Thermal Efficiency Simulation of Working Fluids Performance on Small Scale Organic Rankine Cycle (ORC) with Biomass Energy

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Abstract. This paper presents the comparative analysis of working fluids R-134a, R-414B, R-404A, and R-407C on small scale Organic Rankine Cycle (ORC) with biomass of coconut shell as heat energy. Simulation of the close system using Cycle Tempo software and compared with mathematical calculation models using Engineering Equation Solver (EES) software. The property of working fluids is obtained by using Reference Fluid Properties (REFPROP). The best result performance of ORC was shown by working fluid R-404A with thermal efficiency ranges between 7.48-7.53% and electric power output range between 0.074-0.091 kW. This condition operated on the turbine inlet temperature at 60 °C, difference turbine working temperature of 15 °C, condensing temperature of 25 °C, and water boiler mass flow rate of 3 lpm. A comparison of thermal efficiency simulated by Cycles Tempo and EES has an average coefficient of determination (R²) is 99.20%.

1. Introduction

Rankine cycle is a thermodynamic cycle that converts thermal heat into mechanical work. Organic Rankine Cycle (ORC) is a modified Rankine cycle that uses working fluids from carbon-based or organic materials such as refrigerants i.e. hydrocarbons, CO₂, H₂O, CCl₄, and CHCs that will drive turbines to produce electricity [1]. Small scale ORC power generation system consists of 4 main components are evaporator, turbine/expander, condenser, and pump. Research related to the development of ORC focuses on the selection and conditioning process of working fluids and heating energy sources. Previous ORC simulation with solar thermal sources using a working fluid R-134a show the results of thermal efficiency of about 8.25% [2]. Utilization of solar hybrids and husk biomass as an ORC heat source with working fluids R123, R134a, and R600a shows the thermal efficiency range in 8.70-13.5% [3]. Although working at lower temperatures and pressures than water fluids in the conventional Rankine cycle, organic fluids are capable of producing higher efficiencies.

Design and performance tests of shell and tube heat exchangers boiler with heat source from a coconut shell fired had conducted [4]. It has shown that water temperature on a boiler reaches 70.77-86.55 °C at a flow rate of 1, 2, and 3 liters per minute (lpm) on biomass feed of 5-10 kg/hour. These results can be used as basic data for the development of small scale ORC with heat sources from biomass fuels. After the heat sources obtained, the next ORC design stage is the selection of the right type of refrigerant and optimal operating conditions for optimal performance.

The objective of this study was to analyze the performance of various refrigerants type as a working fluid on a small scale ORC model with coconut shell biomass as a heat energy source by thermal simulation approach. The refrigerants were R-134a, R-414B, R-404A, and R-407C. These fluids selection considers the thermal characteristics and wide application in industrial and household fields. The parameters conditions to be simulated are water boiler heat as an ORC evaporator, flow
rate of water boiler, temperature of the fluid in and out of the ORC turbine (expander), condensation temperature, and working pressure of the system. Thermodynamic in the steam compression cycle generally simulated by Cycle Tempo software, which provides a variety of analysis tools [5]. However, some users have a problem using it because of complicated procedures and became a hindrance to getting results in a relatively short time. Engineering Equation Solver (EES) is a software that can solve linear, nonlinear, differential, and other mathematical equations, including thermodynamic laws. EES expected to be able as an alternative simulation tool on performance analysis of a steam compression system. In this study, simulation analysis of small scale ORC models will be performed using Cycle Tempo software and comparing with mathematical models using EES software. The results can be used as a reference in determining the optimum working parameters in the development of ORC with biomass as an alternative energy source.

2. Research Method

The research design of the simulation process on small scale ORC performance with biomass energy described as follows:

2.1. Small Scale ORC Model

Figure 1 shows a schematic of the basic ORC principle. The organic Rankine cycle is working by a fluid of refrigerant phase cycle loop in a closed system. The boiler heating some water using biomass as a heat source. Then the liquid refrigerant pumped to a boiler where it is heated to the above boiling point under pressure and change into the superheated phase (gas). The gaseous of refrigerant then expanded in a turbine, and the mechanical energy is converted into electricity in a generator. The gas is cooled in a condenser and change into a subcooled phase (liquid), then refrigerant is again pumped into the boiler repeatedly.

