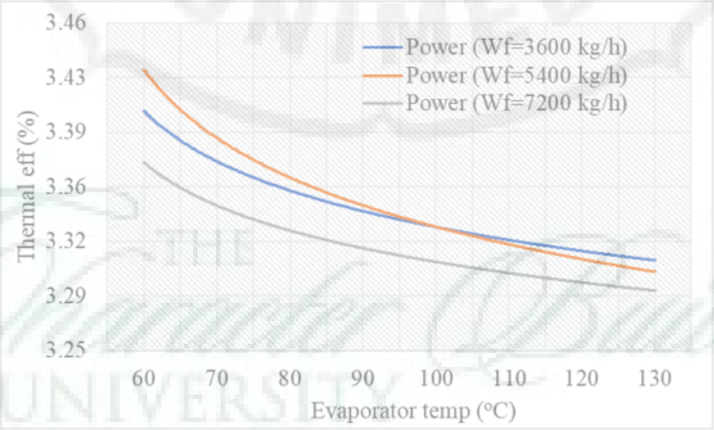

Figure 6. Thermal efficiency on the system with an economizer

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Performance comparison of both models

Figs 7 and 8 explain the performance difference between the two ORC systems using an economizer and without an economizer. ORC systems that use economizers have better performance compared to those that do not use economizers. By adding an economizer unit in an ORC system, the performance can be improved to better than without utilizing an economizer.

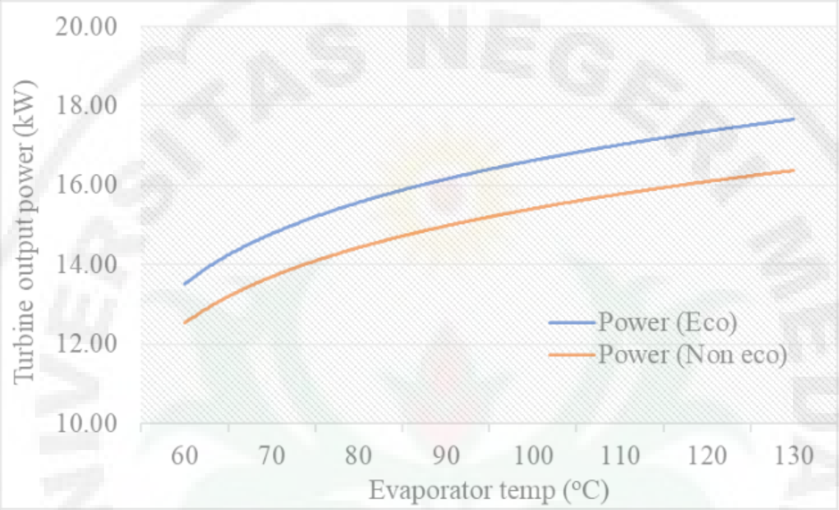

Figure 7. Output power difference with/without using an economizer

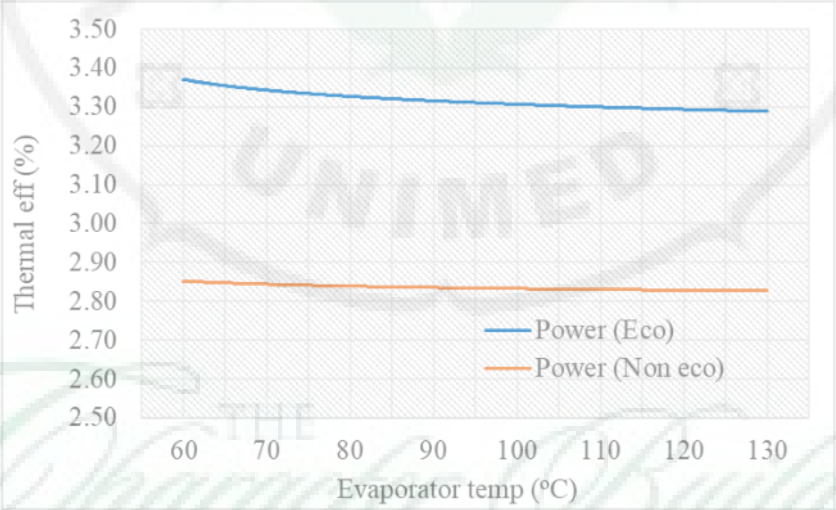

Figure 8. Thermal efficiency difference with/without using an economizer

CONCLUSIONS

Organic Rankine Cycle (ORC) system has been proven to be an effective method for low-grade energy utilization. A model is used to predict the efficiency of a small-scale ORC system. The influence of the R134a working fluid properties and the operating conditions on the system performance is evaluated. Aspen Hysys is used for the analysis of the ORC system under various operating conditions is conducted. The simulation results reveal that the R134a as a working fluid in the ORC system can generate a considerable net power output.

Of course, R134a is a type of refrigerant that is commonly used in air conditioning and refrigeration systems. However, it can also be used as a working fluid ORC because of its thermodynamic properties. Another advantage of R134a is that the system does not need to use a superheated unit.

ORC is a thermodynamic cycle that is used to convert thermal energy into mechanical energy. It is similar to a conventional Rankine cycle, but instead of using water as the working fluid, it uses an organic fluid with a lower boiling point. The organic fluid vaporizes at a lower temperature and pressure than water, making it more suitable for use in low-temperature heat sources. Overall, R134a has the necessary thermodynamic properties to be used as a working fluid in an ORC, and its use can lead to efficient and cost-effective energy generation from low-temperature heat sources.

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