![Figure 1. The schematic of basic ORC principle](image)

This mini scale ORC model using biomass of coconut shell as a boiler fuel with a feed rate of 5 kg/hour and water flow rate at the heat exchanger of 1, 2, and 3 liters per minute (lpm). Data of the water temperature inlet-outlet boiler as an evaporator and the water flow rate obtained from previous studies [4], as shown in Table 1. In this study, four different types of working fluids will be simulated, namely, R-134a, R-414B, R-404A, and R-407C. The determination of the fluids is based on the thermal characteristics and referred to refrigerant standards by National Refrigerants [6] and ASHRAE safety standards [7]. Physical properties of working fluids are obtained using REFPROP software that can calculate the thermodynamic and transport properties of various refrigerants.
Table 1. Average water temperatures inlet-outlet boiler in water flow rate

| Water flow (litter per minute) | Heat water as an ORC evaporator (°C) |
|-------------------------------|-------------------------------------|
|                               | Inlet  | Outlet |
| 1                             | 73,63  | 86,55  |
| 2                             | 70,77  | 77,74  |
| 3                             | 71,60  | 76,35  |

The boundary condition of ORC working parameters that will be simulated describe below:

1. Working fluids have phase changed to gas or evaporated at 60 °C with turbine working pressure between 10 and 15 bars.
2. Working fluids have phase changed to liquid or condensed in the temperature range of 20-30 °C, with a pressure drop difference of 2 bars at the turbine.
3. The fluid temperature on the turbine ranges from 60-85 °C, with variations temperature difference inlet and outlet at the turbine of 5 °C, 10 °C, and 15 °C.

2.2 Simulation Process

The simulation assumed the model is in a steady state-closed system and the working fluid in the steam phase during flow on to the turbine. The output of this simulation is information about temperature, enthalpy, working pressure, mass flow rate, power, and isentropic efficiency of each refrigerant scenario. The system boundary and specified working fluid properties then entered as input based on small scale ORC model with Cycle Tempo Release 5. The model work diagram of the simulation process is shown in Figure 2. In this study, evaluation with EES version 6.8 for performance and thermal analysis will be compared with the Cycle Tempo simulation.

![Figure 2. The layout of small scale ORC model simulation using biomass energy](image)

The parameters and equations used in data processing and analysis stage [8] are described as follows:

Energy balance on Rankine cycle simulation

\[ \text{Energy balance on Rankine cycle simulation} \]
\[ \sum_{j=1}^{n} \bar{m}_{m,in}(j)h_{in}(j) - \sum_{i=1}^{n} \bar{m}_{m,out}(i)h_{out}(i) = Q + W \]  

(1)

Heat (kJ) in on the Evaporator

\[ Q_{in} = \bar{m}_{m,in}(h_3 - h_2) \]  

(2)

Heat (kJ) out on the Condenser

\[ Q_{out} = \bar{m}_{m,out}(h_3 - h_2) \]  

(3)

Work (watt) out on the turbine

\[ W_{out} = \bar{m}_{m,out}(h_3 - h_4) \]  

(4)

Work (watt) in on the pump

\[ W_{in} = \bar{m}_{m,in}(h_2 - h_1) \]  

(5)

Thermal isentropic efficiency on Rankine cycle

\[ \eta = \frac{W_{out} - W_{in}}{Q_{in}} \times 100\% \]  

(6)

Back Work Ratio (BWR) equation as follow

\[ BWR = \frac{\dot{W}_{in}}{\dot{W}_{out}} \]  

(7)

Where \( h \) is the enthalpy (kJ/kg), \( \bar{m}_m \) is the mass flow of the working fluids (kg/s). The simulation conducted in a steady state-closed system.

3. Result and Discussion

3.1 Working Fluids Characteristic and Properties

A substance in the liquid phase that existing at a temperature below normal boiling point is called subcooled or undercooled. While the substance in the gas phase that has not condensed is called superheated. In the liquid and gas mixture, the mass fraction of the substance is called the fluid quality (ratio of the mass gas and liquid saturation). It has a value between 0 (liquid saturation) to 1 (gas saturation) [9].

Condensation temperature refers to the fluid that exits the condenser due to the release of heat into the environment. The performance of heat exchangers is not specifically analyzed in this study. Turbine temperature refers to fluid after heating the evaporator and entering the turbine. In this section, the thermal heat energy converted into mechanical work that can produce electricity. Based on simulation, working fluids R-134a and R414B have entered the subcooled phase at 8 bars pressure in any variation of condensation temperature. Working fluids R-404A and R-407C enter the subcooled phase at a pressure of 13 bars with the same condensation temperature. Refrigerant must be in a superheated phase when entered the turbine. Biomass combustion in the water boiler was used as a fuel source. It is proven that the water heat enough to change the phase from liquid (subcooled) into gases (superheated) of working fluid at temperature 60 °C and 10 bars pressure for refrigerant R-134a and R-414B, 15 bars for R-404A and R407C. Table 2 shows the pressure, enthalpy, and quality/phase of refrigerant for ORC simulation.
### Table 2. Thermal properties of refrigerant as a working fluid in small scale ORC

| Temp. (°C) | Pressure (bars) | R-134a | R-414B |
|------------|-----------------|--------|--------|
|            |                 | Enthalpy (kJ/kg) | Phase (kg/kg) | Enthalpy (kJ/kg) | Phase (kg/kg) |
| Condensation |                 |                    |                |                    |                |
| 20         | 8               | 227.49             | Subcooled     | 223.74             | Subcooled     |
| 25         | 8               | 234.55             | Subcooled     | 229.83             | Subcooled     |
| 30         | 8               | 241.72             | Subcooled     | 306.04             | Mixture, x= 0.40734 |
| Turbine Inlet |               |                    |                |                    |                |
| 60         | 10              | 441.53             | Superheated   | 426.49             | Superheated   |

| Temp. (°C) | Pressure (bars) | R-134a | R-414B |
|------------|-----------------|--------|--------|
|            |                 | Enthalpy (kJ/kg) | Phase (kg/kg) | Enthalpy (kJ/kg) | Phase (kg/kg) |
| Condensation |                 |                    |                |                    |                |
| 20         | 13              | 228.68             | Subcooled     | 229.13             | Subcooled     |
| 25         | 13              | 236.27             | Subcooled     | 236.70             | Subcooled     |
| 30         | 13              | 381.14             | Superheated   | 301.52             | Mixture, x=0.32201 |
| Turbine Inlet |               |                    |                |                    |                |
| 60         | 15              | 411.92             | Superheated   | 449.08             | Superheated   |

#### 3.2 Performance Analysis of Small Scale ORC

The results of thermal efficiency simulation in each refrigerant can be seen in Figure 3-5. Under the temperature of 30 °C condensations, the working fluid R-414B, R-407C, and R-404A can’t be operated. It happens because the properties of the R-414B and R-407C are still in a mixed-phase between gas and liquid, thus affecting on pump flow. Since R-404A is still in the superheated phase, which causes the pump not to work as well and getting stuck.

Condensation temperature affects efficiency in the ORC, because of the heat energy released from the working fluid to the cooling fluid. The lower condensation temperature states that the heat energy released is higher, so to raise the temperature of working fluid when entering the turbine requires higher energy as well. The difference temperature between the inlet-outlet turbine states the change from heat energy to mechanical work [10]. The higher difference temperature of the turbine has an impact on increasing thermal efficiency. This happens because the decrease in temperature of the working fluid that occurs in the turbine indicates that heat energy stored in the working fluid is converted into mechanical motion. The higher mechanical work that is formed caused, the higher power to generated electricity [11].
Figure 3. Thermal efficiency in the ORC scenario inlet-outlet turbine temperature difference of 5 °C.

Figure 4. Thermal efficiency in the ORC scenario inlet-outlet turbine temperature difference of 10 °C.
Analysis with EES software shows the results that are not different from the Cycle Tempo. Correlation of thermal efficiency between the ORC simulation results of the two methods expressed in $R^2$ values. It was found that the coefficient determination of two simulations is close to 1, with an average value of 99.20%. Therefore, Cycle Tempo and EES can be used in performing analysis on small scale ORC simulations. Optimizations obtained in this simulation are working fluid operating at turbine working temperature of 60 °C, turbine working temperature difference of 15 °C, and condensation temperature of 25 °C. The maximum thermal efficiency obtained was in the range of 7.482-7.537% with the working fluid R-404A. Figure 6 shows the maximum thermal efficiency value of each ORC working fluid.

**Figure 5.** Thermal efficiency in the ORC scenario inlet-outlet turbine temperature difference of 15 °C.

![Thermal Efficiency Diagram](image)

**Figure 6.** Diagram of the maximum thermal efficiency value of each refrigerant

The maximum power in ORC simulations occurs under conditions of a turbine temperature difference of 15 °C and water flow at 3 lpm. Figure 7 shows the power that can be achieved from the
4. Conclusion
Analysis of thermal efficiency performance of working fluids on small scale ORC models with biomass energy conducted by Cycle Tempo and EES software has been able to provide thermal efficiency and power information for each working condition. From the two simulations performed, the best performance is shown by working fluid R-404A with thermal efficiency between 7.482-7.537% and the power range between 0.0744-0.0911 kW, where ORC operates at turbine working temperature of 60 °C, turbine working temperature difference at 15 °C, condensation temperature of 25 °C and mass flow rate of 3 lpm. A comparison of thermal efficiency between two software performed has an average coefficient of determination (R²) of 99.20%. This shows that ORC simulations can also be done with simpler devices using common thermodynamic mathematical formulations such as Engineering Equation Solver (EES).

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